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Measuring Fission Chain Dynamics Through Inter-event Timing of Correlated Particles

Mateusz Monterial

Doctoral Committee:

- Professor Sara A. Pozzi, Chair
- Professor Christine A. Aidala
- Dr. Shaun Clarke
- Dr. Peter Marleau, Sandia National Laboratories
- Professor David K. Wehe

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Motivation
Correlated Timing as a Unique Signature

- Applications
  - Non-proliferation and safeguards
  - Arms control treaty verification
  - Emergency response
- Characterization/imaging
  - Is it Special Nuclear Material?
  - Is it weaponized?
  - Material properties
    - Mass, multiplication, isotopic
- Method
  - Measuring time correlate gammas and neutrons for non-destructive assay of nuclear material

IAEA International Atomic Energy Agency

Non-proliferation

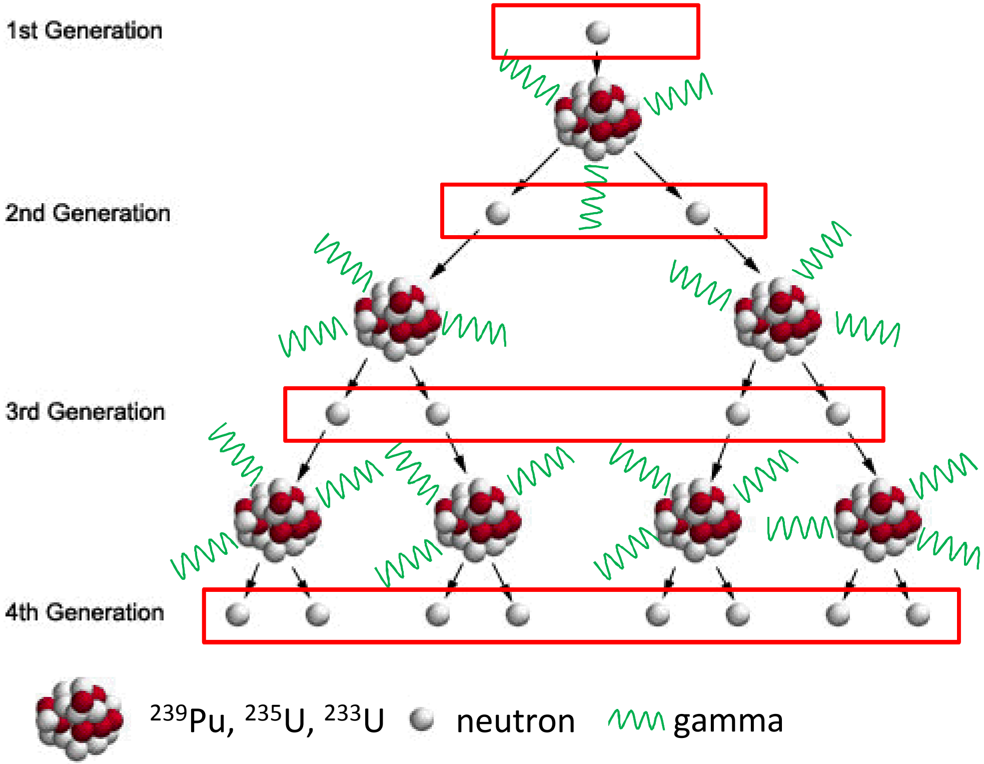
Arms control treaty verification

NNSA Joint Technical Operations Team

Emergency response

Bilateral nuclear stockpile reduction

What is so special about SNM?
Basic vocabulary and definitions



http://www.atomicarchive.com/Fission/Fission2.shtml

Fission products:

- 2 - 4 neutrons per fission ($\bar{\nu}_n$)
- 7 - 9 gammas per fission

Quantities of Interest:

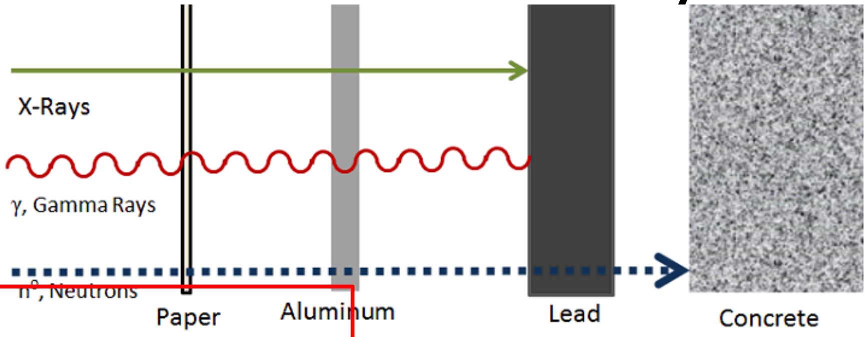
$$k = \frac{neutrons\ in\ one\ generation}{neutrons\ in\ preceeding\ generation}$$

Subcritical multiplication – *total* neutrons created per source neutron:

$$\boldsymbol{M = \frac{1}{1-k}}$$

Current Methods for Non-destructive Assay

Drawbacks and Limitations



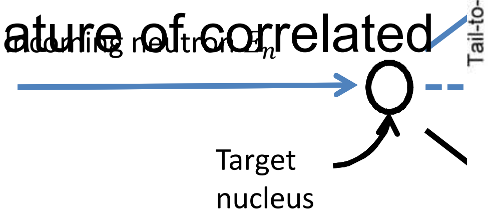
1. Gamma-ray spectroscopy
   - Attenuation and self-shielding
2. Total neutron rate
   - Easily spoofed
   - Spontaneous & induced fission and (α,n) sources are indistinguishable
3. Multiplicity Counting
   - Requires high efficiency, necessitates large detection system
   - Efficiency has to be well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

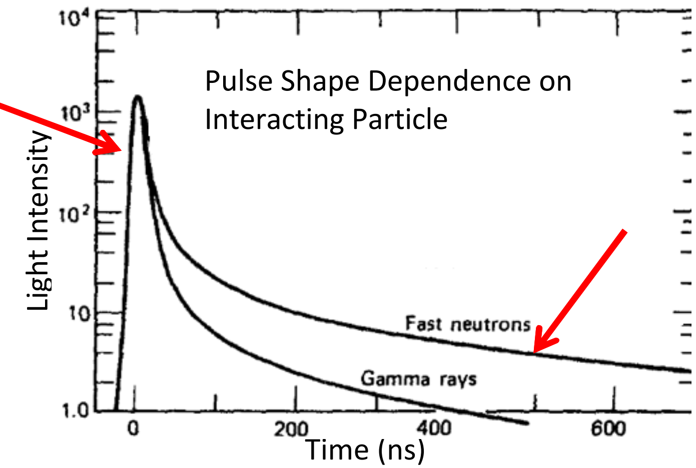
→ Thermal neutron capture detectors (He-3)

Fast Organic Scintillators

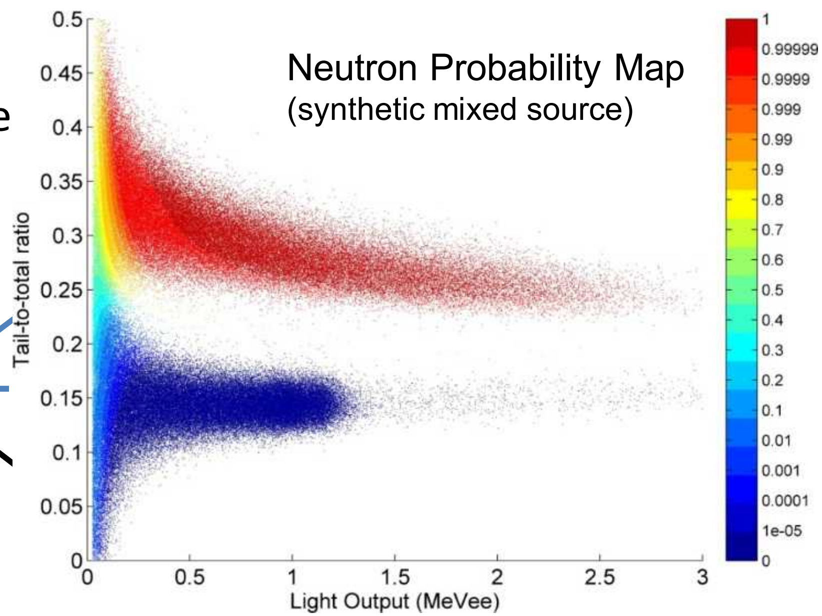
Three main new advantages

1. Fast rise time
   - Sub-nanosecond timing resolution
2. Incident neutron energy
   - Light output proportional to proton recoil
3. PSD Capable
   - Discriminate neutrons and gamma rays
   - Gamma rays provide clean timing signature of correlated event





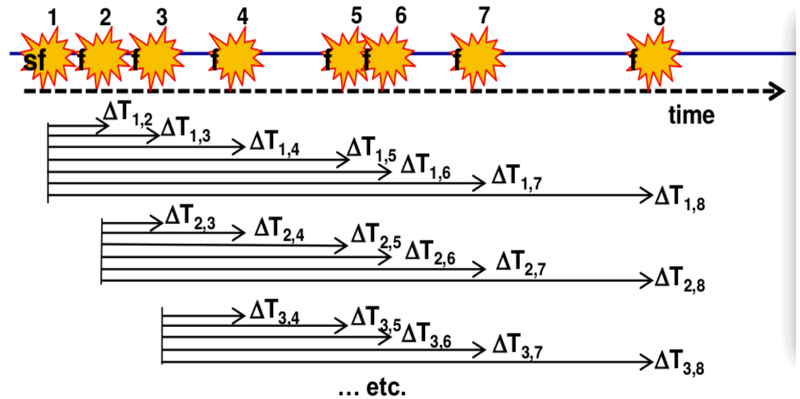
Glenn Knoll Radiation Detection & Measurement 3rd Edition

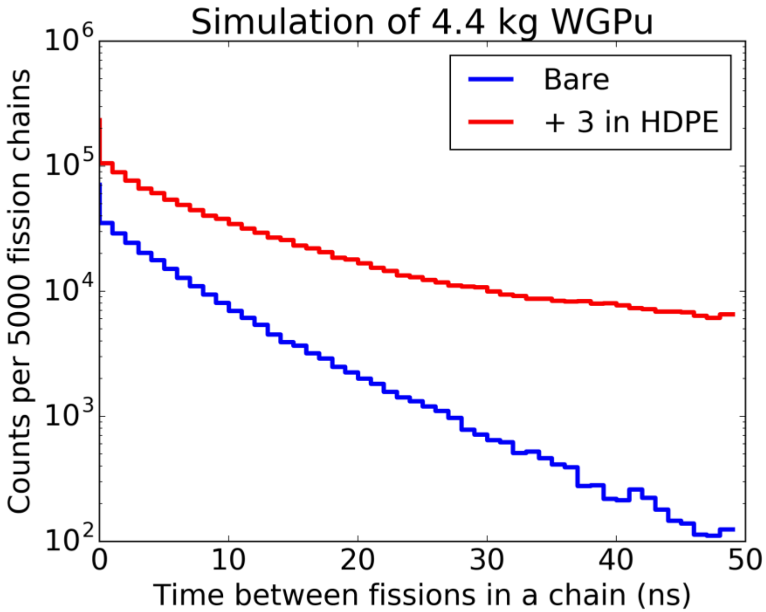


Research Objectives

1. Determine presence of fissile material *and* any coupled material by measuring effects of *timing* between fission events in a fission chain.
2. Characterize fissile material and with a physical model.
3. Demonstrate any other potential information carried by a correlated gamma-neutron pair.

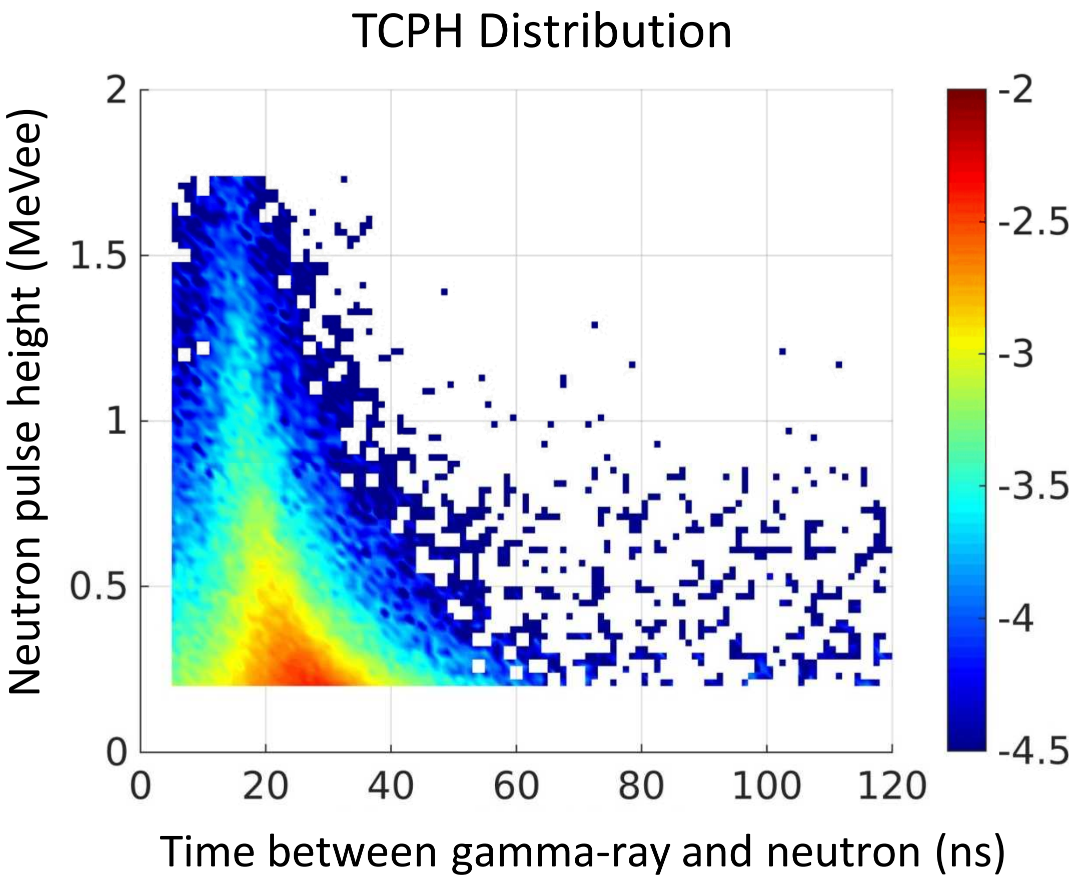
Distribution of times between fission events in a chain





Time Correlated Pulse Height Distributions

Background on previous work



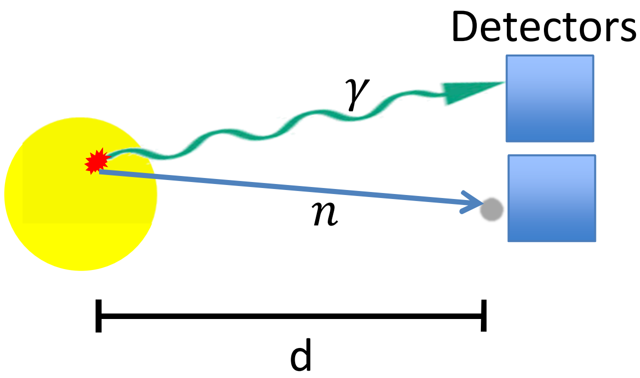
1. TCPH is the bivariate histogram of the measured quintiles
2. Physical interpretation is not obvious
3. Difficulty of dealing with a 2D distribution (both qualitative and quantitative)

Same Fission Gamma-Neutron Correlations

Time Of Flight Fixed by Estimated Energy (TOFFEE)

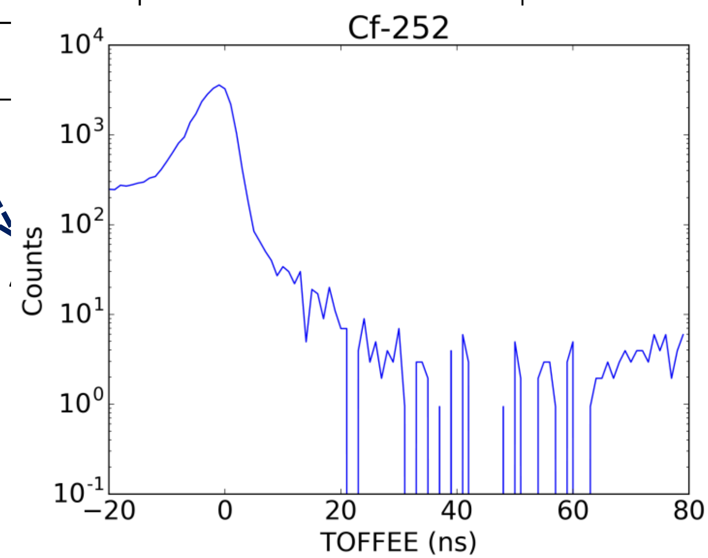
E_n: neutron energy
R_γ: distance traveled by gamma ray
R_n: distance traveled by neutron

$$\Delta T_{n-\gamma} - \left(R_n \sqrt{\frac{m}{2E_n}} - \frac{R_\gamma}{c} \right) = 0$$



Time of arrival difference between γ and neutron	Time of flight difference between γ and neutron
Measured	

