SAND2016-7181PE

Exceptional service in the national interest

Sandia National Laboratories

Nuclear Material Characterization and Imaging using fast neutrons

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UC Davis NSSC Summer School, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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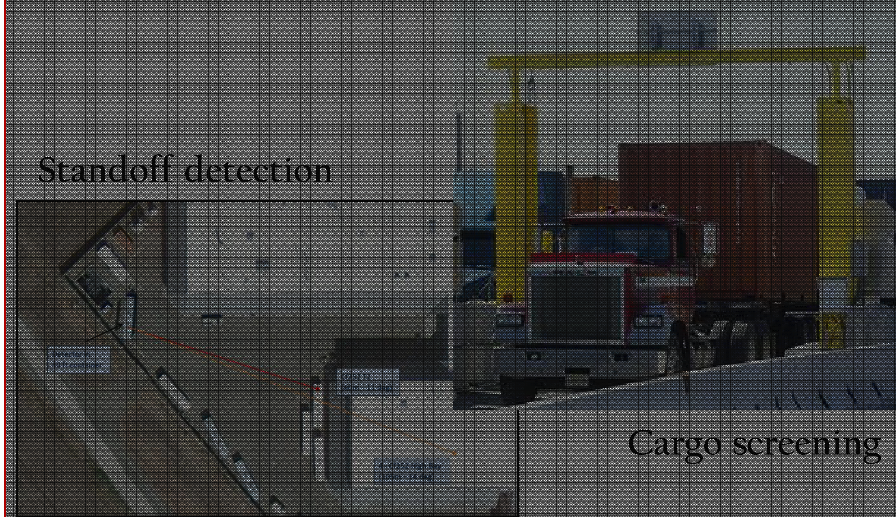
Special Nuclear Material - detection/imaging



SNM detection/localization

- Low signal rate
  - Need large area detectors!
- Low signal to background
  - Need background discrimination!

Arms control treaty verification

emergency response

SNM characterization/imaging

- Material properties
  - Mass, multiplication, isotopics
- High resolution required
  - Fine detector segmentation
- Multiple or extended sources

Summary

- What's so special about special nuclear material (SNM)?
- Characterization of SNM
  - What signatures can be used?
  - Neutrons: slow and fast.
  - Correlated Timing
  - 3D imaging
- Warhead confirmation for verification of treaty compliance
  - Challenge problem
  - Authentication vs. Certification
  - Comparison measurements
  - CONfirmation using a Fast-neutron Imaging Detector with Anti-image NULL-positive Time Encoding (CONFIDANTE)

Nuclear Material?

As defined by the IAEA:

Nuclear Material – metals uranium, plutonium, and thorium in any form.

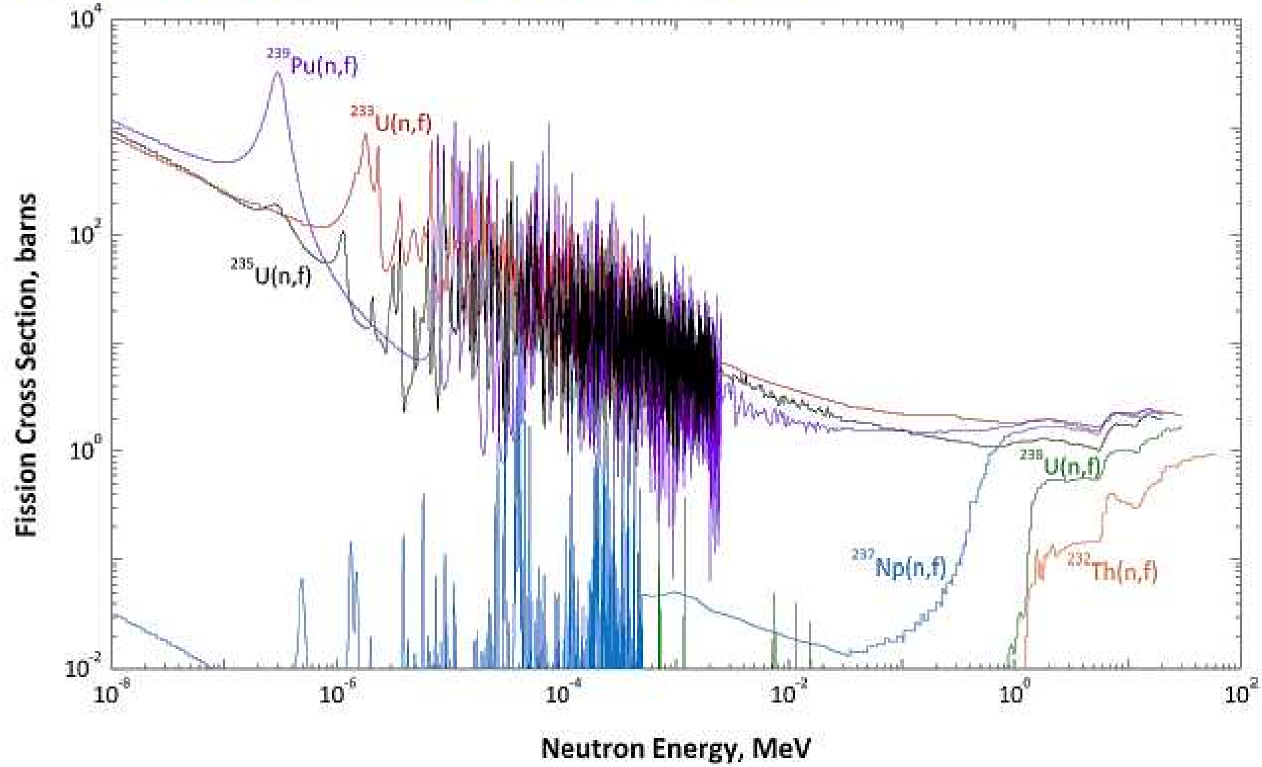
Special Nuclear (fissile) Material – U-233, U-235, Pu-239

Source Material – everything that is not special

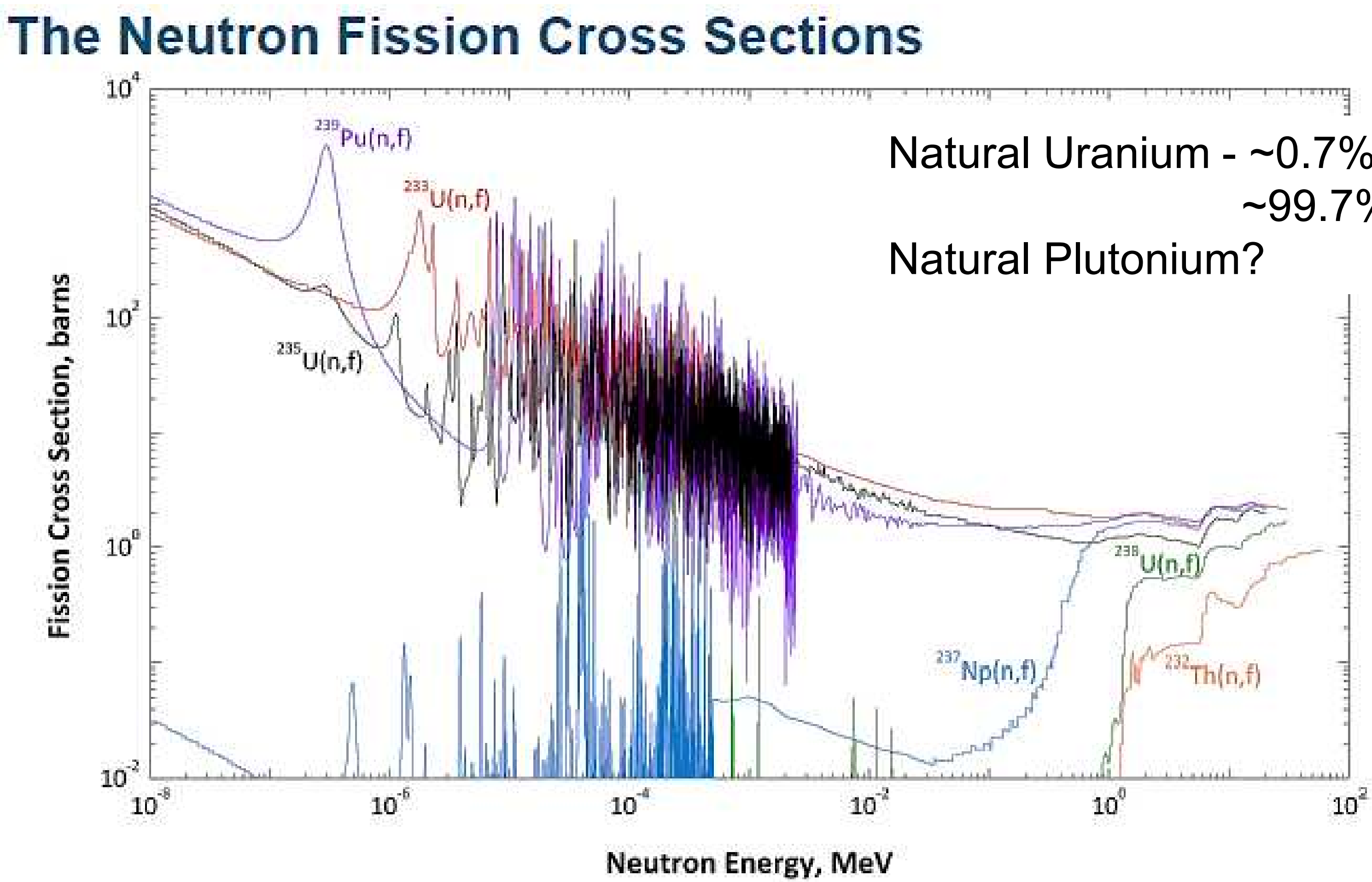
What's so special?