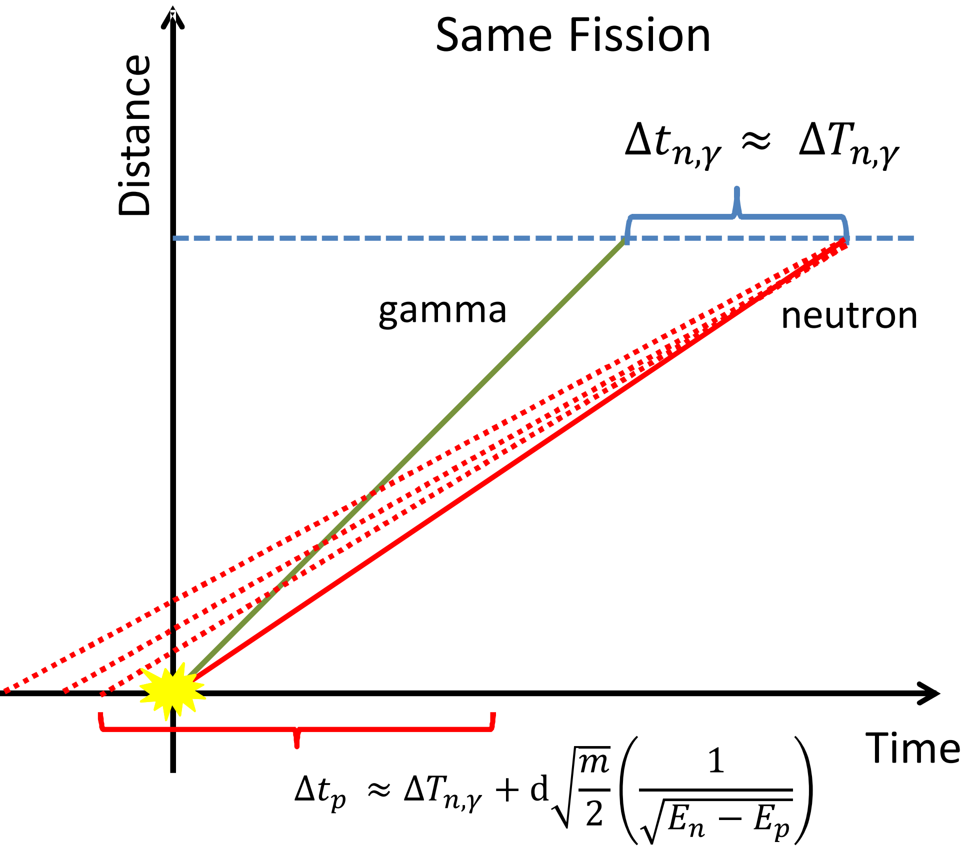
$$\Delta t_{n,\gamma} - \Delta t_p \leq 0$$



Measured Quantities:

- Time between correlated γ and neutron: $\Delta t_{n,\gamma}$
- Proton recoil energy: $E_p \leq E_n$
- Source-to-detector distance: $d \approx R_n = R_\gamma$

Same Fission Gamma-Neutron Detection Space-Time

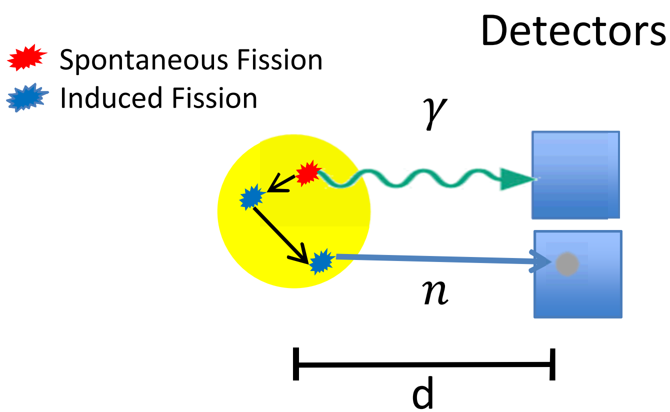


1. Neutron and gamma are born from the same fission event
2. They travel some distance the detectors
3. The measured and actual difference in time-of-flight is equivalent
4. When subtracting estimated time of flight of the neutron, the result is less than zero

$$\Delta t_{n,\gamma} - \Delta \mathrm{t_p} \leq 0$$

Neutron-Gamma Correlation – Fission Chain

Time Of Flight Fixed by Estimated Energy (TOFFEE)



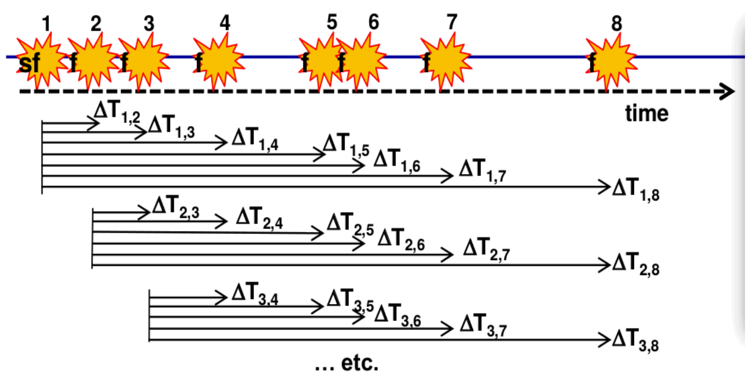
Time difference between fission events in a chain

$$\Delta t_{n-\gamma} - \Delta t_p \leq \Delta T_g$$

Measured time difference between neutron and nearest γ

Estimated travel time difference between neutron and gamma

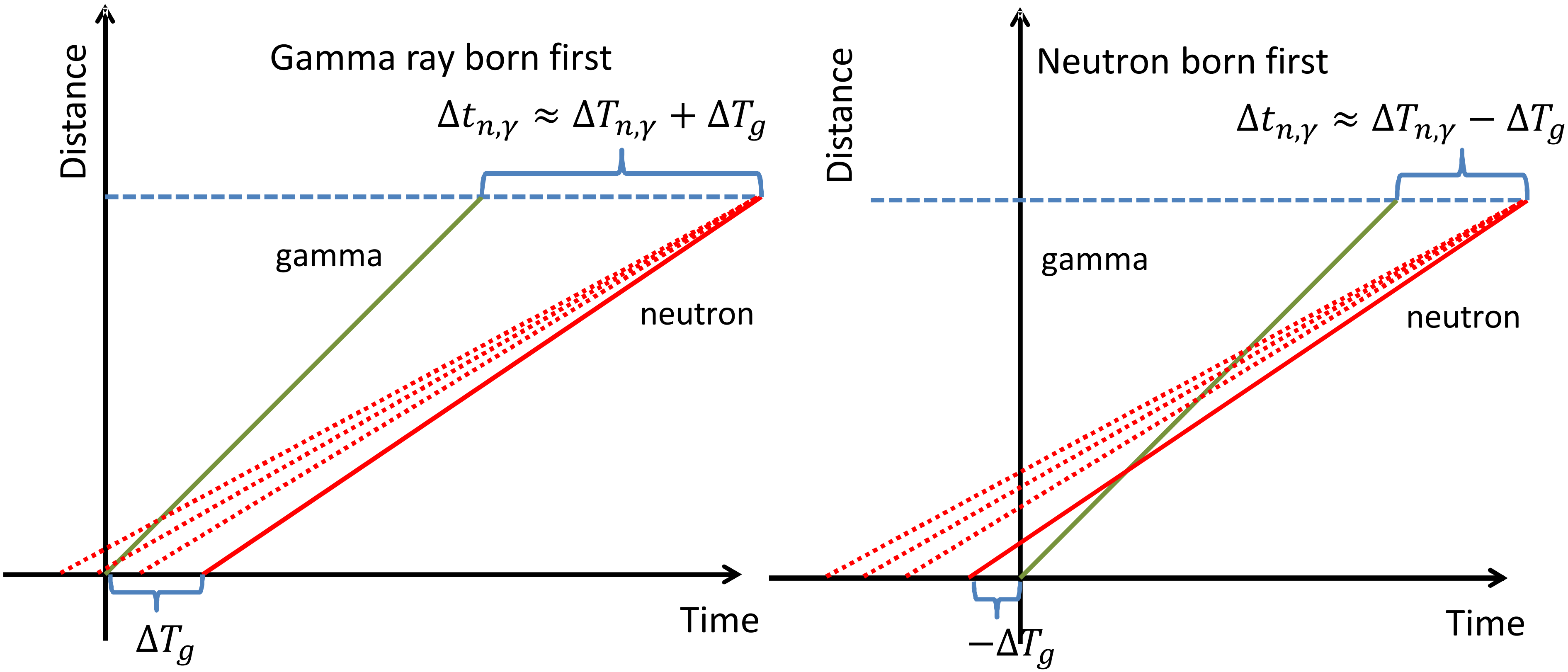
Distribution of times between fission events in a chain



$$\Delta T_g > 0 \text{ if } f_1 = \gamma \ \& \ f_2 = n$$

$$\Delta T_g < 0 \text{ if } f_1 = n \ \& \ f_2 = \gamma$$

Fission Chains Gamma-Neutron Space-Time



$$\Delta t_{n,\gamma} - \Delta \mathrm{t_p} \leq \Delta T_g$$

$$\Delta t_{n,\gamma} - \Delta \mathrm{t_p} \leq -\Delta T_g$$

TOFFEE Sensitivity to Fissile Material and Configuration

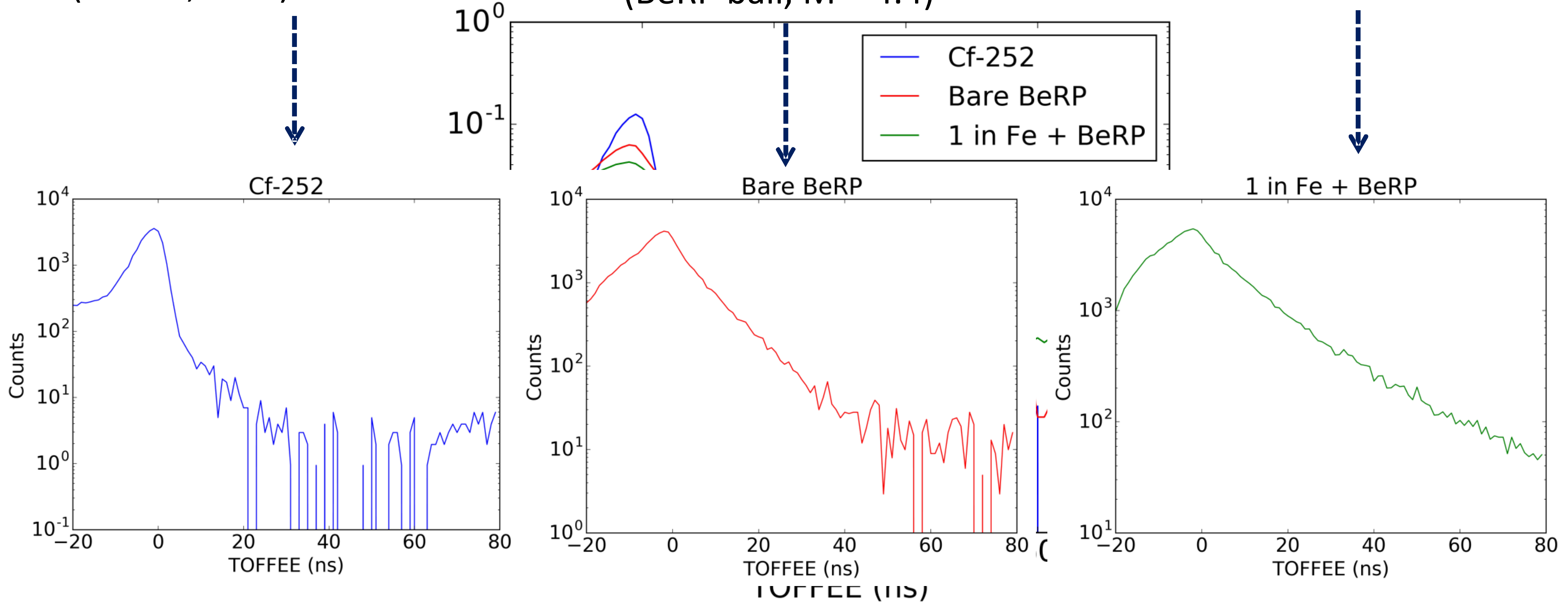
TOFFEE is sensitive to:

1. Fissile vs. fissionable
2. Fissile materials with different neutron multiplication
3. Bare vs. reflected fissile cores

Non-fissile fission source (Cf-252, M=0)

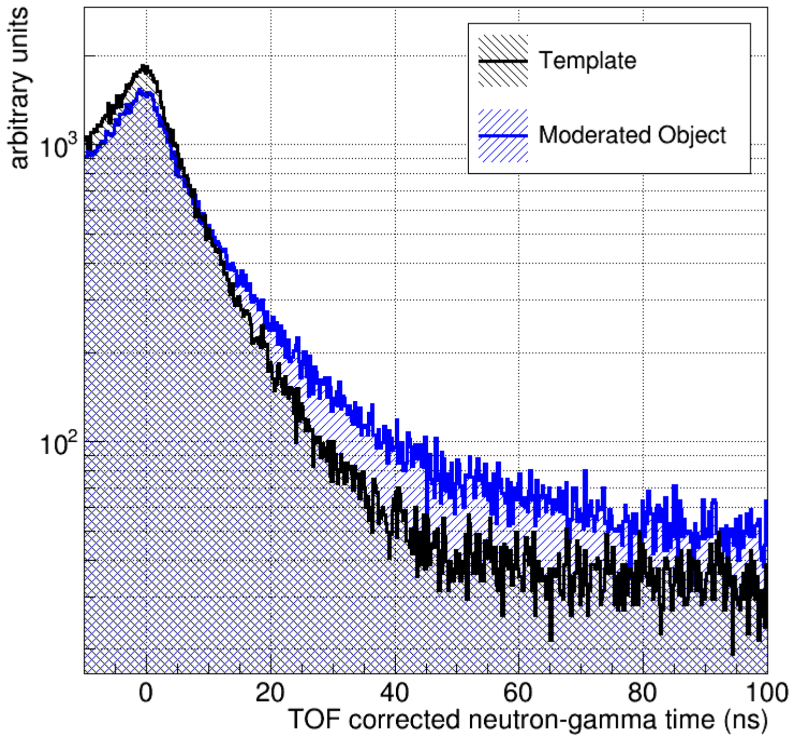
Fissile material (BeRP ball, M = 4.4)

Reflected Fissile material (BeRP ball, M = 6.48)



Comparing TOFFEE Distributions

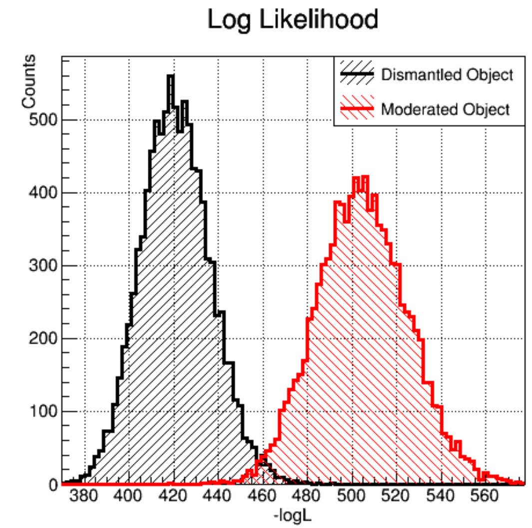
- Align peak to zero
  - Source-to-detector distance
- Subtract background (-1500-500 ns)
- Compare measurement to template
  - Threshold on log-likelihood
- Determine match
  - Pass/Fail threshold?

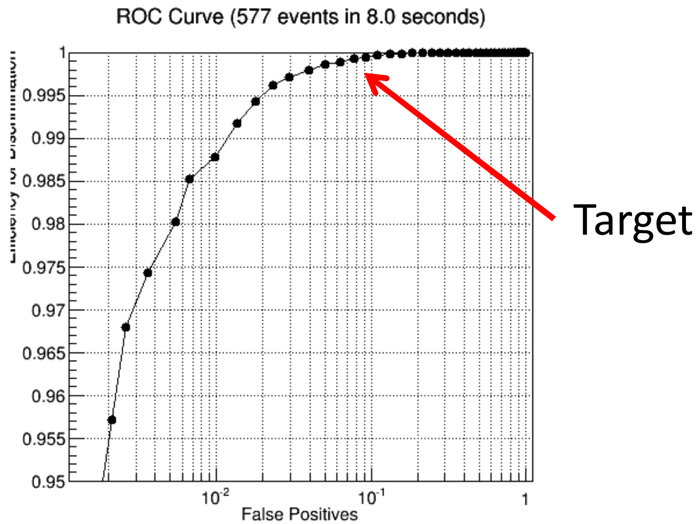


$$L = \sum_{i=0}^{n} -\log\left(P(x_i|\mu_i)\right)$$

Determine Minimum Dwell Time for Confirmation

1. For specific *dwell time* throw 10,000 random trails
   – Build log-likelihood distributions
2. Calculate Receiver Operator Curves (ROC)
3. Determine False Positive (FP) rate at 99% True Positive (TP) Rate
4. Repeat step (1) with increased dwell time (more counts) if FP > 1% at TP = 99%