Isotope	Induced Thermal Fission Multiplicity ν
^{232}U	3.13
^{233}U	2.4
^{234}U	2.4
^{235}U	2.41
^{236}U	2.2
^{238}U	2.3
^{237}Np	2.70
^{238}Pu	2.9
^{239}Pu	2.88
^{240}Pu	2.8
^{241}Pu	2.8
^{242}Pu	2.81
^{244}Cm	3.46
^{252}Cf	4.06

The Neutron Fission Cross Sections



Where can I get some?



Natural Uranium - ~0.7% U-235
~99.7% U-238

Natural Plutonium?

Can I make it?

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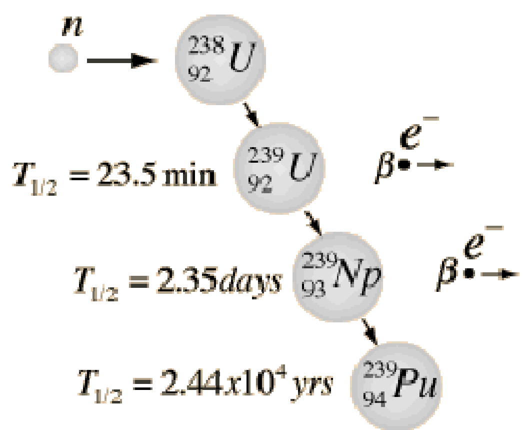
The Passive Neutron Signatures

Isotope	Half Life	Spontaneous Fission Yield (n/s-kg)	Spontaneous Fission Multiplicity ν	Induced Thermal Fission Multiplicity ν
^{232}U	71.7 yr	1,300	1.71	3.13
^{233}U	1.59×10^5 yr	0.86		
^{234}U	2.45×10^5 yr	5.02		
^{235}U	7.04×10^8 yr	0.299		
^{236}U	2.34×10^6 yr	5.49		
^{238}U	4.47×10^9 yr	13.6		
^{237}Np	2.14×10^6 yr	0.114		
^{238}Pu	87.7 yr	2.59×10^6		
^{239}Pu	2.41×10^4 yr	21.8		
^{240}Pu	6.56×10^3 yr	1.02×10^6		
^{241}Pu	14.35 yr	50 ±		
^{242}Pu	3.76×10^5 yr	1.72×10^6		
^{244}Cm	18.1 yr	1.08×10^{10}		
^{252}Cf	2.65 yr	2.34×10^{15}		

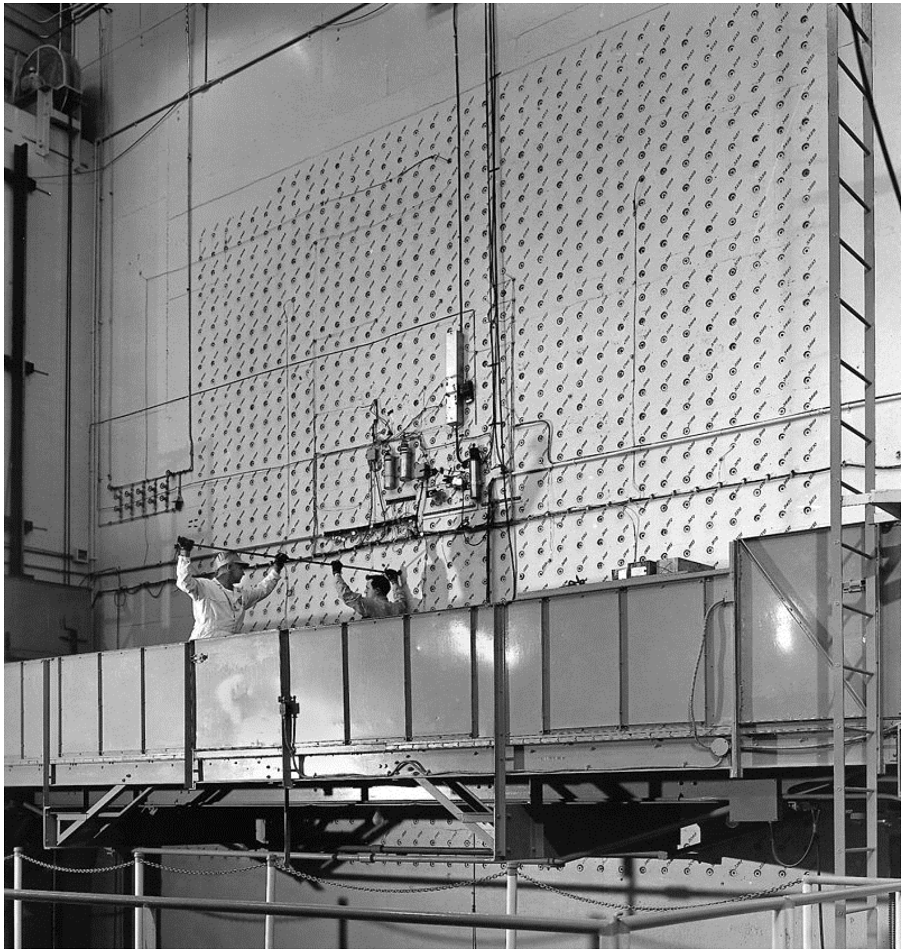
There isn't natural Plutonium to be found, but …