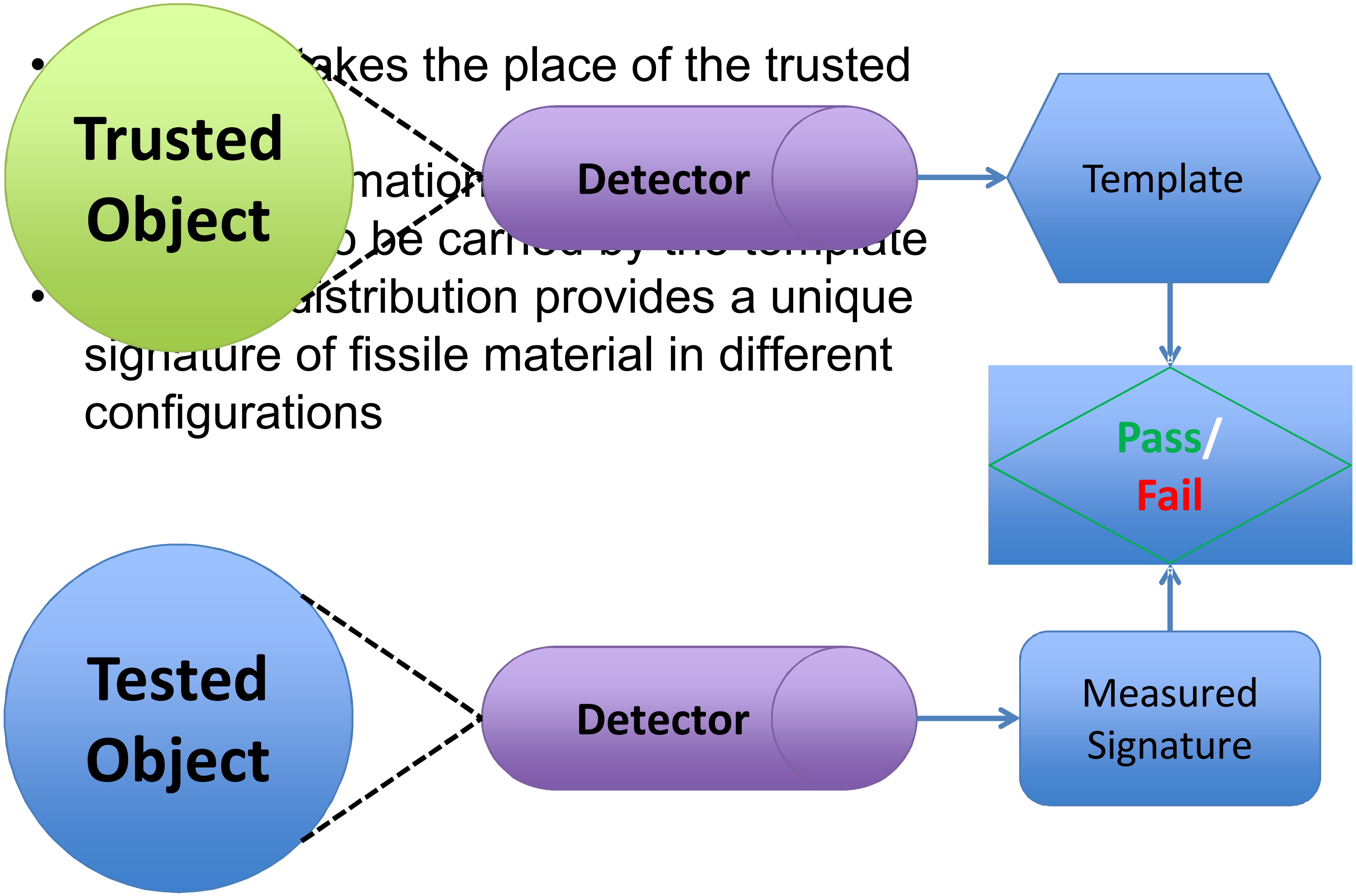




Template-based Verification with TOFFEE

Dismantlement and Item Confirmation for Treaty Verification

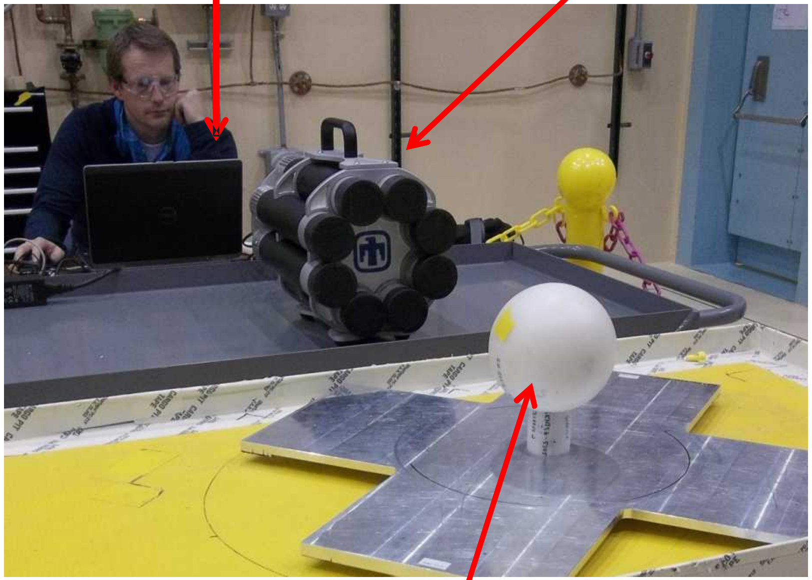
- … takes the place of the trusted … mation … o be carried by the template
- … distribution provides a unique signature of fissile material in different configurations



Measurements of Fissile Material

Computer/digitizer

Stilbene array



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

HEU (93.15% enriched)

Training Assembly for Criticality Safety (TACS)

Photo from LLNL-TR-489234

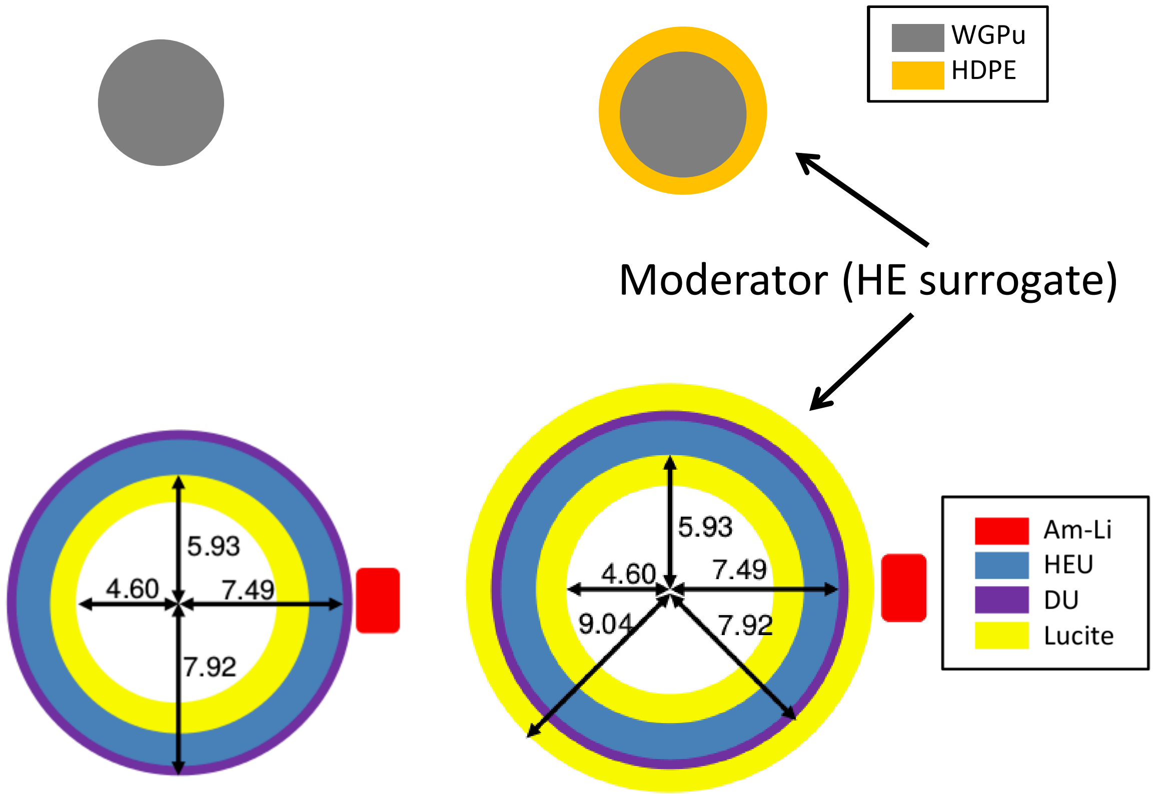
Dismantlement Confirmation

Defining removal of high explosive

Trusted Object | Tested Object

BeRP ball

TACS shells



*dimensions in cm

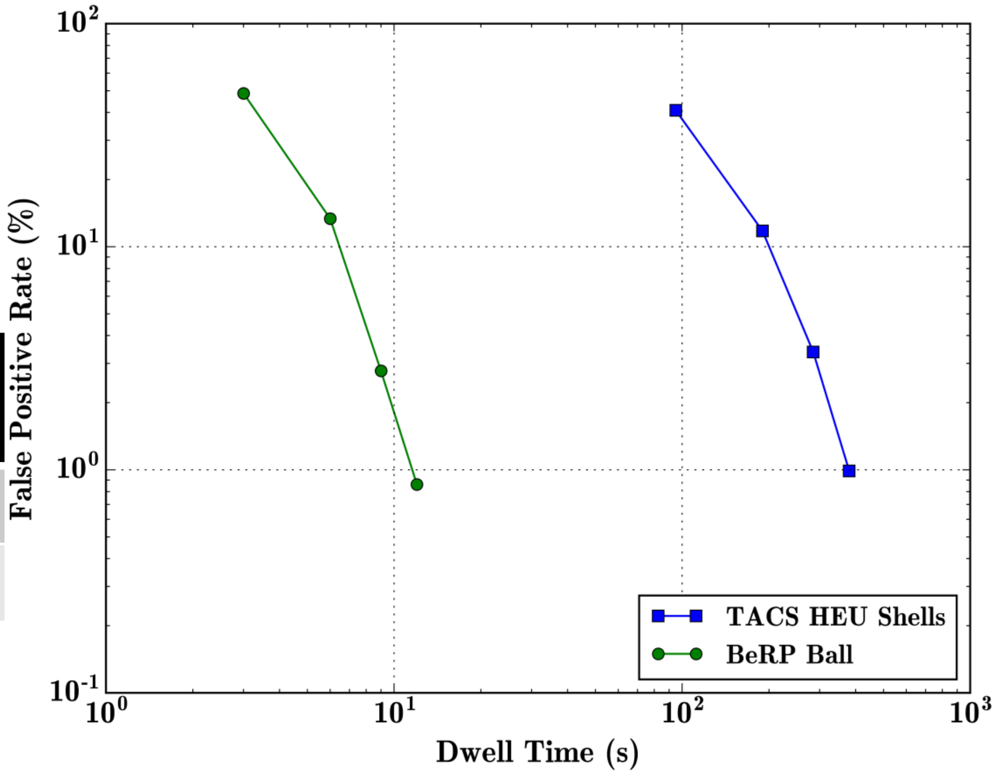
Results – Dismantlement Confirmation

Minimum dwell time to confirm dismantlement

- **Template:** Bare (non-moderated) object
- **Test:** Moderate object
- Threshold: TP = 99%
  FP < 1%

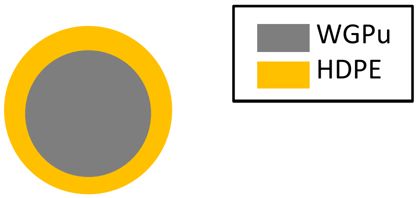
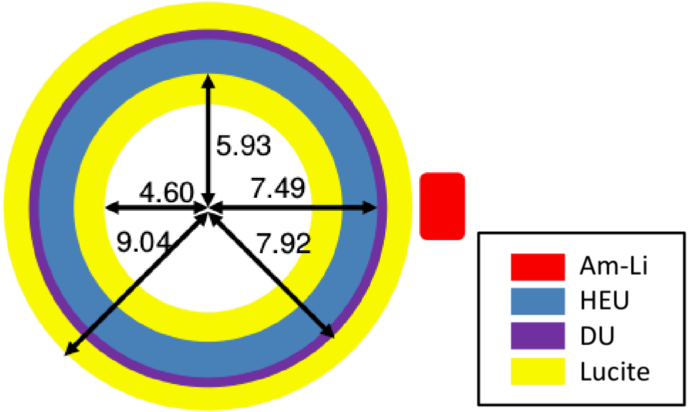
Min. Dwell Time for Dismantlement Confirmation

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



Item Confirmation

Defining plausible spoof objects

	Trusted Object	Tested Objects
BeRP Ball		1. Cf-252 2. Pu Oxide Shells (Hemis)
TACS (HEU)		1. Cf-252 2. Pu Oxide Shells (Hemis)

Results – Item Confirmation

Minimum dwell time to confirm fissile material

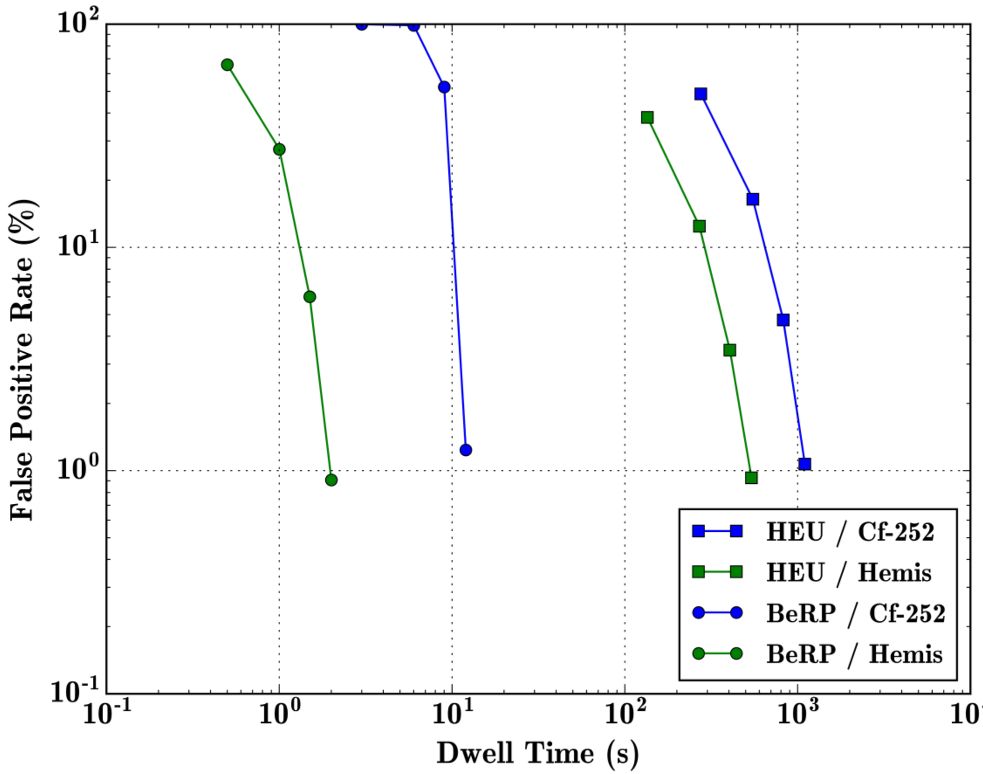
- **Template**: Moderated BeRP and TACS
- **Test:** Non-multiplying Cf-252 and Hemi Shells (Pu Oxide)

Min. Dwell Time for Item Confirmation

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

Min. Dwell Time for Item Confirmation

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



Extracting Physical Parameters from TOFFEE

Parametric Experiments and Simulations

- TOFFEE distribution was shown to discriminate between fissile assemblies
- A physical model is required to extract physical parameters by fitting the TOFFEE distribution
- Use point-kinetics model (energy and spatially independent), which describes the neutron population change, which tracks with the density of fissions in a fissile material

Measurements of BeRP ball

- Bare
- 0.5 in Steel
- 1.0 in Steel
- 1.5 in Steel
- 1.0 in Nickel

Simulations

- 0.5 – 6 in Steel
- 0.5 – 6 in Nickel
- 0.5 – 6 in Tungsten
- 0.5 – 6 in Aluminum

Two-region point kinetics

Core:

Neutron multiplication — Return from reflector — Loss in the core (abs & leakage)

$$\frac{dN_c}{dt} = \frac{k_c}{l_c} N_c + f_{rc} \frac{N_r}{l_r} - \frac{N_c}{l_c}$$

Reflector:

Influx from the core — Loss in the reflector

$$\frac{dN_r}{dt} = f_{cr} \frac{N_c}{l_c} - \frac{N_r}{l_r}$$

N_c & N_r: the number of neutrons in the fissile core and reflector regions

l_c & l_r: neutron lifetimes in the fissile core and reflector regions

k_c : multiplication factor in the fissile core region

$f = f_{cr} * f_{rc}$: fraction of neutrons that leak to reflector AND return to the core

Solution is a double exponential

$$N_c(t) = N_o[(1-R)e^{tr_1} + Re^{tr_2}]$$

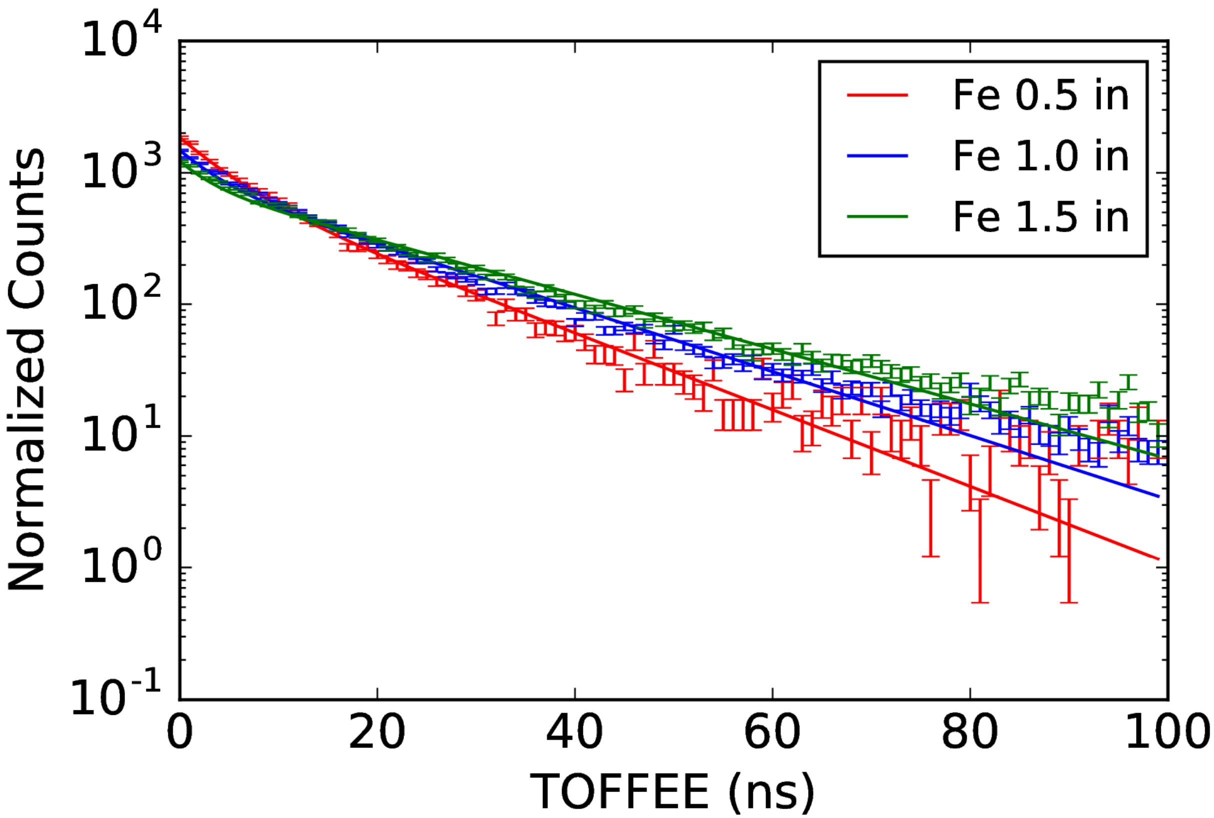
$$r_{1,2} = \frac{\pm\sqrt{4l_c l_r(f + k_c - 1) + \left(l_c - l_r(k_c - 1)\right)^2} - l_c + l_r(k_c - 1)}{2l_c l_r}$$