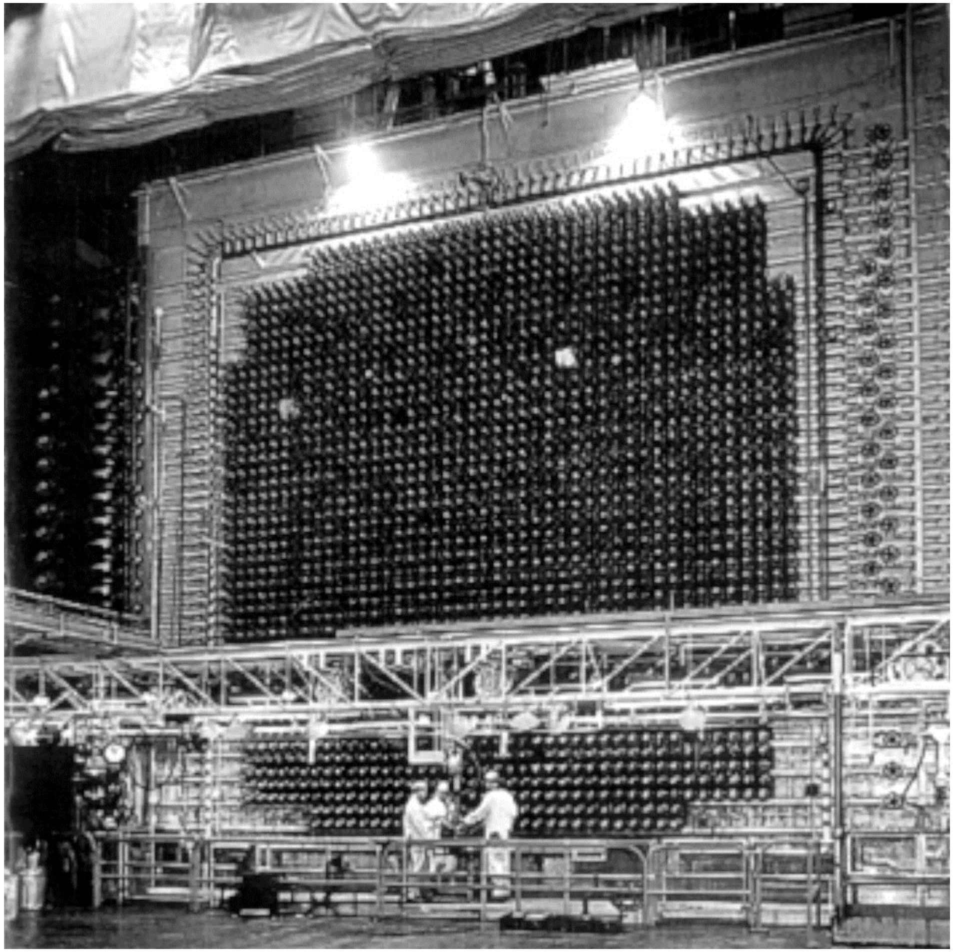
Ref: "Panda Book", values with ± have significant uncertainty