Scale Parameter: $R = \dfrac{r_1 - \alpha}{r_1 - r_2}$

Rate parameter in a bare configuration : $\alpha = \dfrac{k_c - 1}{l_c}$

Fitting Strategy for Reflected Configurations

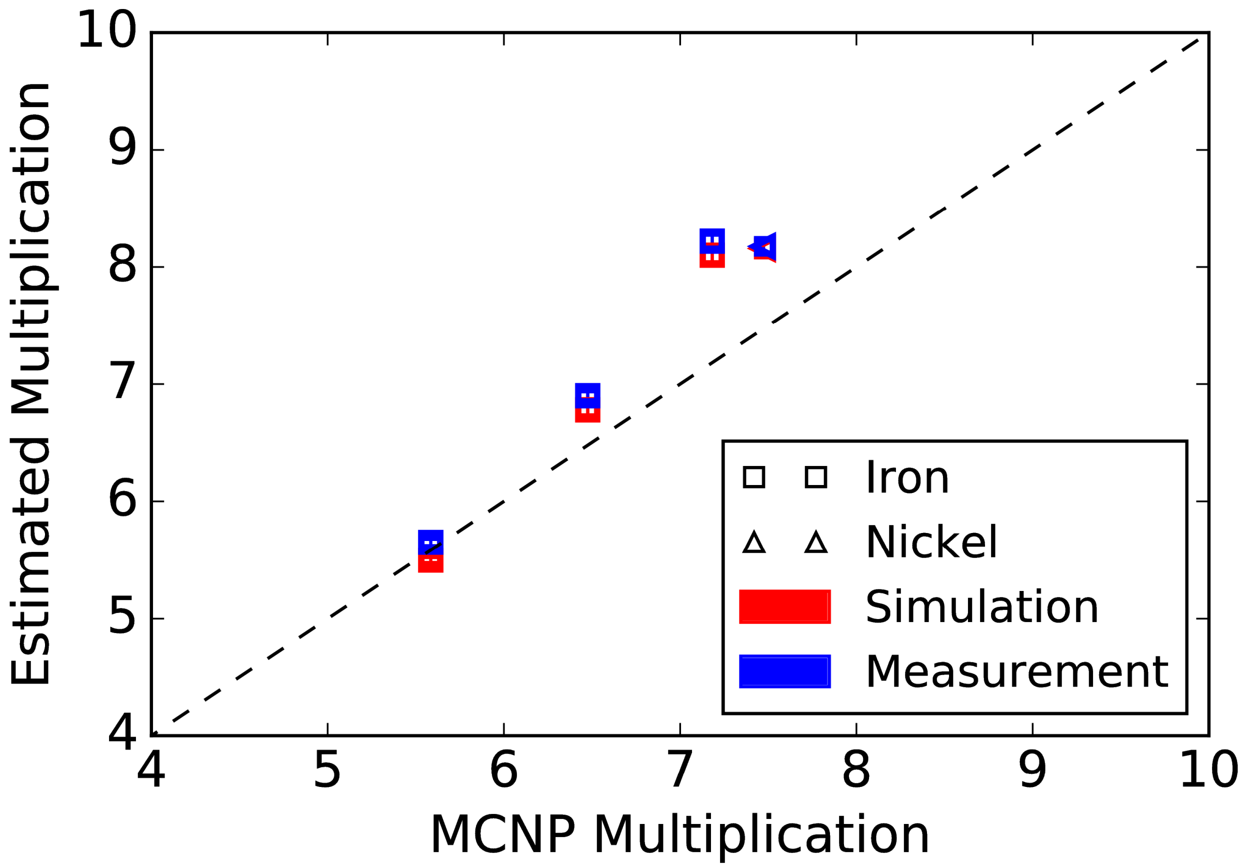
$$N_c(t) = N_o[(1-R)e^{tr_1} + Re^{tr_2}]$$



- Allowing reflection fraction (f) and neutron lifetime (l_r, l_c) produces muddled results
- Solution: fix k_c and l_c to what the core parameters are from the fit of the bare case

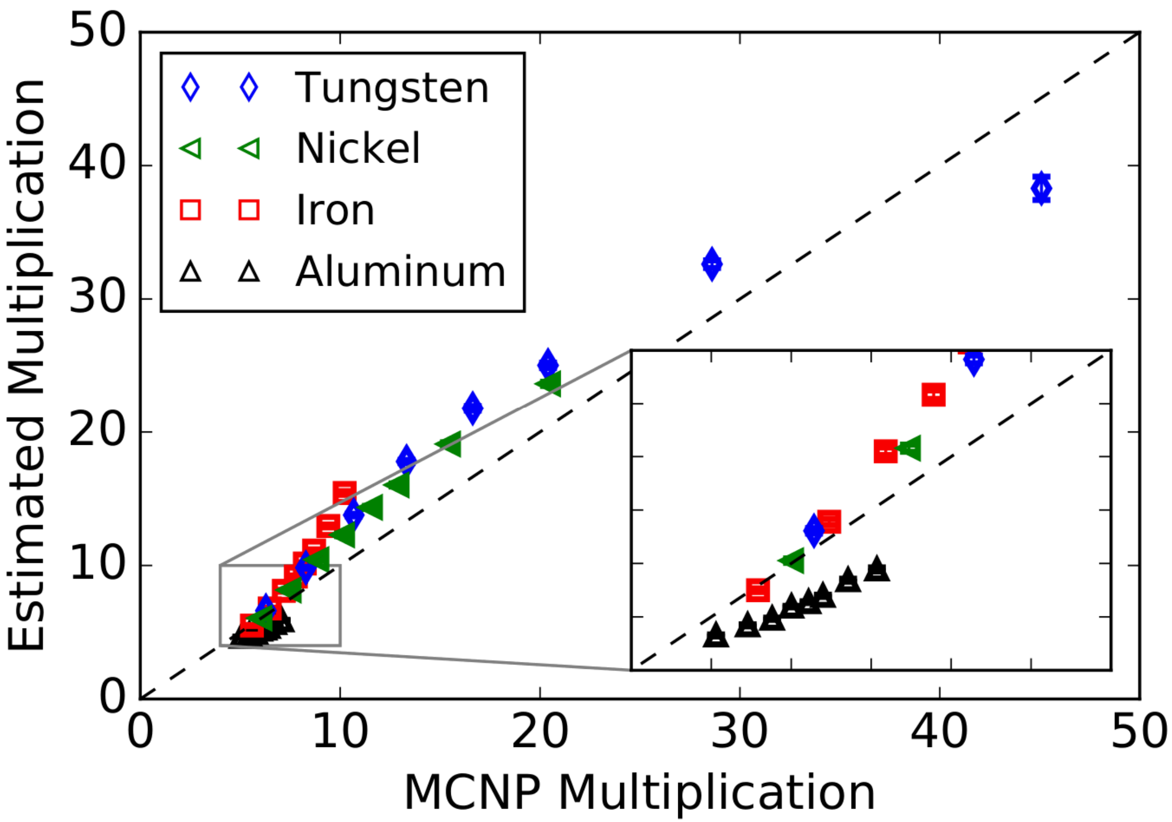
Estimating Multiplication of Reflected Assemblies

Measurement vs Simulation



$$k = \frac{k_c}{1 - f}$$

Extended Simulations



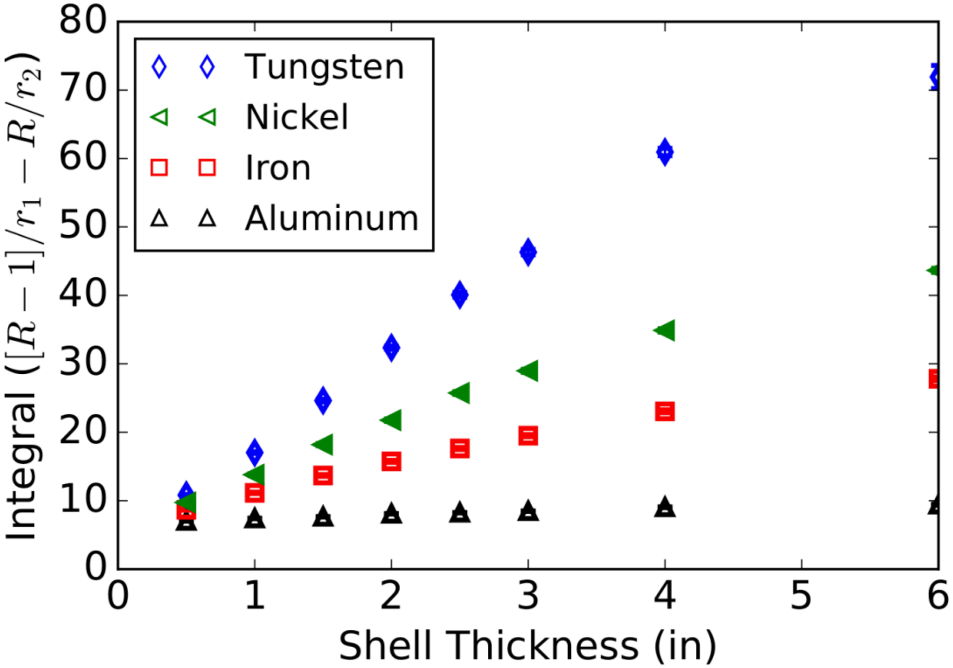
$$k = \frac{k_c}{1 - f}$$

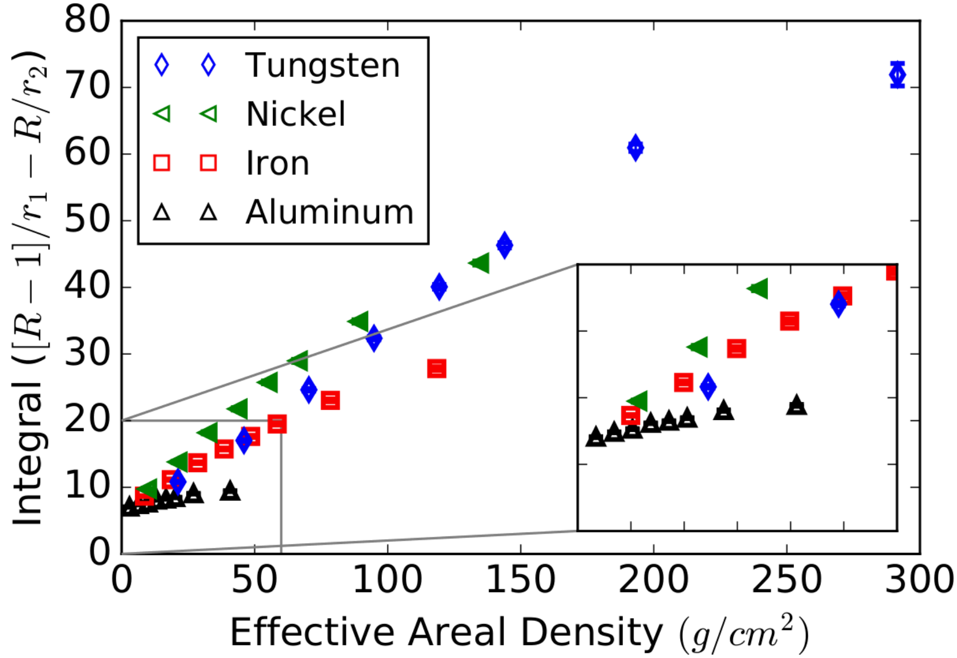
$$M = \frac{1}{1 - k}$$

- Average deviation:
  - 13% Al, 22% Fe, 17% Ni, 21% W
- Limitations of the model with energy independence
- Core parameters are fixed

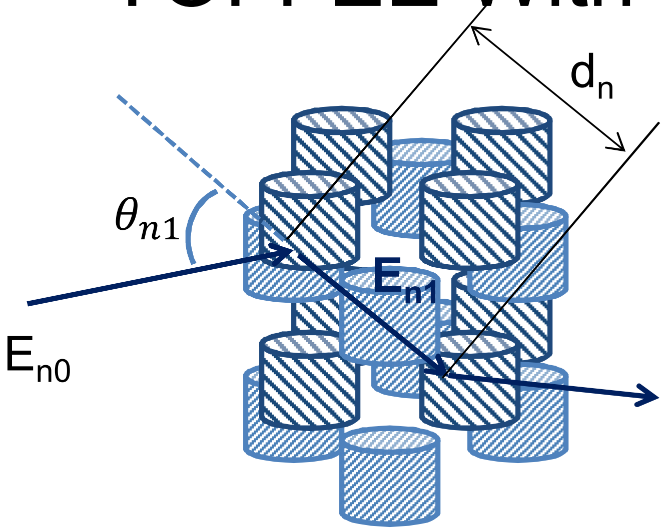
Shell Thickness and Areal Density

Determine Material Type or Amount





TOFFEE With Better Energy Estimate



$$\Delta t_{n-\gamma} - \left(R_n \sqrt{\frac{m}{2E_{n0}}} - \frac{R_\gamma}{c} \right) \approx \Delta T_g$$

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

$$E_{n1} = \frac{m_n}{2} \times \frac{{d_n}^2}{TOF^2}$$

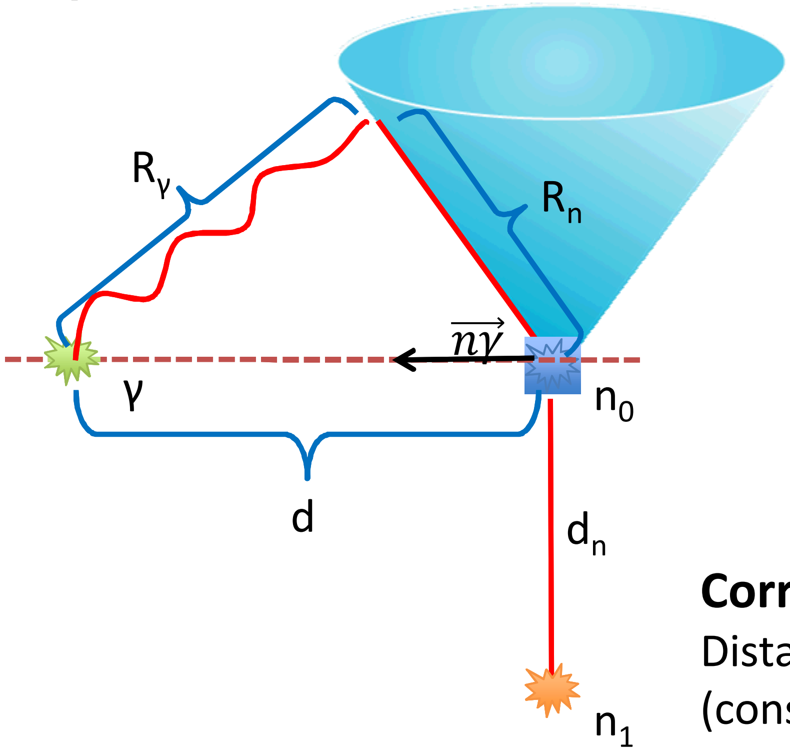
$$E_{n0} = E_p + E_{n1}$$

$$cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}}$$

MINER: the Mobile Imager of Neutrons for Emergency Response

16 independent 3”x3” EJ-309 liquid scintillator cells

γ-n-n 3-D reconstruction



Double scattered neutron:

1. Energy (or velocity) of the incident neutron

$$v_n = \sqrt{2E_p m_n} + \left(\frac{d_n}{\Delta t_{n_0,n_1}}\right)$$

2. Cone of possible source locations

$$\cos^2\theta_{n_1} = \frac{E_{n_1}}{E_{n_0}}$$

Correlated gamma:

Distance to the source (constrained by conical surface)