First Nuclear Reactors

ORNL X-10 Graphite Reactor
graphite moderated, air cooled

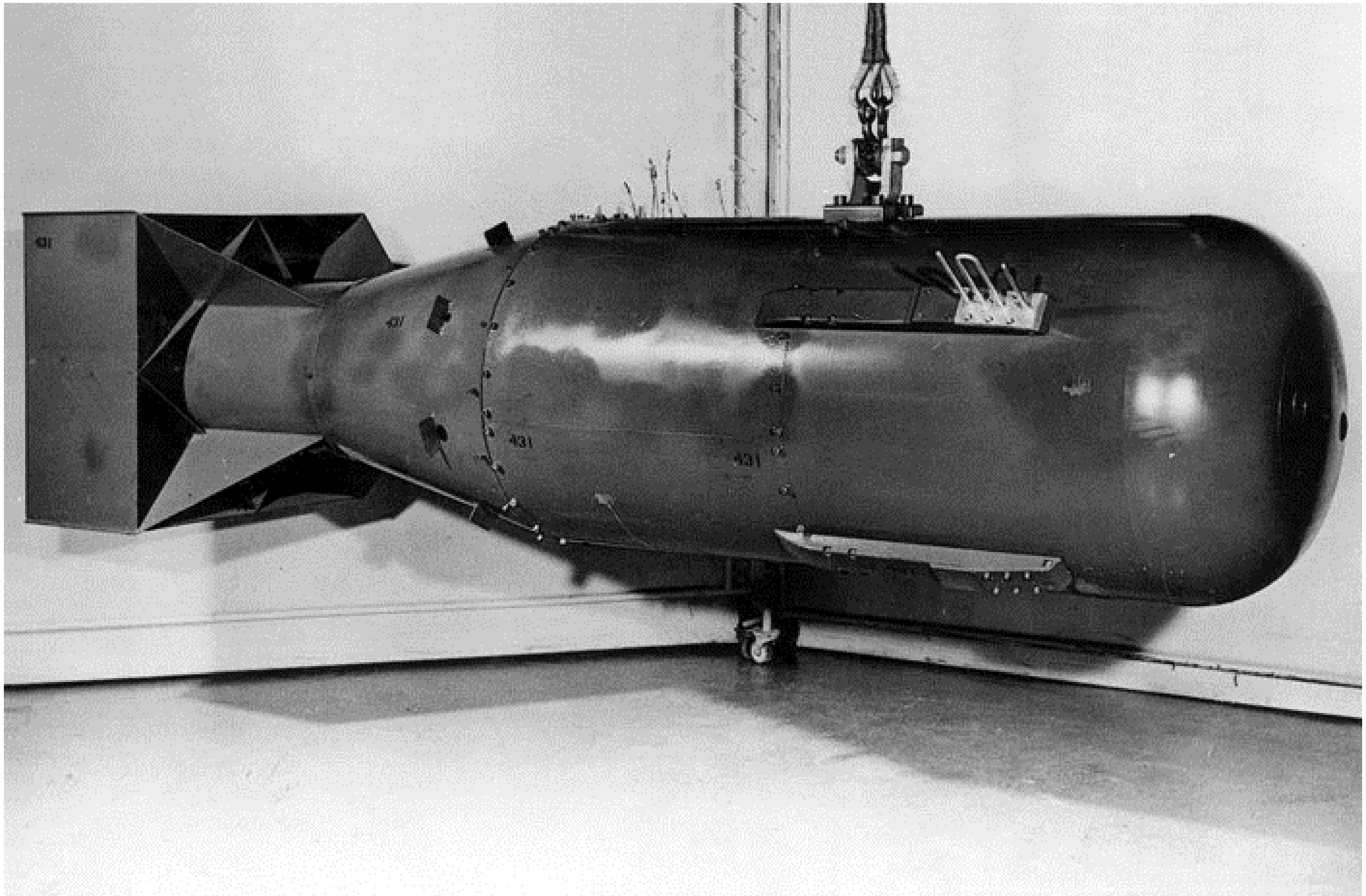


Hanford B Reactor
graphite moderated, water cooled



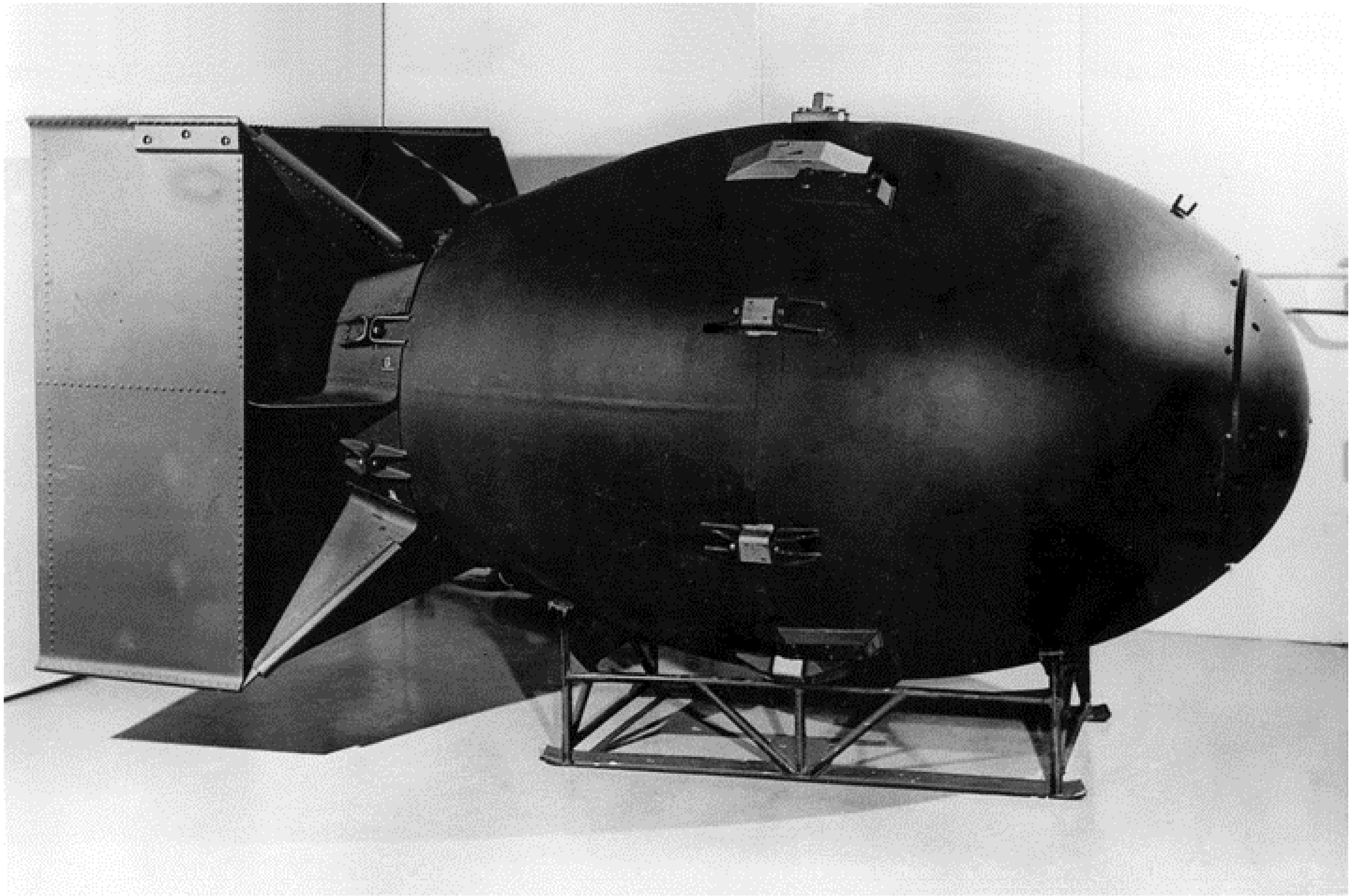
Little Boy

Highly Enriched Uranium (HEU) - >20% U-235



Fat Man

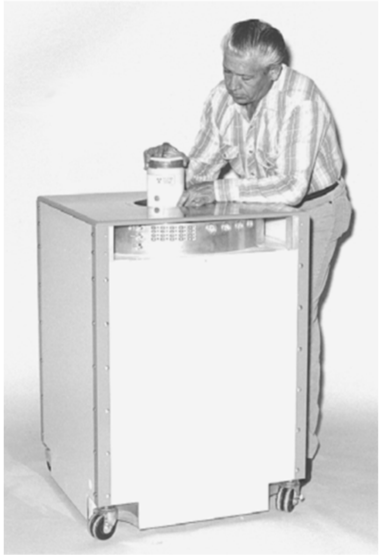
Weapons Grade Plutonium (WGPu) - >93% Pu-239



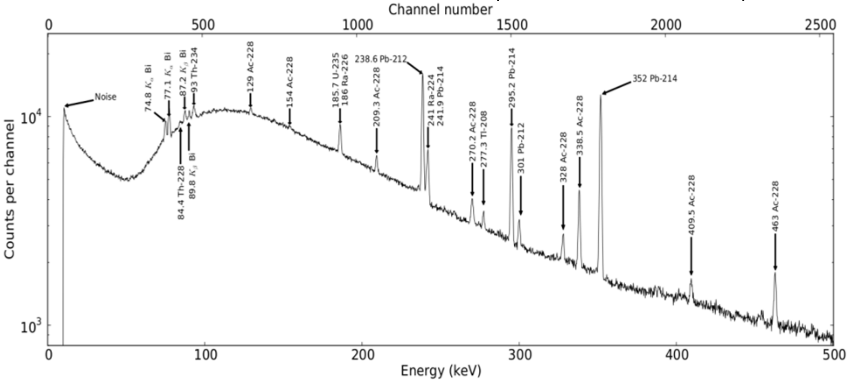
Current Methods

Measurable Unique Signatures of Fissile Material

1. Radiography
   - Geometry
2. Gamma spectrum
   - Isotopic content
3. Total neutron rate
   - Assay of the contents of specific materials
4. 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).*



Special Nuclear Material Detection

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Gamma-rays

Isotope	Energy (keV)	Activity (γ/g-s)
^{234}U	120.9	9.35×10^4
^{235}U	143.8	8.40×10^3
	185.7	4.32×10^4
^{238}U	766.4	2.57×10^1
	1001.0	7.34×10^1
^{238}Pu	152.7	5.90×10^6
	766.4	1.387×10^5
^{239}Pu	129.3	1.436×10^5
	413.7	3.416×10^4
^{240}Pu	45.2	3.80×10^6
	160.3	3.37×10^4
	642.5	1.044×10^3
^{241}Pu	148.6	7.15×10^6
	208.0	2.041×10^7
^{241}Am	59.5	4.54×10^{10}
	125.3	5.16×10^6

Neutrons

Isotope	Half Life	Spontaneous Fission Yield (n/s-kg)
^{232}U	71.7 yr	1,300
^{233}U	1.59×10^5 yr	0.86
^{234}U	2.45×10^5 yr	5.02
^{235}U	7.04×10^8 yr	0.299
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^{238}Pu	87.7 yr	2.59×10^6
^{239}Pu	2.41×10^4 yr	21.8
^{240}Pu	6.56×10^3 yr	1.02×10^6

Tables courtesy of David Chichester, INL

Special Nuclear Material Detection – why neutrons?

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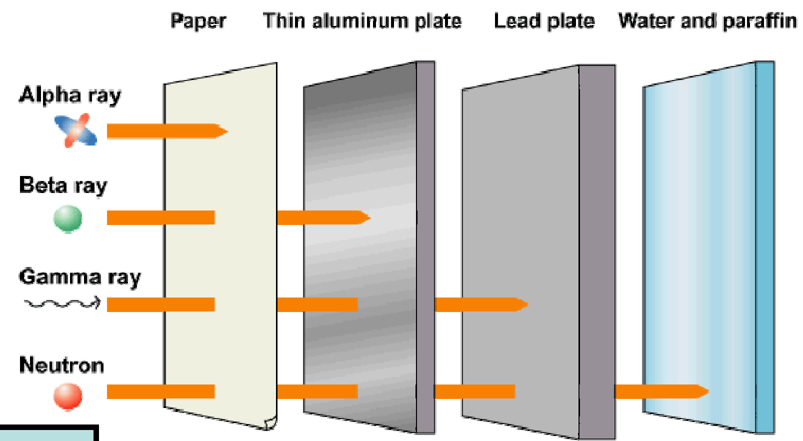

www.remnet.jp

The Passive Gamma-Ray Signatures

Isotope	Energy (keV)	Activity (γ/g-s)	Mean Free Path (mm) (High-Z, ρ)	Mean Free Path (mm) (Low-Z, ρ)
^{234}U	120.9	9.35 x 10^{4}	0.23	69
^{235}U	143.8	8.40 x 10^{3}	0.36	73
	185.7	4.32 x 10^{4}	0.69	80
^{238}U	766.4	2.57 x 10^{1}	10.0	139
	1001.0	7.34 x 10^{1}	13.3	159
^{238}Pu	152.7	5.90 x 10^{6}	0.40	75
	766.4	1.387 x 10^{5}	9.5	139
^{239}Pu	129.3	1.436 x 10^{5}	0.27	71
	413.7	3.416 x 10^{4}	3.7	106
^{240}Pu	45.2	3.80 x 10^{6}	0.07	25
	160.3	3.37 x 10^{4}	0.45	76
	642.5	1.044 x 10^{3}	7.4	127
^{241}Pu	148.6	7.15 x 10^{6}	0.37	74
	208.0	2.041 x 10^{7}	0.86	83
^{241}Am	59.5	4.54 x 10^{10}	0.14	38
	125.3	5.16 x 10^{6}	0.26	70

These materials are dense; self-shielding is not negligible

Ref: "Panda Book"

Table courtesy of David Chichester, INL

Current Methods

Drawbacks and Limitations

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1. Geometry/Radiography
   - Insensitive to element/isotope type
   - Poor penetration
2. Gamma spectrum
   - Attenuation and self-shielding
3. Total neutron rate
   - Spontaneous & induced fission and (α,n) sources are indistinguishable
4. Correlated counts
   - Requires high efficiency, necessitates large detection system
   - Efficiency has to be well known
   - Detector lifetime of 10-30 μs is long compared to fission chain processes
   - Neutron energy information is lost due to moderation

→ He-3 based technologies

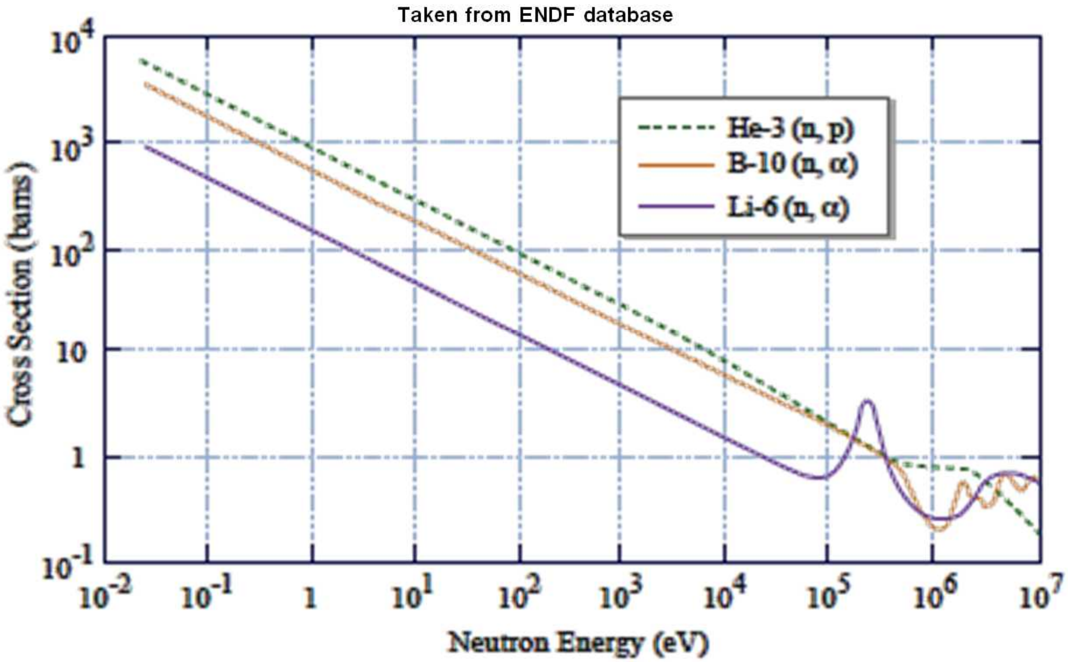
Thermal Neutron Detection

- **High thermal cross section** **(efficiency)**
- **High Q-value** **(discrimination)**

n + ^{3}He → ^{3}H + ^{1}H + 0.764 MeV

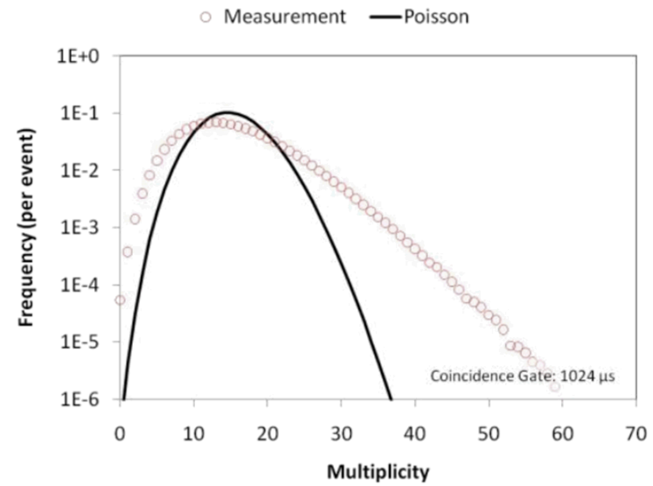
n + ^{10}B → ^{7}Li + α + 2.31 MeV

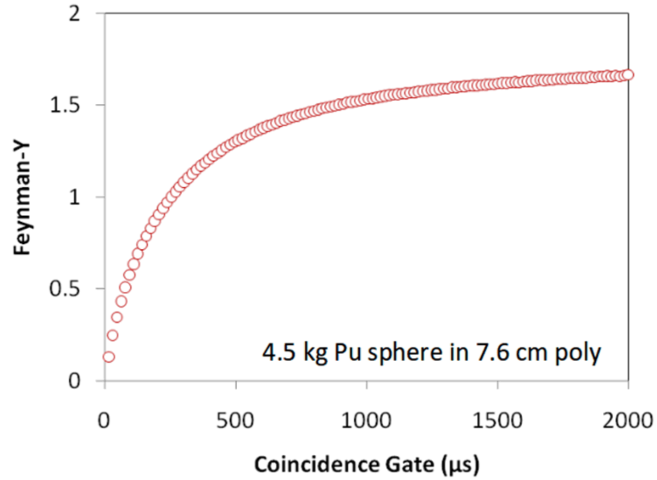
n + ^{6}Li → ^{3}H + α + 4.78 MeV



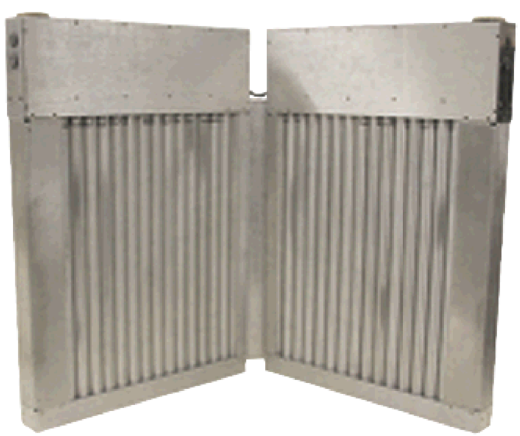
Feynman-Y Approach

- 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



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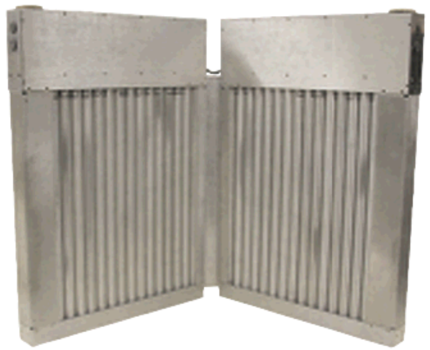
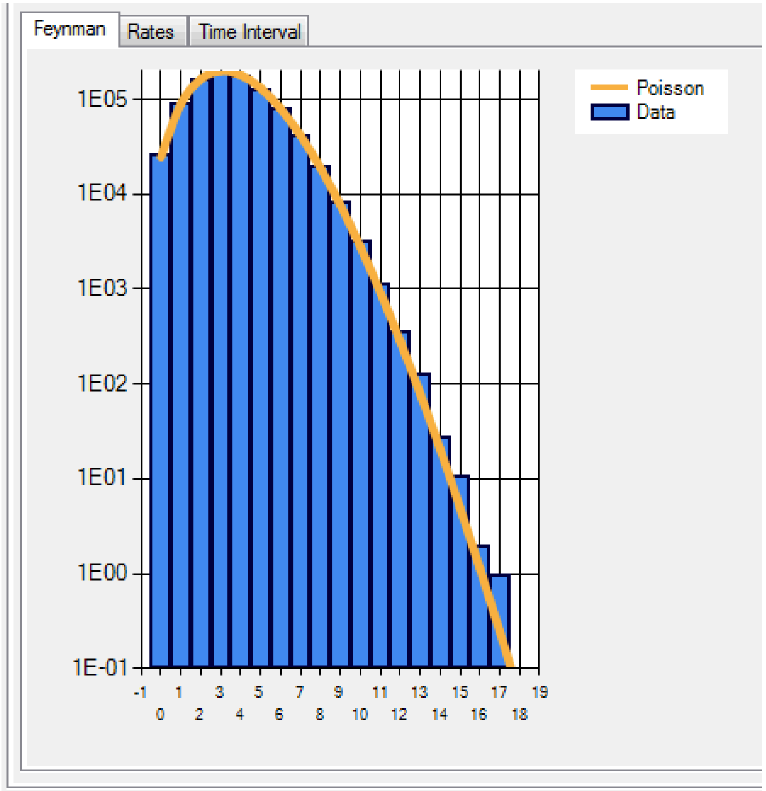
Motivation for using correlated timing

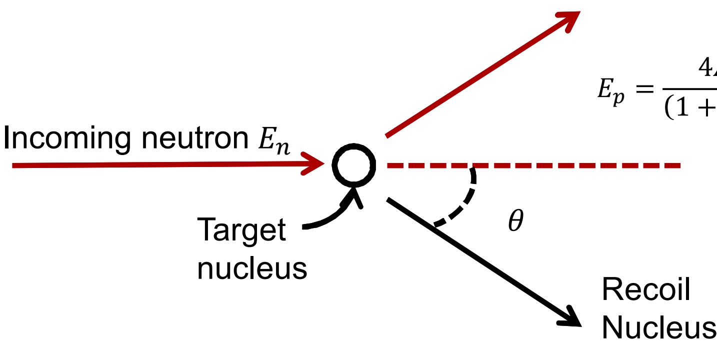
- Multiplicity analysis requires:
  1. High efficiency
  2. Strong knowledge of the efficiency
     a) Distance to the source.
     b) Room return.
     c) Neutron energy spectrum.
  3. Properties of neutron emitting material (multiplicity, cross sections, etc.)
     a) Isotopics – nu bar
     b) (alpha, n) – uncorrelated singles
- We focus on fast fission chain timing:
  1. Can be low efficiency
  2. Does not require knowledge of that efficiency
  3. Can statistically identify the contributions due to spontaneous fission/(alpha, n) and fission chains.