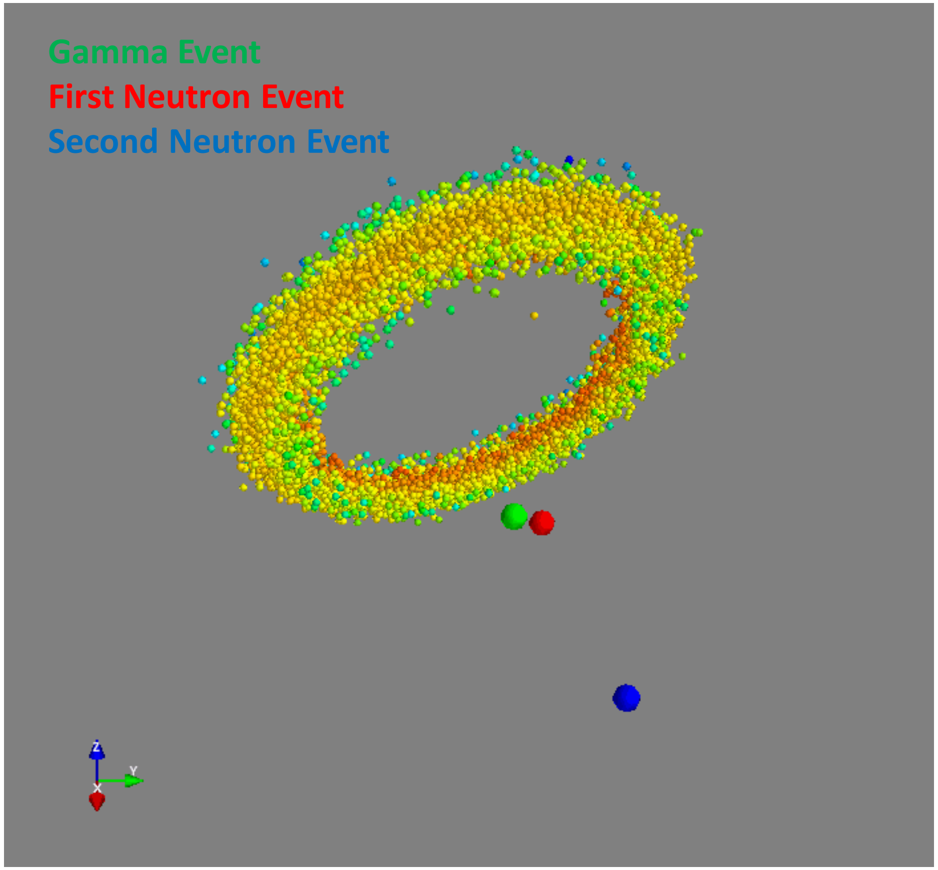
$$\Delta t_{n-\gamma} = \frac{R_n}{v_n} - \frac{R_\gamma}{c}$$

$$R_n = \frac{c^2\Delta t v_n - d v_n^2\mu + \sqrt{v_n^2\left(c^2(\Delta t^2 v_n^2 - 2dv_n\mu\Delta t + d^2) + v_n^2 d^2(\mu^2-1)\right)}}{c^2 - v_n^2}$$

where

$$\mu = \frac{\overrightarrow{n\gamma}}{d} \cdot \widehat{R_n}$$

γ-n-n 3D Reconstruction



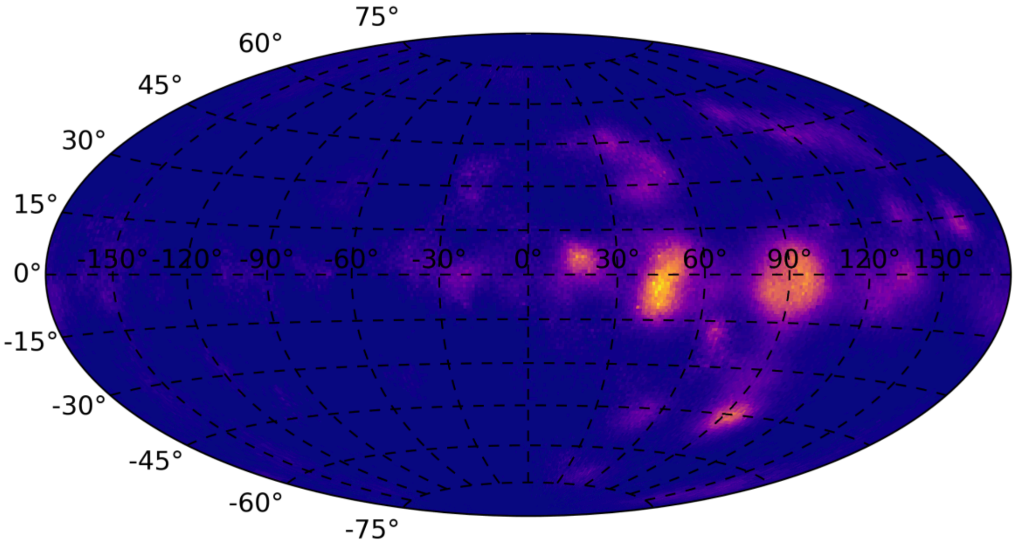
$$cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}}$$

+

$$\Delta t_{n-\gamma} = \frac{\mathrm{R_n}}{v_n} - \frac{R_\gamma}{c}$$

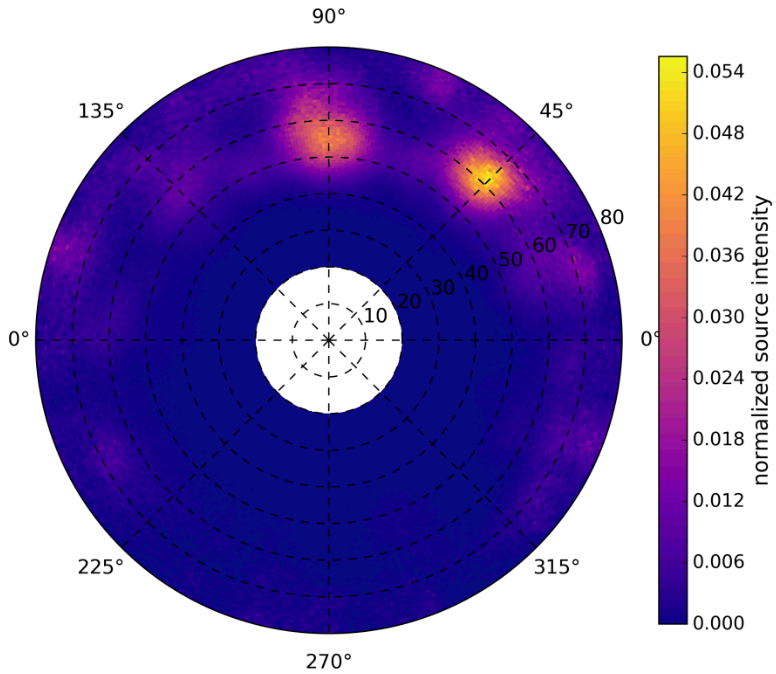
Measurement: γ-n-n 3-D Reconstruction

(Stochastic Origins Ensemble Reconstruction (SOE)),
Two Cf-252 fission sources, 50 & 60 cm from MINER



2D angular view

"top down" view



Measurement: γ-n-n 3-D Reconstruction

Stochastic Origin Ensemble Reconstruction
(~10,000 events with MINER, Cf-252 at 50cm and 60 cm)

$$cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}}$$

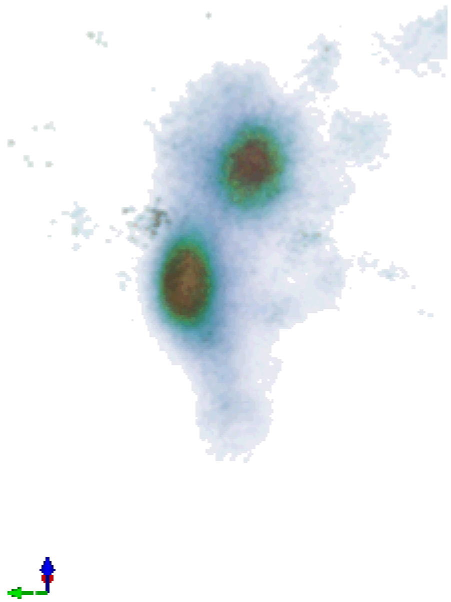
+

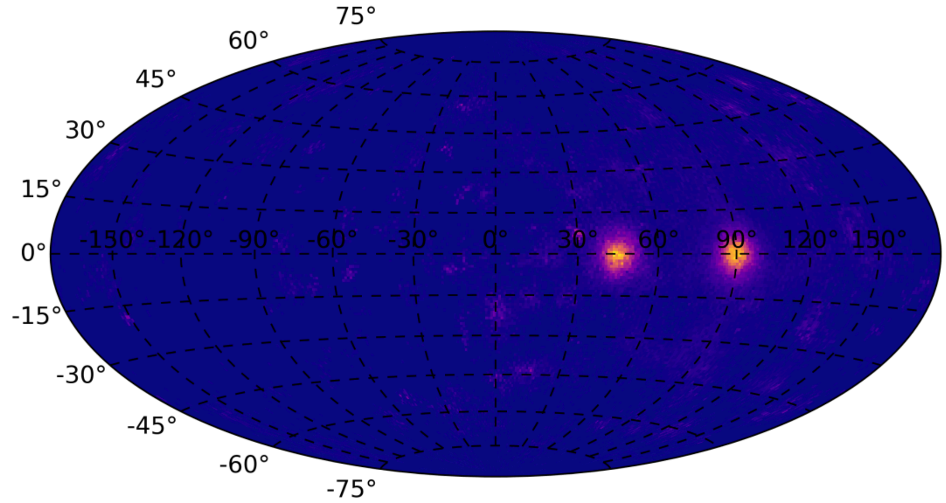
$$\Delta t_{n-\gamma} = \frac{R_n}{v_n} - \frac{R_\gamma}{c}$$

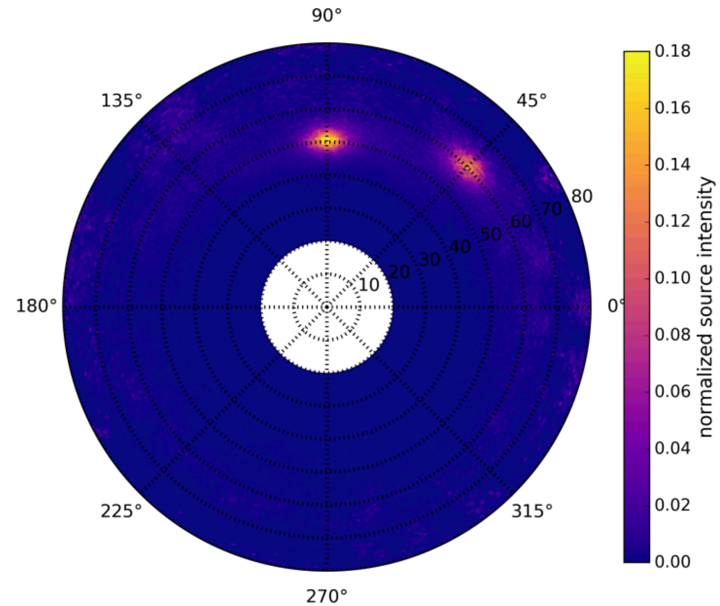
- **Enables 3-D reconstruction.**
- **Can be achieved with a single view when accessibility and/or time is an issue.**

Simulation: γ-n-n 3-D Reconstruction

5 mm spatial resolution
200 ps timing resolution



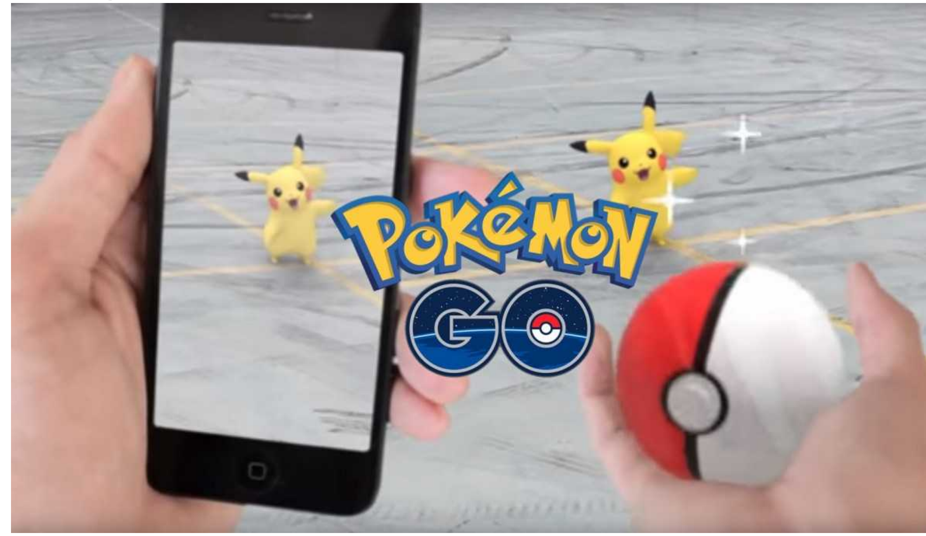




Augmented Reality

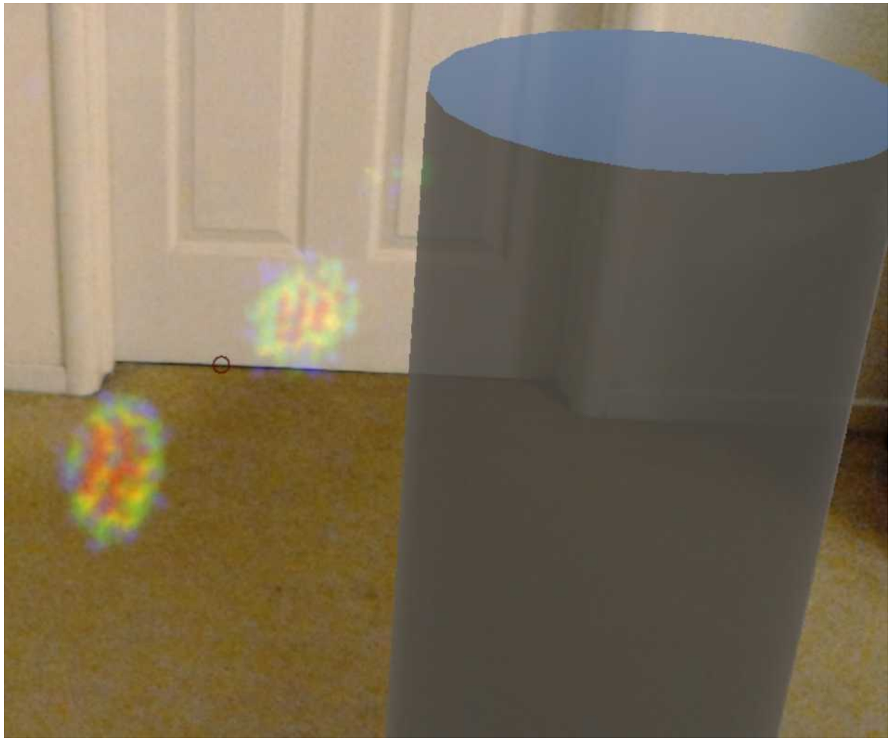
A better way of visualizing 3D images

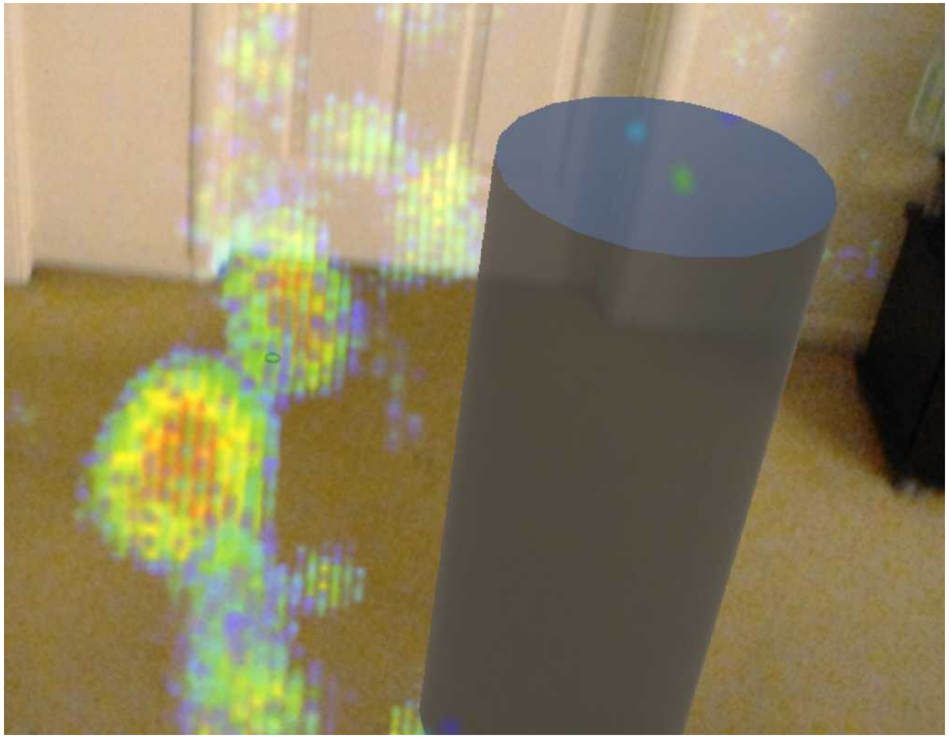
- Visualizing 3D information on 2D screen has limitations
- Augmented reality allows for projection of virtual objects in the real world
- Advantages:
  - Immediate sense of the position and scale of the radiation field
  - Ability to visualize sources behind objects (e.g. through walls or in boxes)



Microsoft Hololens

Augmented Reality In My Living Room





Summary

- TOFFEE distribution relation to the differences in generation times of gamma rays and neutrons correlated from fission chains
- TOFFEE was used to discriminate between (1) fissile and low or non-multiplying source (2) bare and reflected configurations
  - Minimum dwell time for confirmation was a few seconds for WGPu and several minutes for HEU
- Two-region point kinetics provided estimations of multiplication (13-22% error) of reflected assemblies and discrimination between reflector material types or amounts
- Proof-of-concept measurement with the new 3D imaging method was shown to resolve point-sources 10 cm apart

Conclusions

Novel Contributions of the Work

1. Demonstrated novel approach (TOFFEE distributions) characterizing SNM with signature of temporally correlated gammas and neutrons
2. Developed and used a two-region point kinetics model to characterize reflected fissile assemblies
3. Developed a new method for single-side volumetric reconstruction of sources that emit coincident gammas and neutrons (fission, (α, n)).

Future Work

- Use a more exact model of fission chain timing, or a Monte Carlo equivalent, and convolve with same fission distribution in order to fit a fissile measurement
- Simultaneously solve for multiplication and location of measured material
  - 3D imaging assumes the simultaneous birth of neutron and gamma
  - Will provide a 3D map of the multiplication at various points
- Measurements with higher resolution (5 mm and 200 ps) system

Acknowledgements

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Publications

Journal Articles

1. **M. Monterial,** P. Marleau, M. Paff, S. Clarke, S. A. Pozzi, ``Multiplication and Presence of Shielding Material from Time-Correlated Pulse-Height Measurements of Subcritical Plutonium Assemblies". *Nuclear Instruments and Methods in Physics Research Section A* Accepted for publication January 18, 2017.
2. **M. Monterial,** P. Marleau, S. A. Pozzi, ``Single-View 3D Reconstruction of Correlated Gamma-Neutron Sources." *IEEE Transactions on Nuclear Science*, Accepted for publication December 21, 2016.
3. **M. Monterial**, P. Marleau, S. Clarke, S. A. Pozzi, "Application of Bayes' Theorem for Pulse Shape Discrimination", Nuclear Instruments and Methods in Physics Research Section A., 795, September 2015, pp. 318-324.
4. M. Paff, **M. Monterial**, P. Marleau, S. Kiff, A. Nowack, S. Clarke, S. A. Pozzi, "Gamma/neutron time-correlation for special nuclear material detection – Active simulation of highly enriched uranium", Annals of Nuclear Energy, 72, October 2014, pp. 358-366.

Conference Proceedings

1. **M. Monterial**, P. Marleau, S.A. Pozzi, ``Measurement of Time Distribution of Fissions in a Chain with Fast Scintillators``, *2016 IEEE Nuclear and Science Symposium and Imaging Conference*, Oct 29 - Nov 5, 2016, Strasbourg, France.
2. **M. Monterial**, P. Marleau, S.A. Pozzi, ``Demonstration of Time-Correlated Pulse Height Template-based Confirmation Measurements", *57th Annual Institute of Nuclear Materials Management Meeting*, July 24-26, Atlanta, Georgia.
3. **M. Monterial**, P. Marleau, S.A. Pozzi, ``3D Image Reconstruction from Correlated Events of Gamma-Neutron Sources", *Symposium on Radiation and Measurements and Applications*, May 22-26, Berkeley, California.
4. **M. Monterial**, P. Marleau, S. A. Pozzi, "Detection and Characterization of Shielded Highly Enriched Uranium Under Active Interrogation Through Time Correlated Fission Events", IEEE Nuclear Science Symposium, Oct 31 - Nov 7, 2015 San Diego, California.
5. **M. Monterial**, P. Marleau, A. Kaplan, S. A. Pozzi, "Application of Bayes' Theorem for Pulse Shape Discrimination", 2014 ANS Winter Meeting, November 9-13, 2014, Anaheim, California.
6. **M. Monterial**, S. D. Clarke, E. Miller, S. A. Pozzi, P. Marleau, S. Kiff, A. Nowack, "Time-Correlated-Pulse-Height Technique Measurements of Fissile Samples at the Device Assembly Facility," INMM 54th Annual Meeting, July 14-18, 2013, Palm Springs, California.

Measuring Fission Chain Dynamics Through Inter-event Timing of Correlated Particles

Mateusz Monterial

Doctoral Committee:

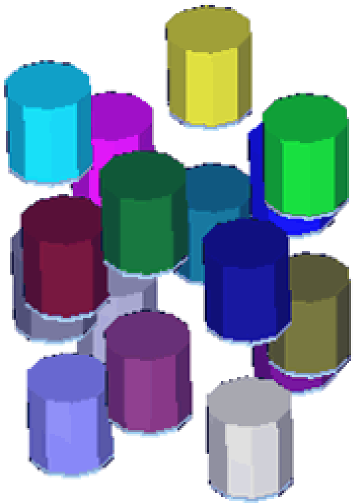
- Professor Sara A. Pozzi, Chair
- Professor Christine A. Aidala
- Dr. Shaun Clarke
- Dr. Peter Marleau, Sandia National Laboratories
- Professor David K. Wehe

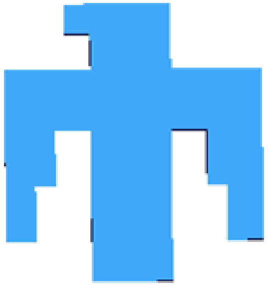
September 13th, 2017

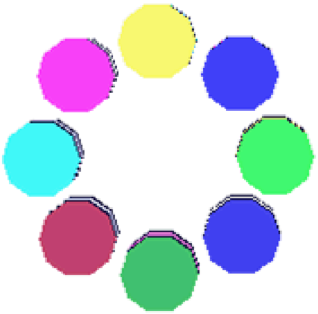
EXTRA SLIDES

SOE

Fun Simulations

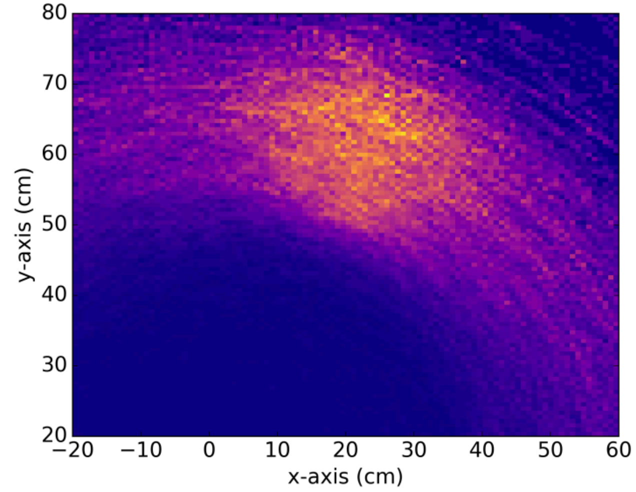






Stochastic Origin Ensemble Reconstruction

Back projection



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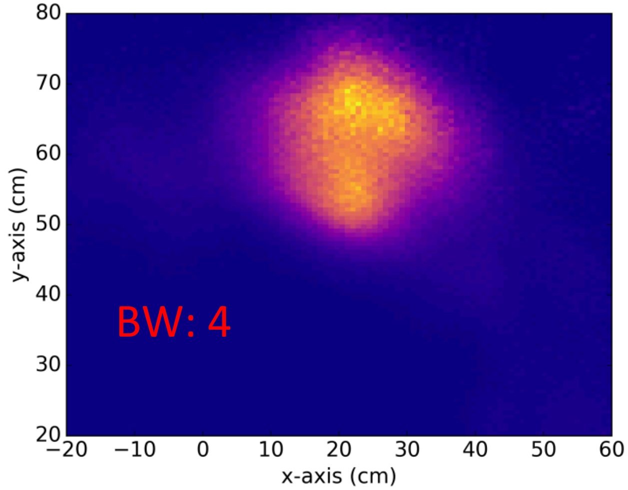
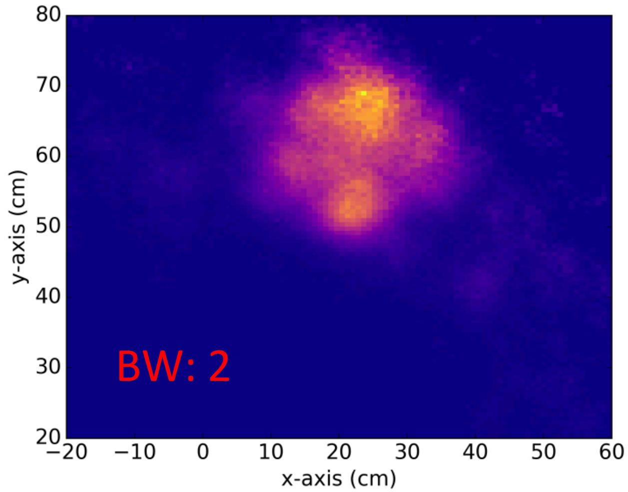
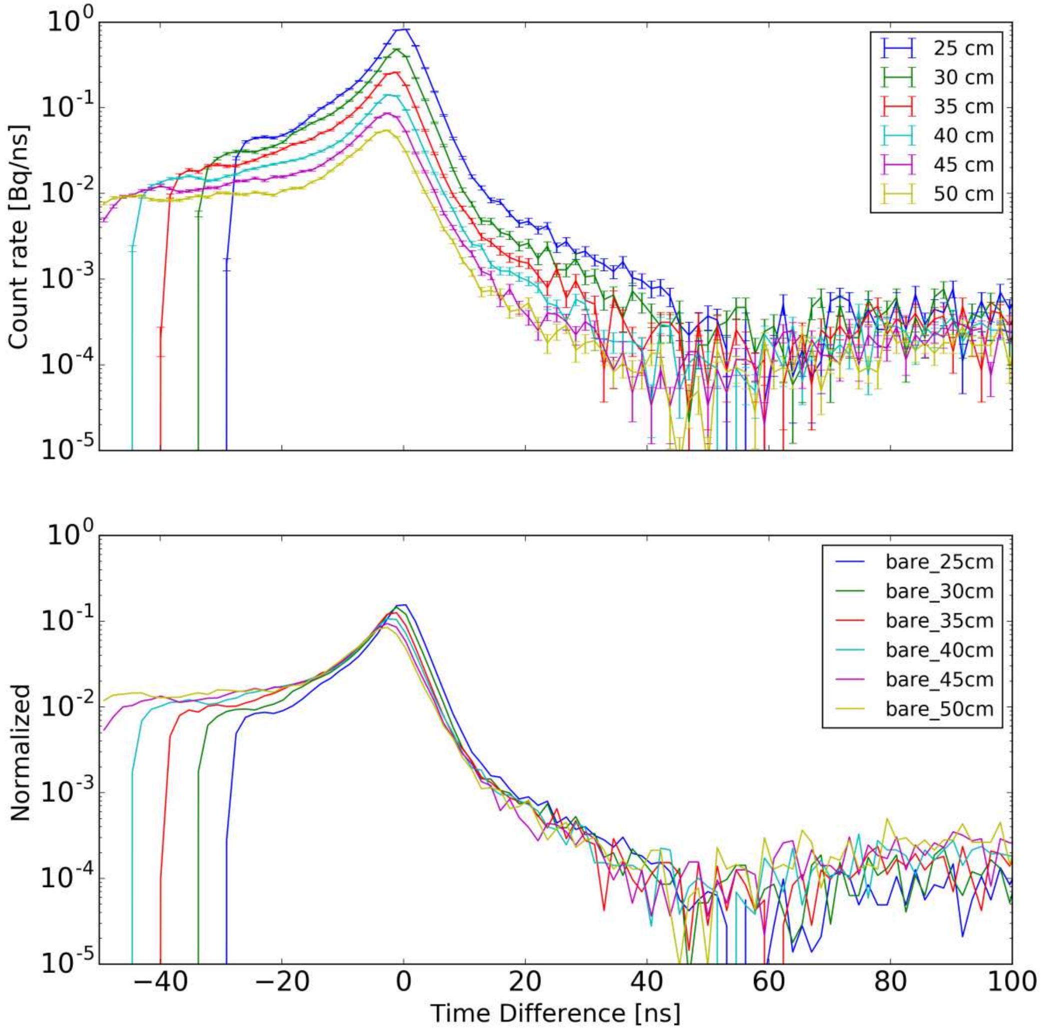




TOFFEE for Cf-252



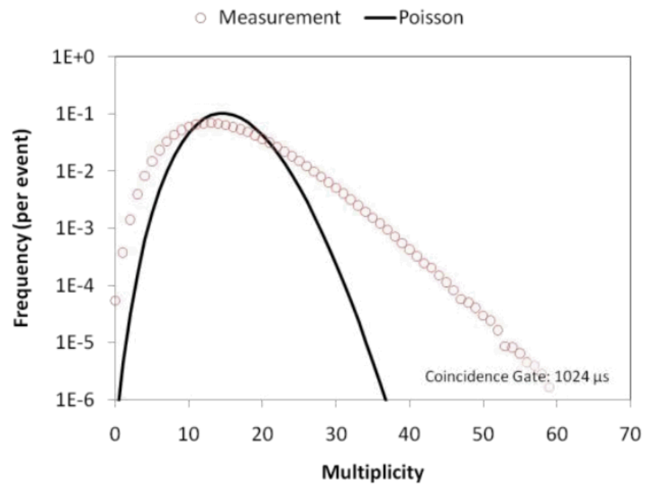
Neutron Coincidence Counting Equations

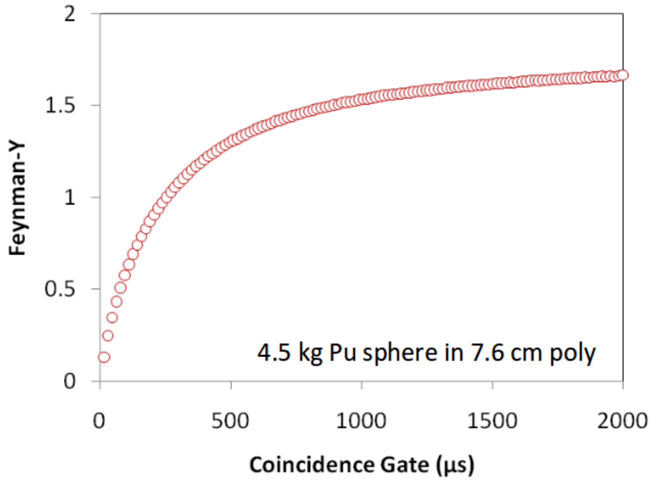
1. $S = F\epsilon M v_{s1}(1+\alpha)$
2. $D = \frac{F\epsilon^2 f_d M^2}{2}\left[v_{s2} + \left(\frac{M-1}{v_{i1}}\right) v_{s1}(1+\alpha)v_{i2}\right]$
3. $T = \frac{F\epsilon^3 f_t M^3}{6}\left[v_{s2} + \left(\frac{M-1}{v_{i1}-1}\right)[2v_{s2}v_{i2} + v_{s1}(1+\alpha)v_{i3}] + 3\left(\frac{M-1}{v_{i1}}\right)^2 v_{21}(1+\alpha)v_{i2}^2\right]$

- F = spontaneous fission rate
- ϵ = neutron detection efficiency
- M = neutron leakage multiplication,
- $\alpha = (\alpha, n)$ to spontaneous fission neutron ratio
- f_d= doubles gate fraction
- f_t= triples gate fraction
- v_{s1}, v_{s2}, v_{s3}= factorial moments of the spontaneous fission neutron distribution
- v_{i1}, v_{i2}, v_{i3}= factorial moments of the induced fission neutron distribution

Feynman-Y Approach

- Measures correlated counts in a fixed gate
- Fission chains create variance in excess of Poisson distribution
- $\frac{\sigma^2}{\mu} = 1 + Y$
  - σ^2: variance
  - μ: mean





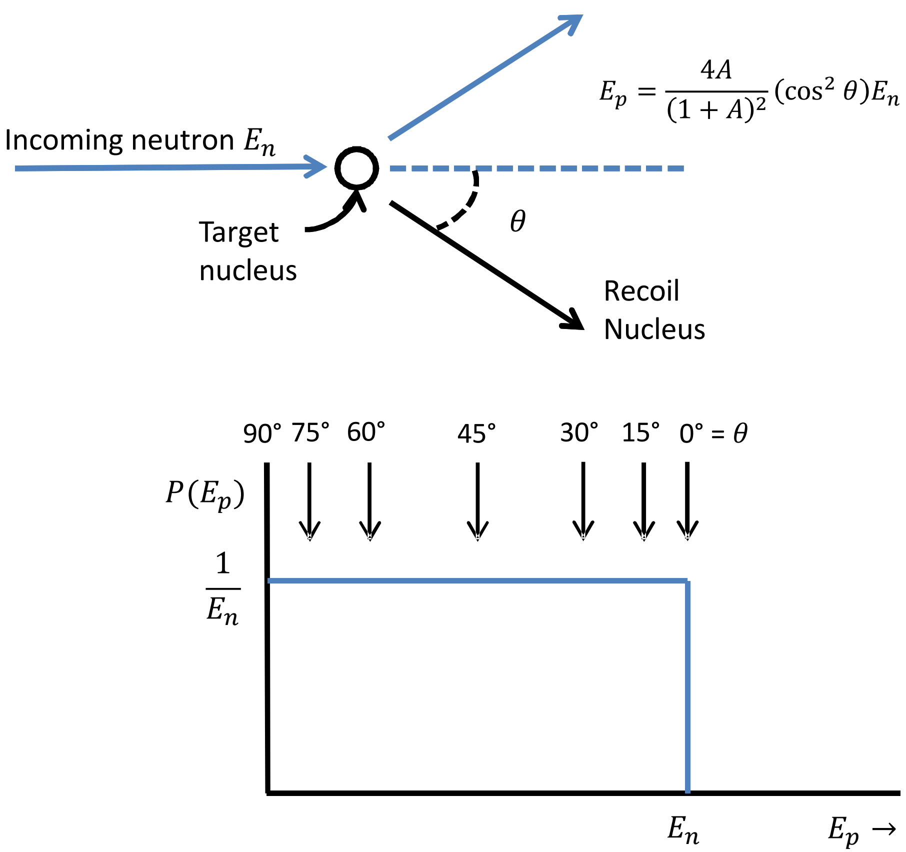
Figures courtesy of John Mattingly: http://web.ornl.gov/sci/nsed/outreach/presentation/2011/Mattingly.pdf

Neutron Sources in Nuclear Fuel Cycle

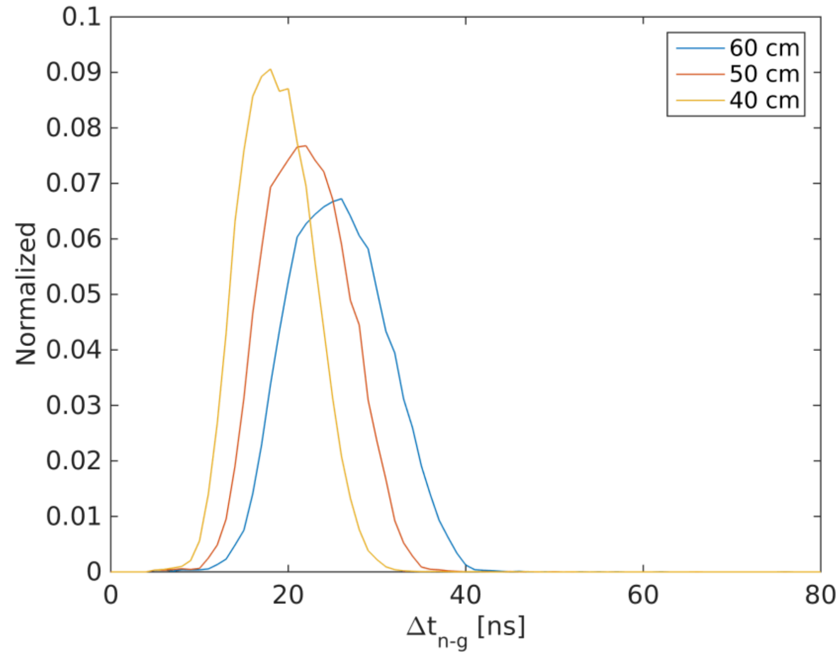
- Spontaneous Fission
  - Pu-238/240/242, Cf-252
  - Energy spectrum is Maxwellian (~2 MeV mean):
    - Sqrt(E) exp(-E/1.43)
- Induced Fission
  - U-233/235, Pu-239
  - Spectrum depend on the energy of incident neutron
- (alpha, n) reactions
  - Alpha + O-18 → Ne-21 + n
  - Alpha + F-19 → Na-22 + n
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