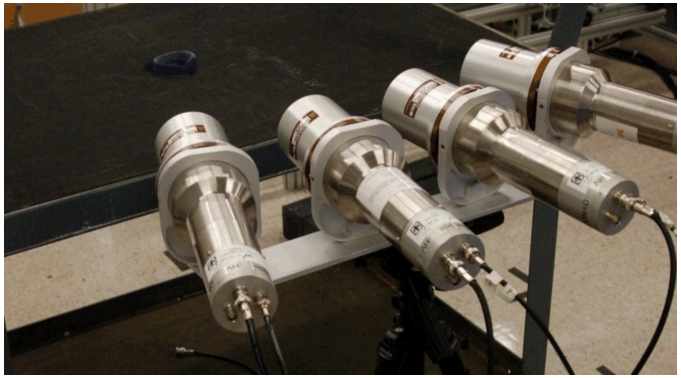


Fast Neutron Detection - Elastic

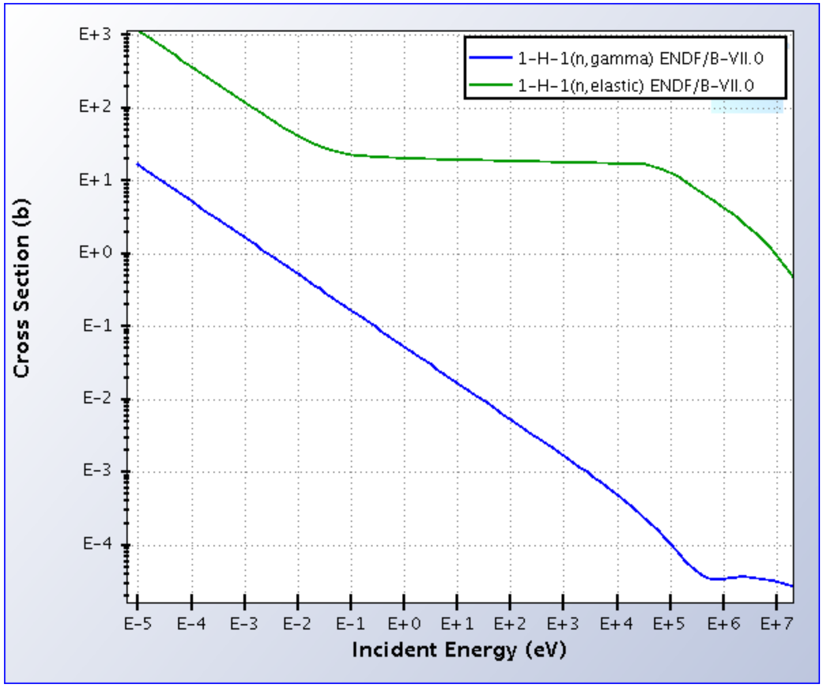
Deposited Neutron Energy



$$E_p = \frac{4A}{(1+A)^2}(\cos^2\theta)E_n$$



Nucleus	Q_{max}/E_n
$^{1}_{1}H$	1.000
$^{2}_{1}H$	0.889
$^{4}_{2}He$	0.640
$^{9}_{4}Be$	0.360
$^{12}_{6}C$	0.284
$^{16}_{8}O$	0.221
$^{56}_{26}Fe$	0.069
$^{118}_{50}Sn$	0.033
$^{238}_{92}U$	0.017



Pulse Shape Discrimination

Pulse Shape Dependence on Interacting Particle

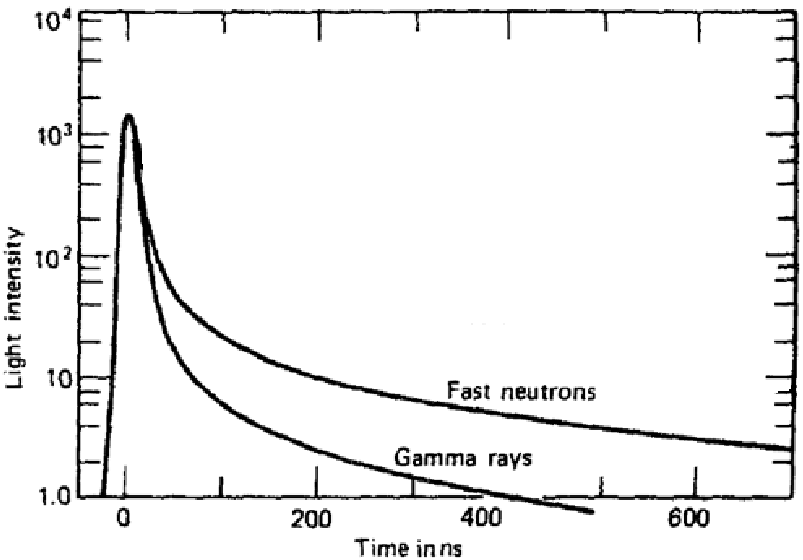
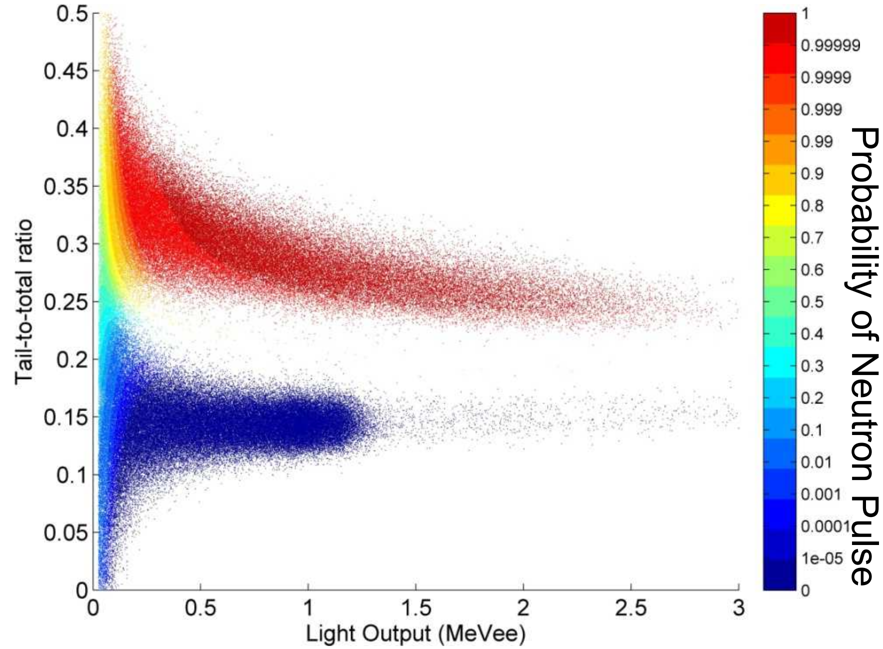