Measured Quantities from Organic Scintillators

Deposited Neutron Energy



Neutron-Gamma Timing

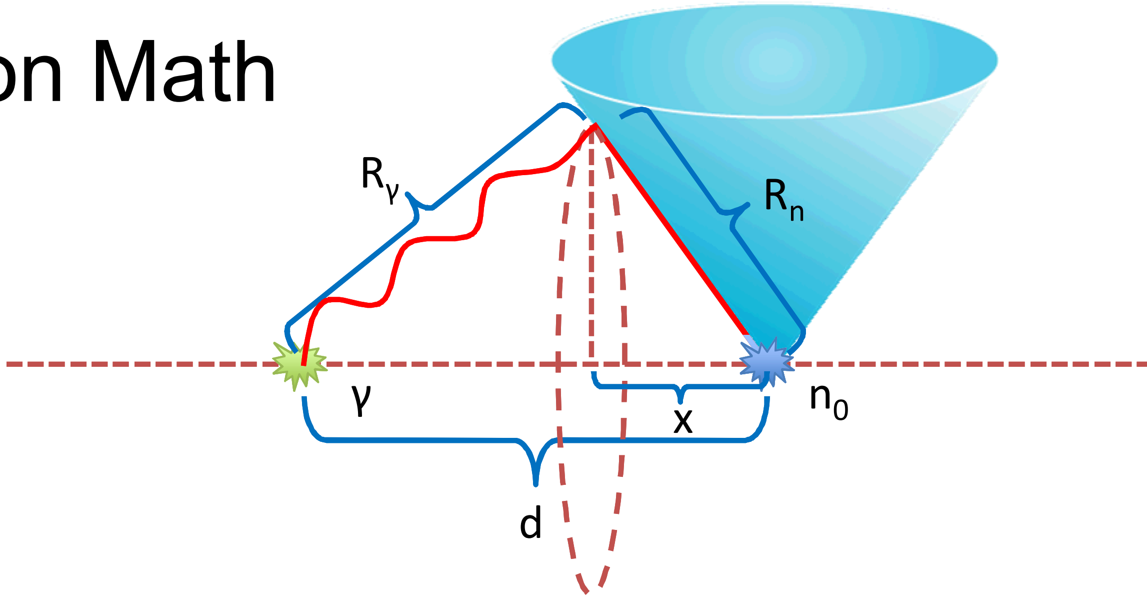


3D Reconstruction Math

$$\Delta t = \frac{R_n}{v_n} - \frac{R_\gamma}{c} \qquad [1]$$

$$x = \frac{(d^2 + R_n^2 - R_\gamma^2)}{2d} \qquad [2]$$

$$x = R_n(\widehat{R_n} \cdot \hat{x}) = R_n \mu \qquad [3]$$



$\widehat{R_n}$ traces the surface of the cone

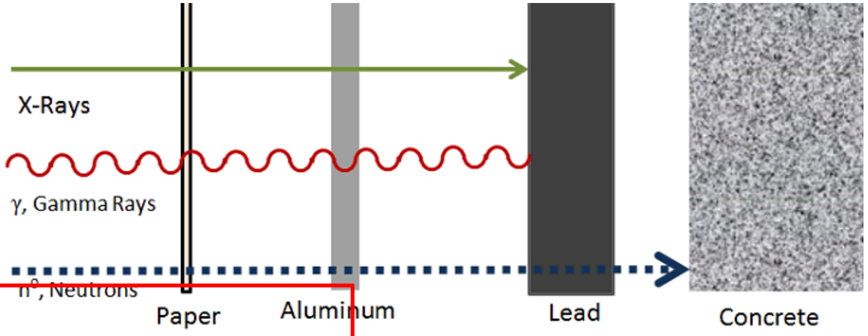
Substitute [1] and [3] into [2] and solve for R_n:

$$\boldsymbol{R_n = \frac{c^2 \Delta t v_n - d v_n^2 \mu + \sqrt{v_n^2(c^2 d^2 - 2c^2 d \Delta t v_n \mu + (c v_n \Delta t)^2 + (d v_n \mu)^2 - (d v_n)^2)}}{c^2 - v^2}}$$

The solution is a parametric equation for R_n in terms of μ, the cosine between cone surface and unit vector between n_0 and γ.

Equation [2] is part of a solution of the intersection of two spheres

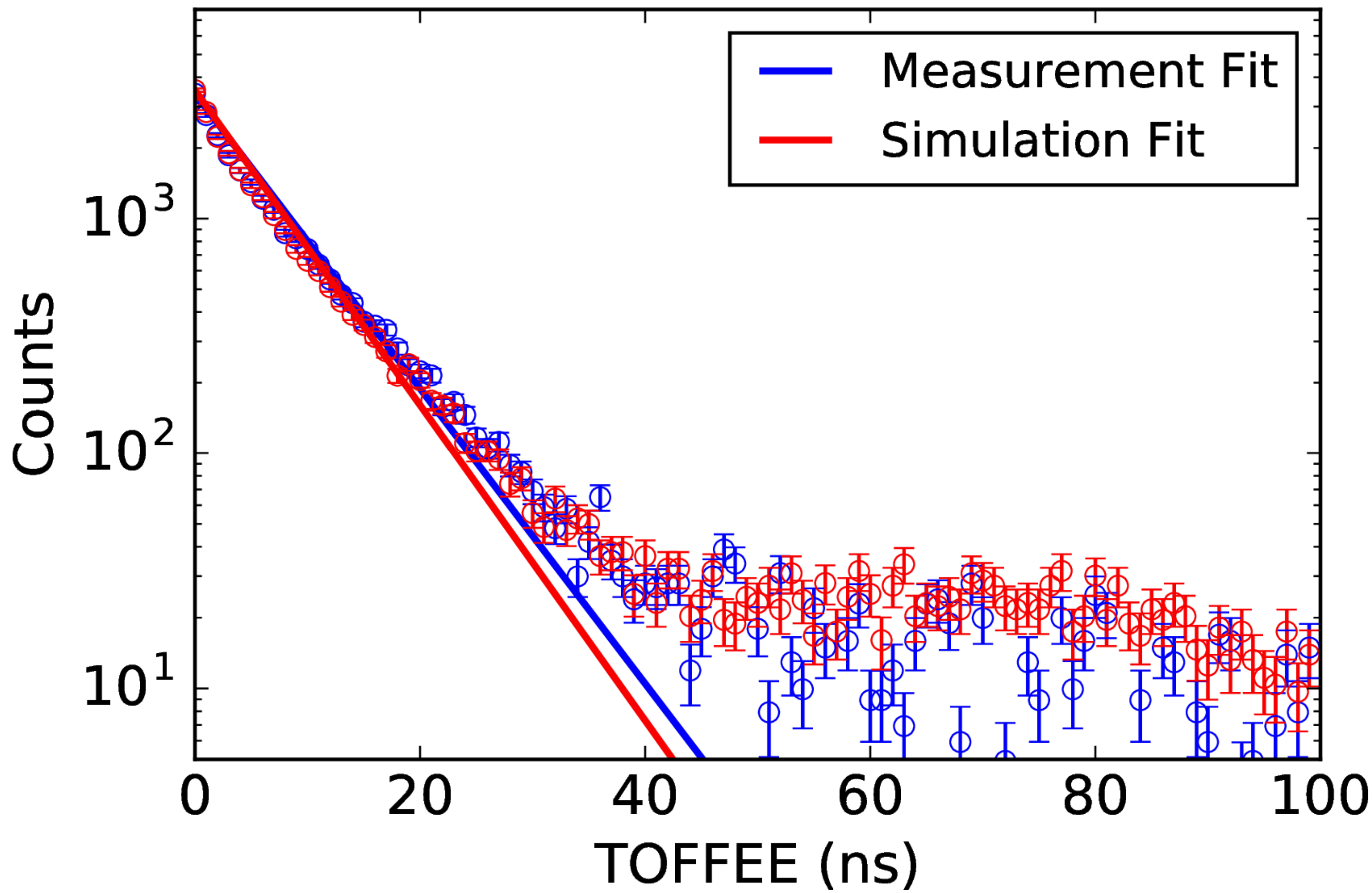
Current Methods
Drawbacks and Limitations



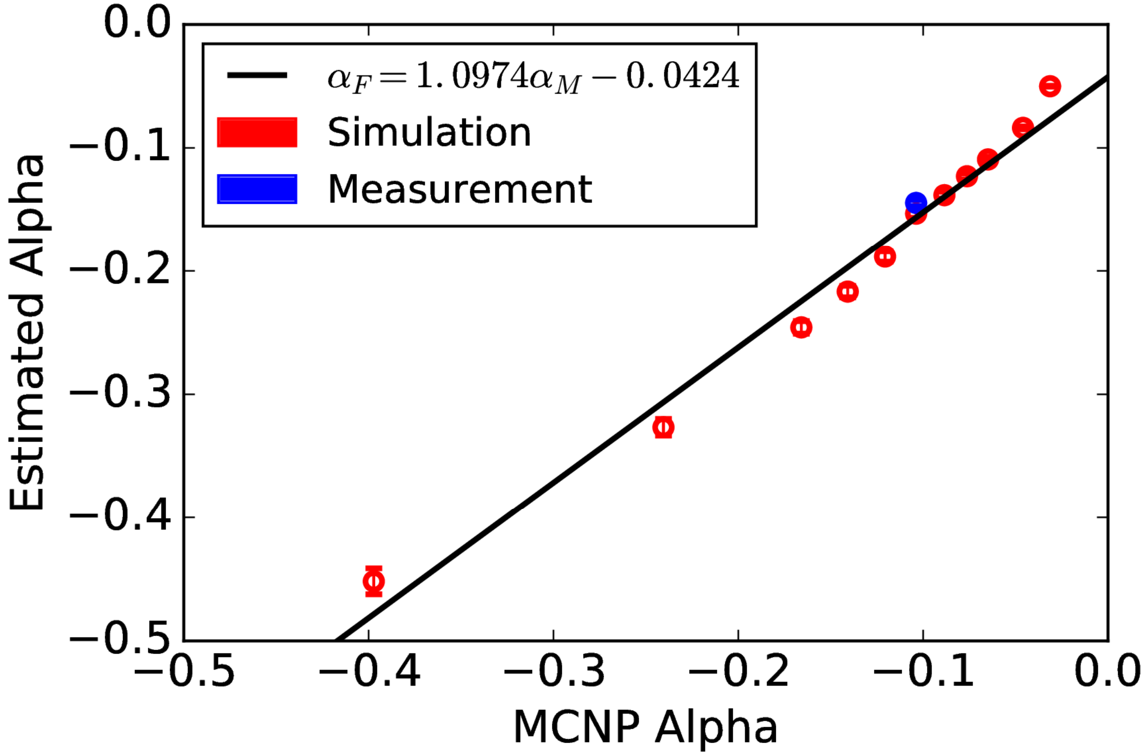
1. Gamma spectrum
   - Attenuation and self-shielding
2. Total neutron rate
   - Easily spoofed
   - Spontaneous & induced fission and (α,n) sources are indistinguishable
3. Multiplicity Counting
   - Requires high efficiency, necessitates large detection system
   - Efficiency has to be well known
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

→ He-3 based technologies

Bare cases (single exponential)



Bare cases with different masses

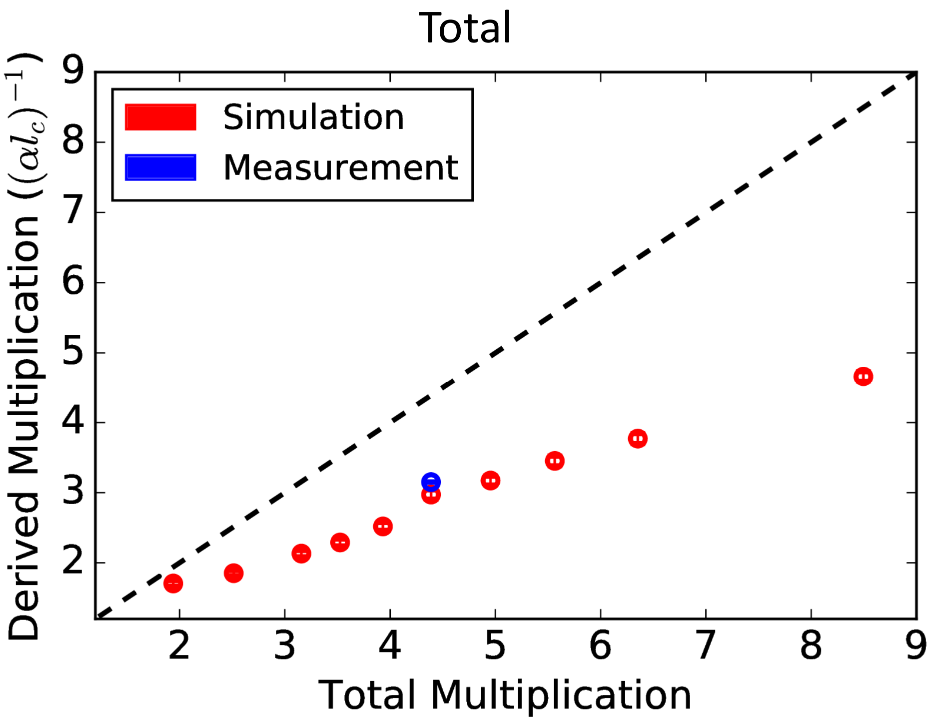


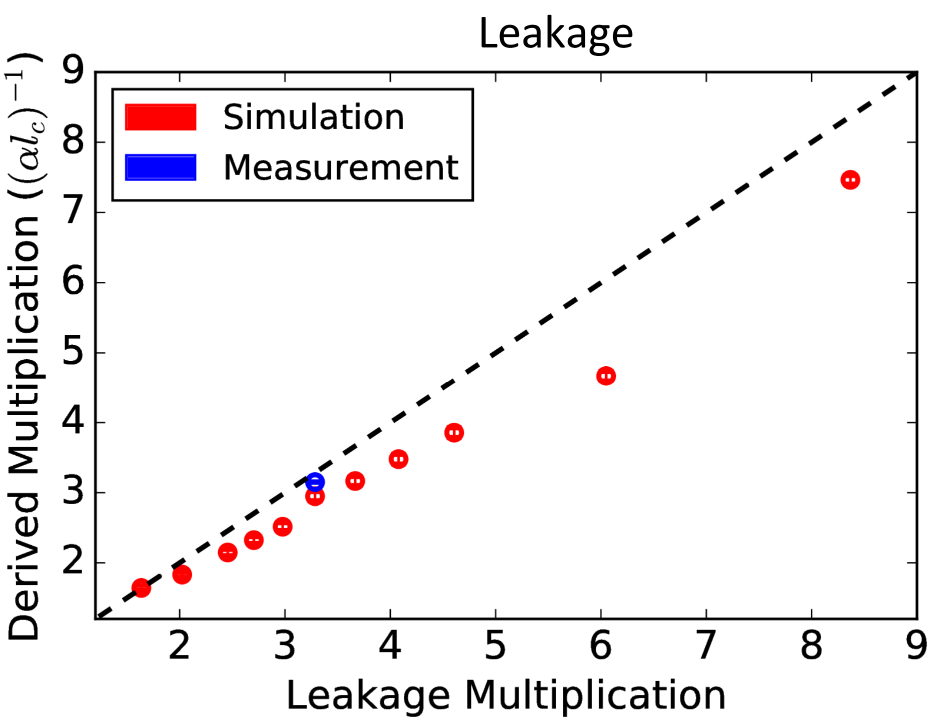
$$M = \frac{1}{1-k} = \frac{1}{\alpha l_c}$$