Figure from Glenn Knoll *Radiation Detection & Measurement 3rd Edition*

Bayesian Probability Map



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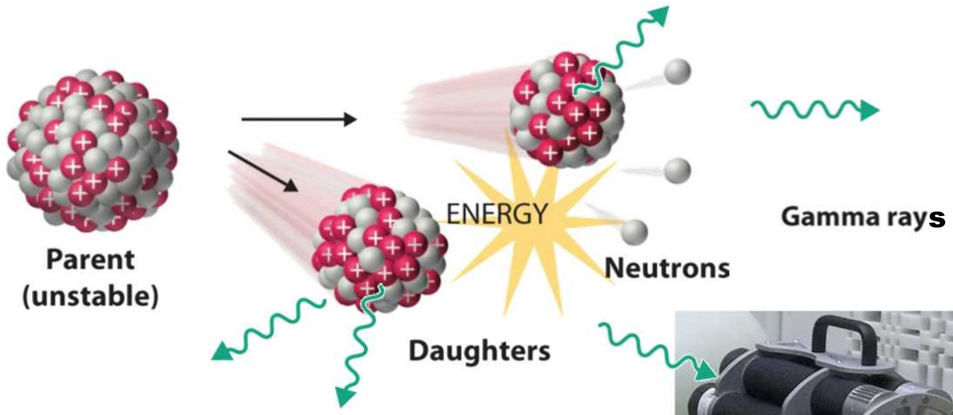
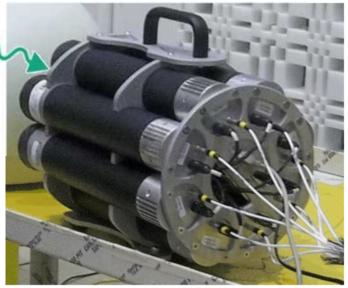
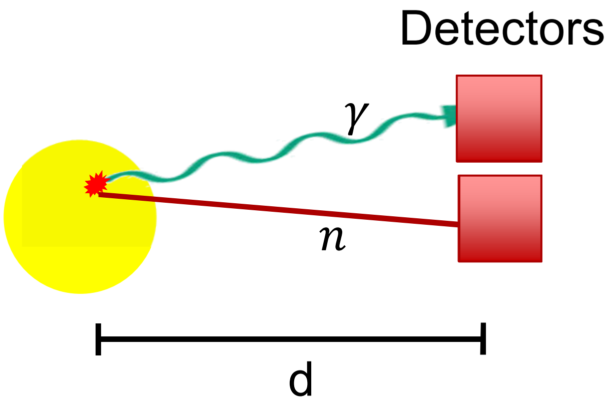
Multiplicity 2 correlation





- 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 Time 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:

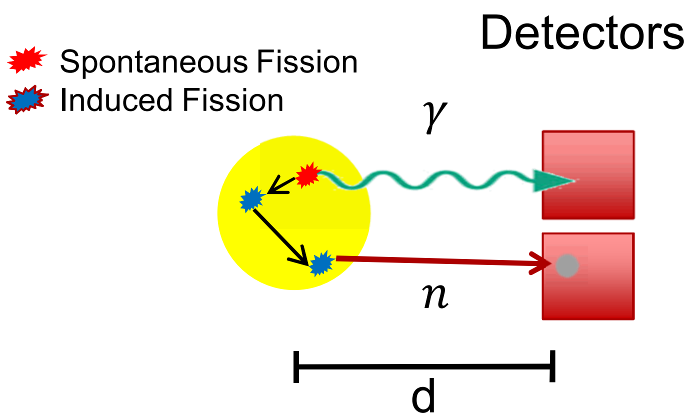
$E_p \leq E_n$

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



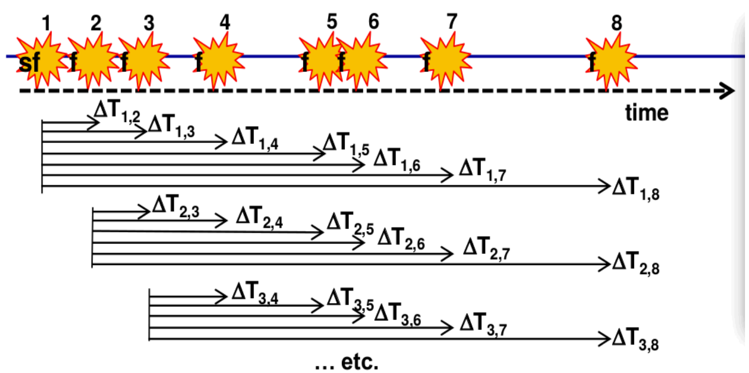
Time difference between fission events in a chain

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

Measured time difference between γ and n

Estimated travel time difference between neutron and gamma

Distribution of times between fission events in a chain



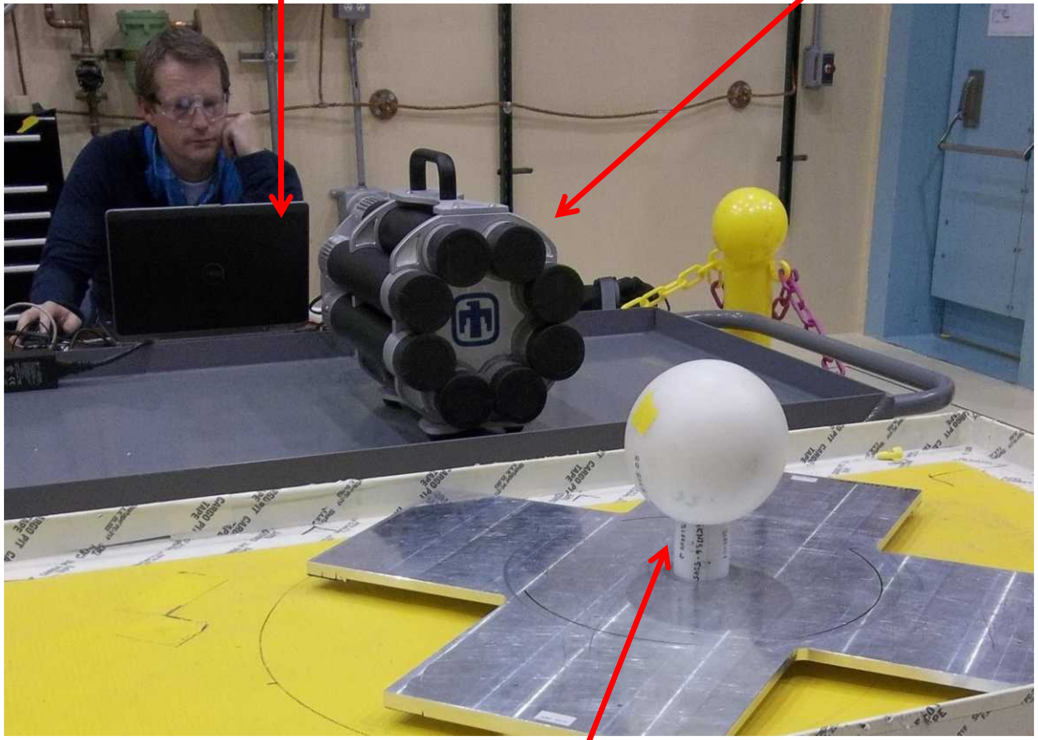
$$\Delta T_{f_1,f_2} > 0 \text{ if } f_1 = \gamma \ \& \ f_2 = n$$