α: from exponential fit

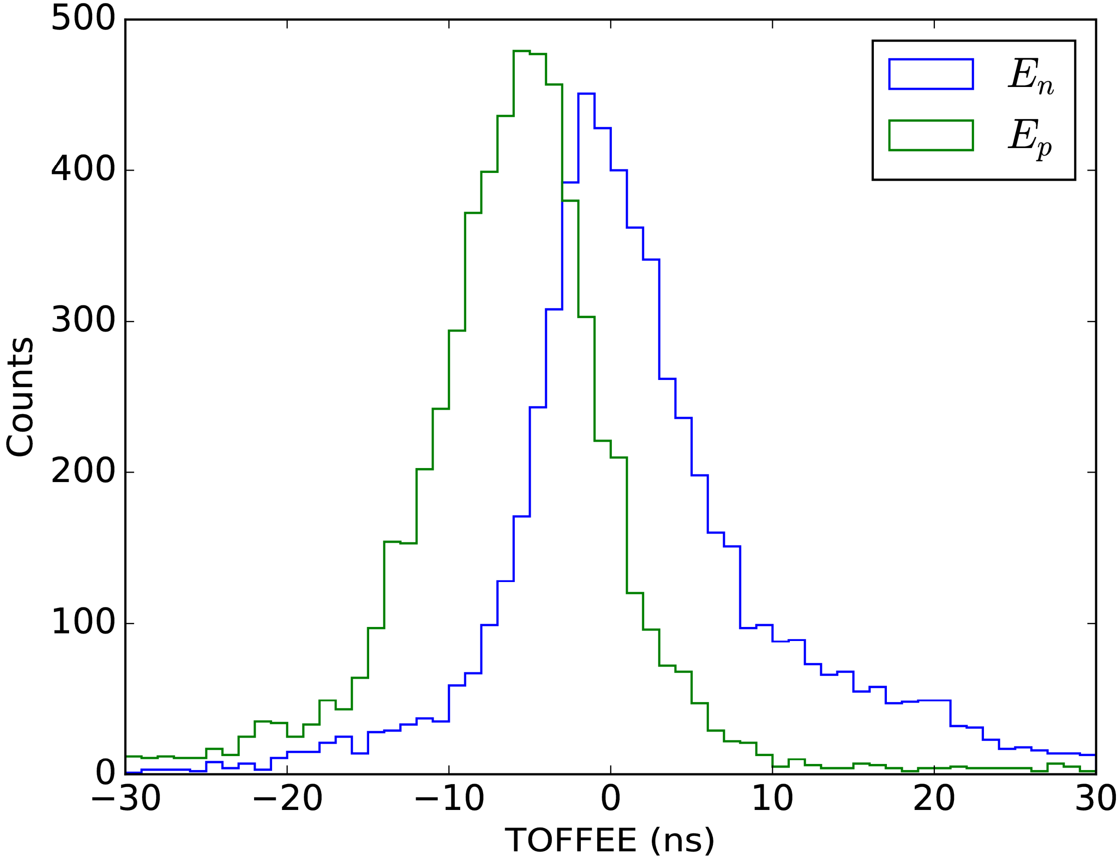
l_c: from MCNP6 calculation

Multiplication



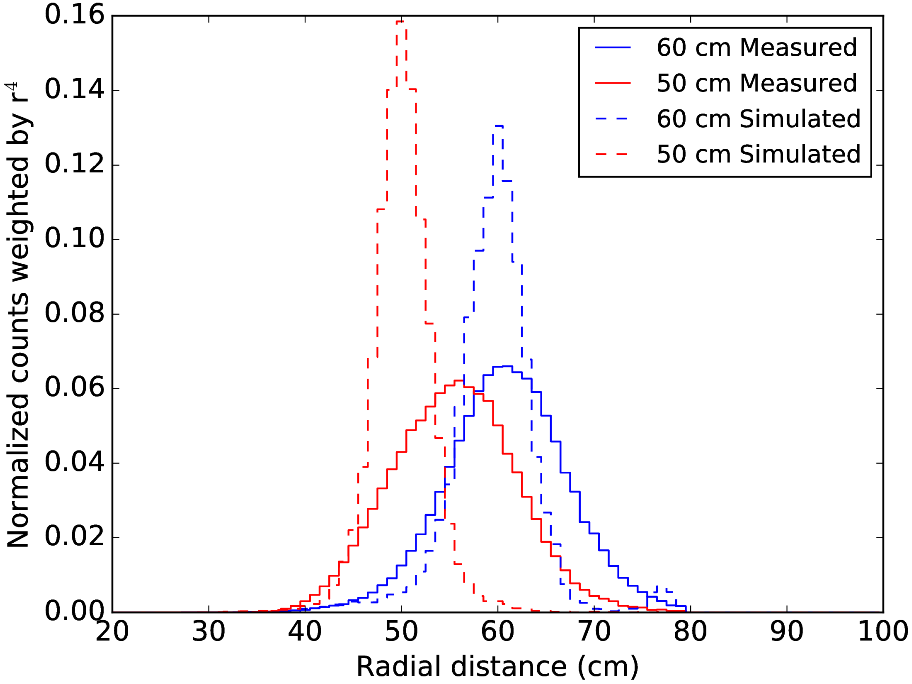


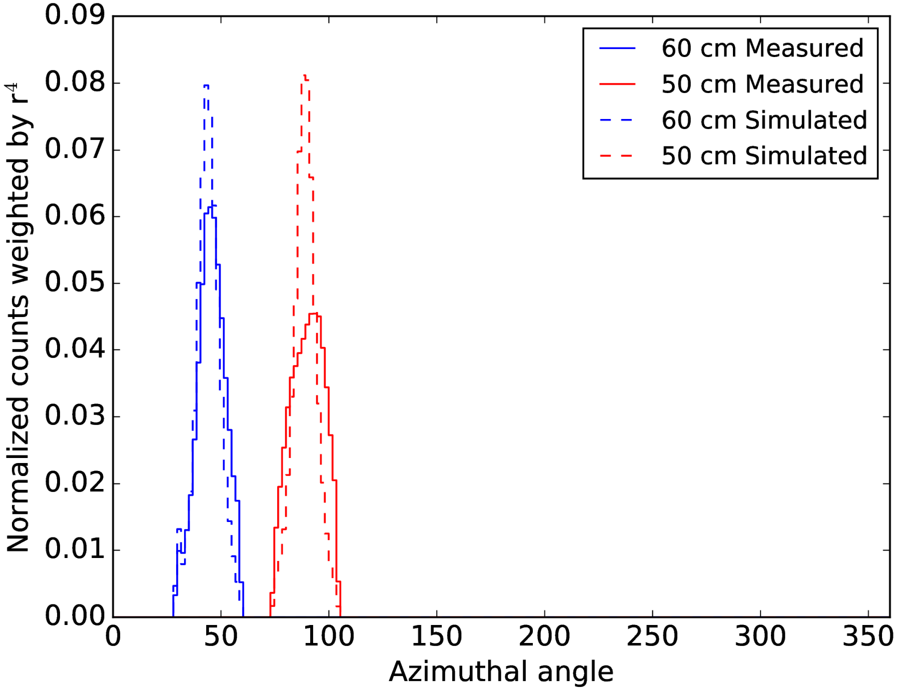
Preliminary experiment with Cf-252



- TOFFEE distribution shifts to the center
- But it does not become very narrow
- However, the double scattered neutron provides some imaging

Improvements with future capabilities





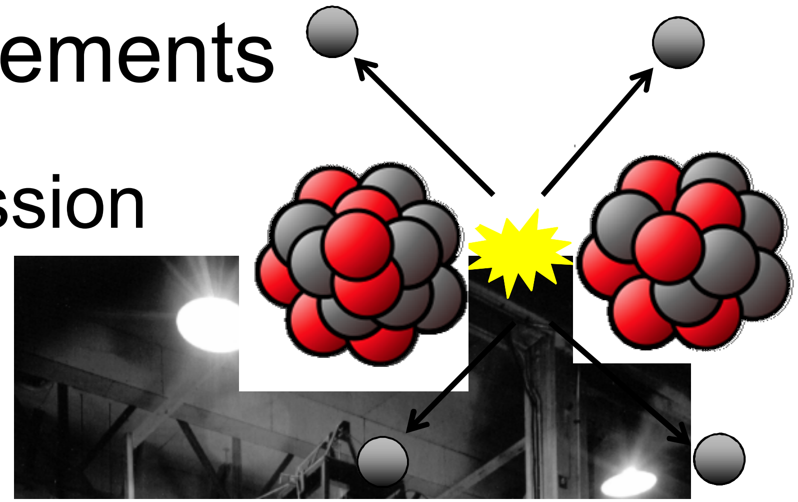
Two-region point kinetics

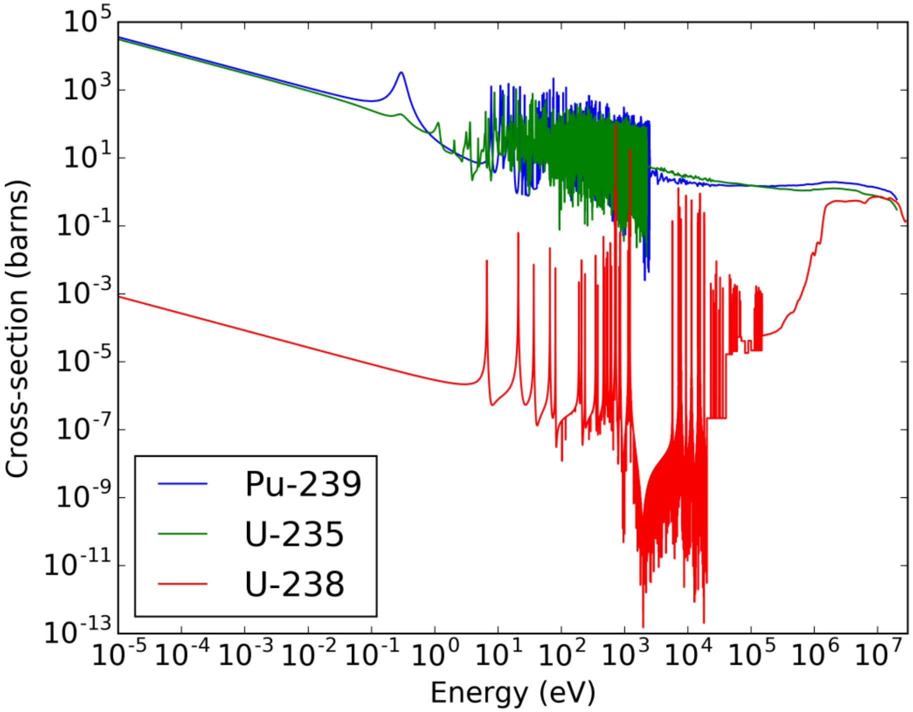
$$\frac{dN_c}{dt} = \frac{k_c - 1}{l_c} N_c + f_{rc} \frac{N_r}{l_r}$$
$$\frac{dN_r}{dt} = f_{cr} \frac{N_c}{l_c} - \frac{N_r}{l_r}$$

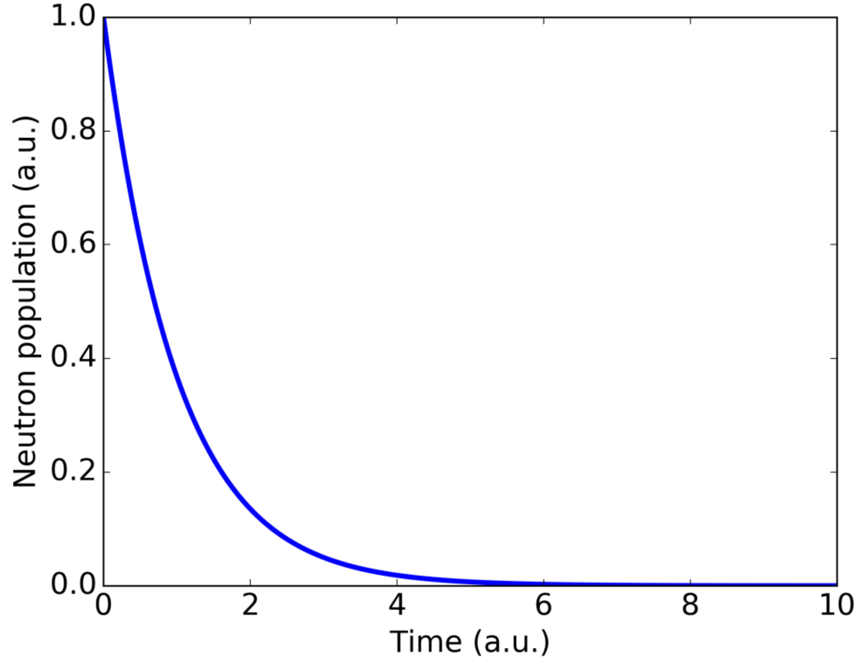
N_c is the number of neutrons in the fissile core region
N_r is the number of neutron in the reflector
k_c is the multiplication factor in the fissile core region
l_c is the neutron lifetime in the fissile core region
l_r is the neutron lifetime in the reflector region
f_{cr} is the fraction of neutron that leak from the fissile core region into the reflector
f_{rc} is the fraction of neutrons that leak from the reflector back into the core

Manhattan project measurements

- Number of neutrons per fission
- Fission cross-sections
- Neutron prompt lifetime







An alternative approach

- Rossi observed excess fluctuations from measurements of LOPO reactor at Los Alamos
- Postulated it was due to fission chains evolving at characteristically short time scales
- Fluctuations at near criticality could provide the prompt neutron lifetime

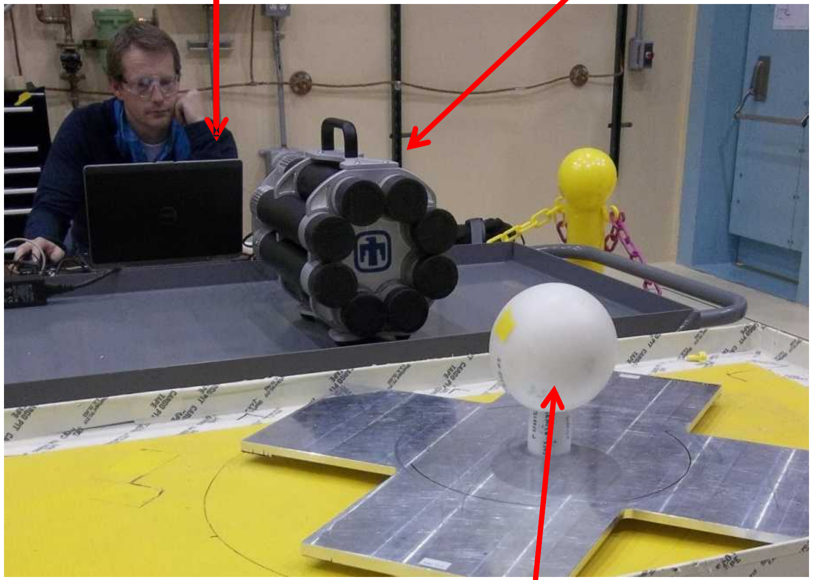
Bruno Rossi

Richard Feynman

Experiments

Computer/digitizer

Stilbene array



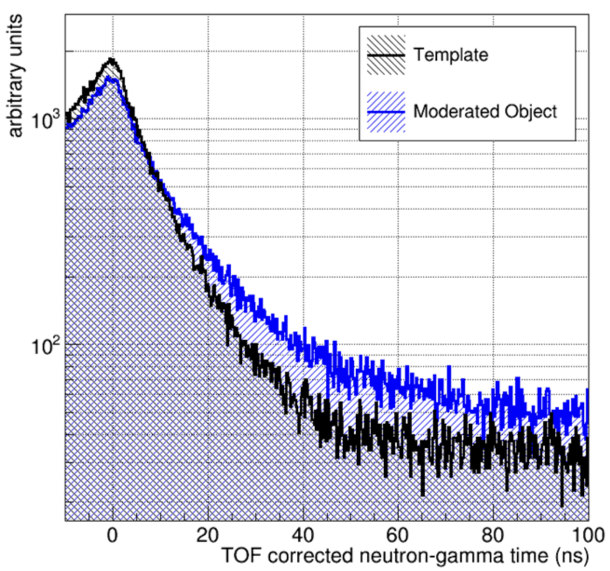
Beryllium Reflected Plutonium (BeRP) ball in a 1” shell of High Density Polyethylene

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

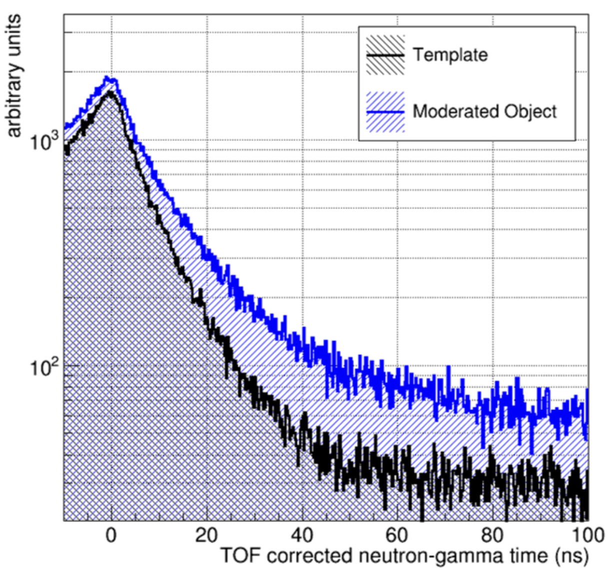
Data Analysis - Normalization

- Gamma-neutron rate provide more discriminating metric than shape alone
- Comparisons normalize to both counts and time to demonstrate the difference

Count Normalized



Time Normalized

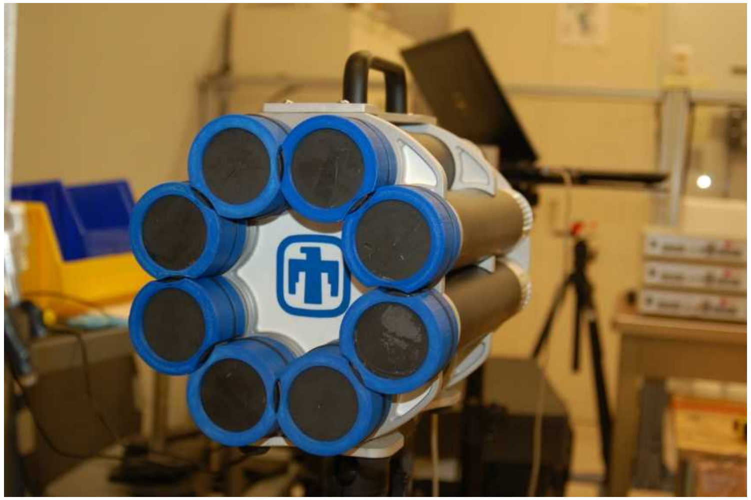


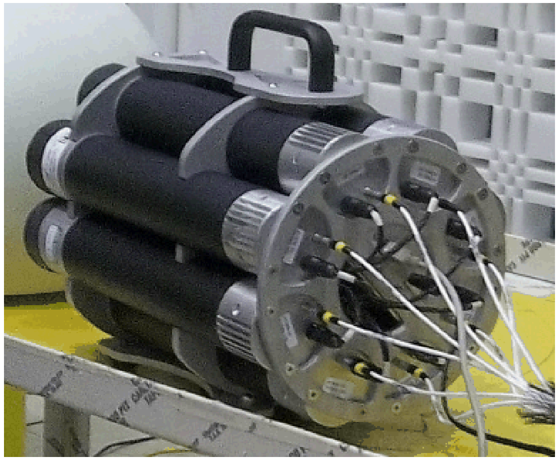
Fast Correlation Discrimination Capable Organic Scintillators

The measurement system

System advantages:

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





"The 8-shooter"
Array of Stillbene crystal scintillator