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

Correlated Radiation Signatures - Stilbene Array

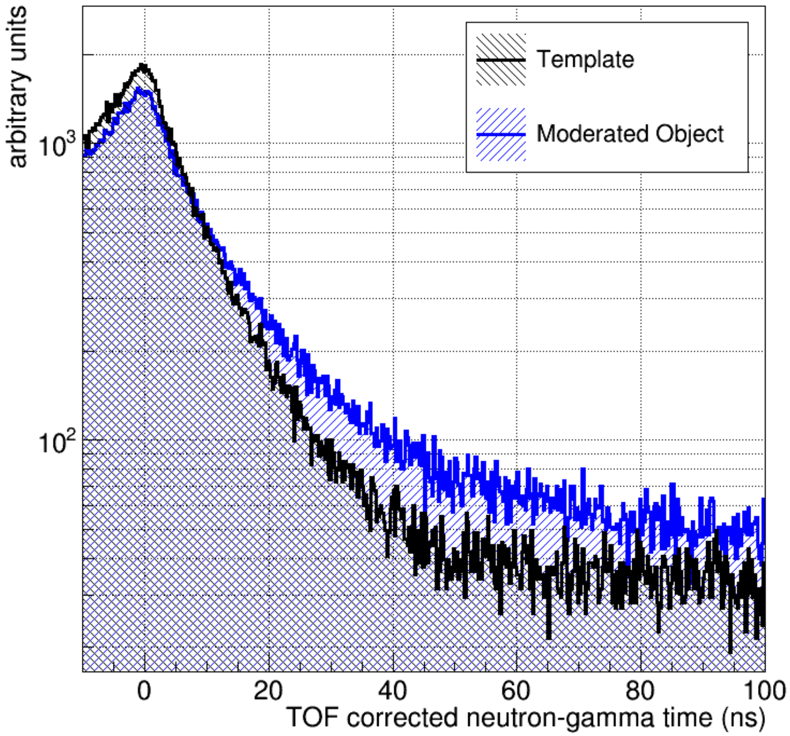
Computer/digitizer

Stilbene array



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

Timing distributions for the bare and moderated BeRP ball



99% True Positive,
1% False Positive:
8 seconds

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

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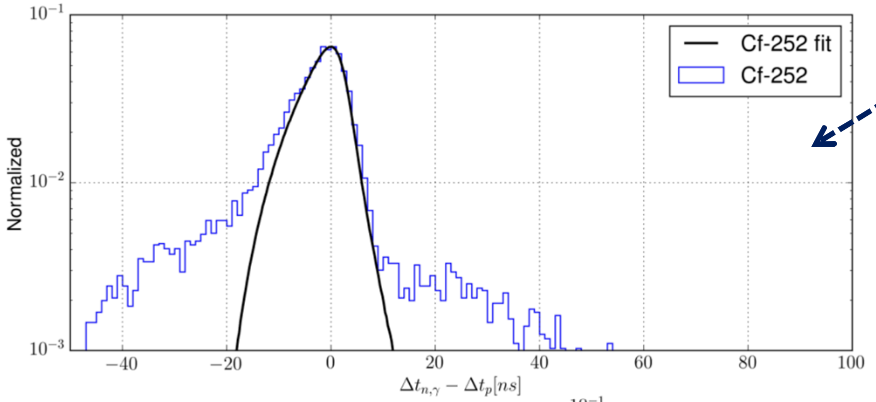
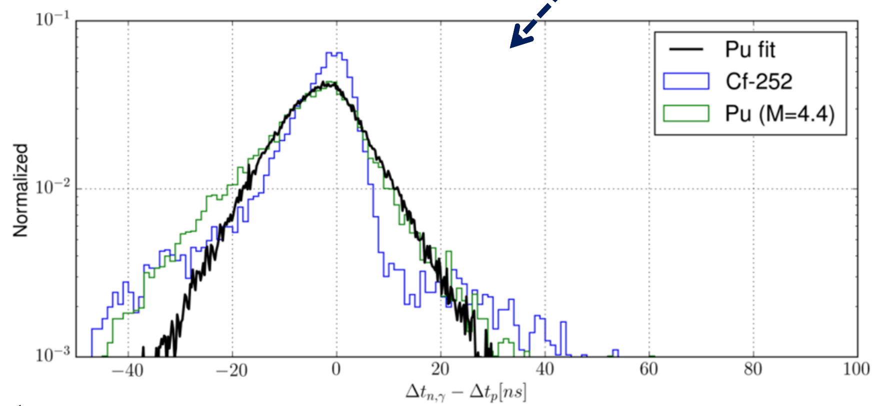
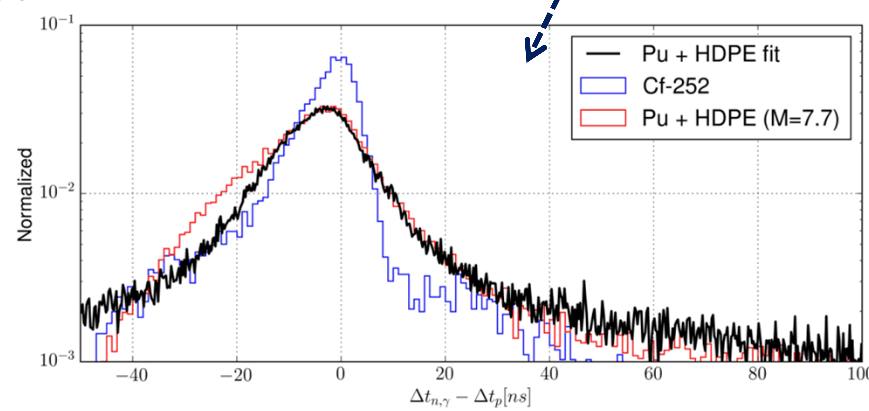


Non-fissile fission source

Fissile material
(BeRP ball, M = 4.4)



Moderated Fissile material
(BeRP ball, M = 7.7)

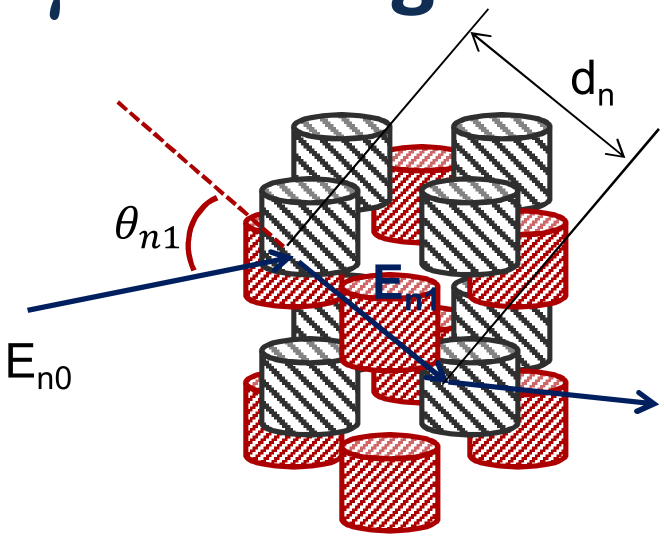


$\Delta T_{f_1,f_2}$ can discriminate:

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

Simple fission chain models fit the distribution well!

γ-n timing + better energy estimate



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

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

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

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

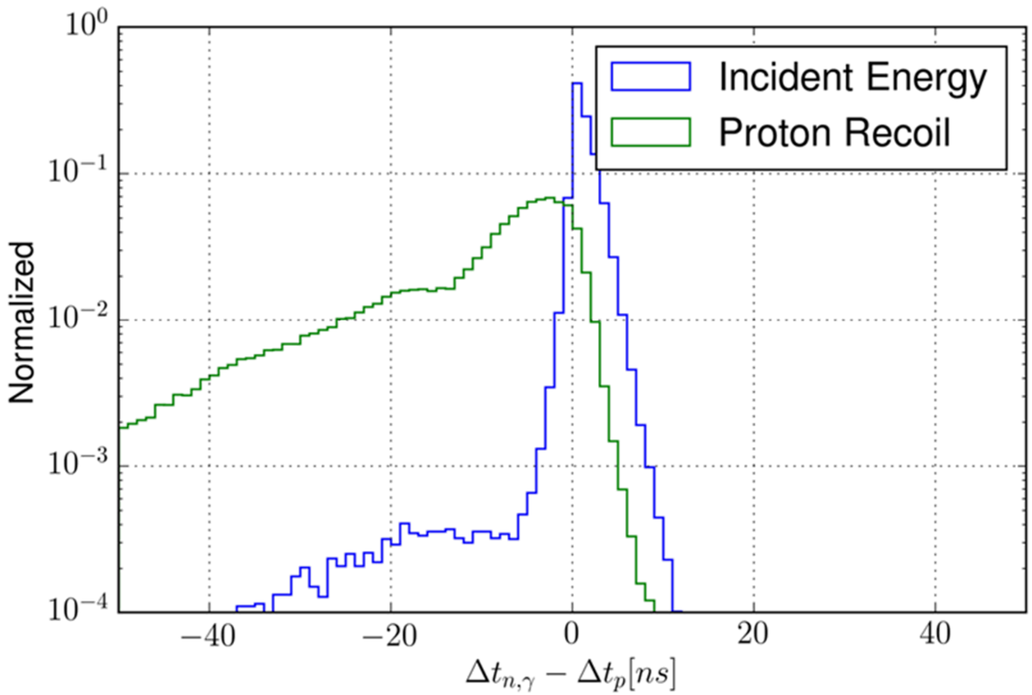
$$cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}}$$

MINER: the Mobile Imager of Neutrons for Emergency Response

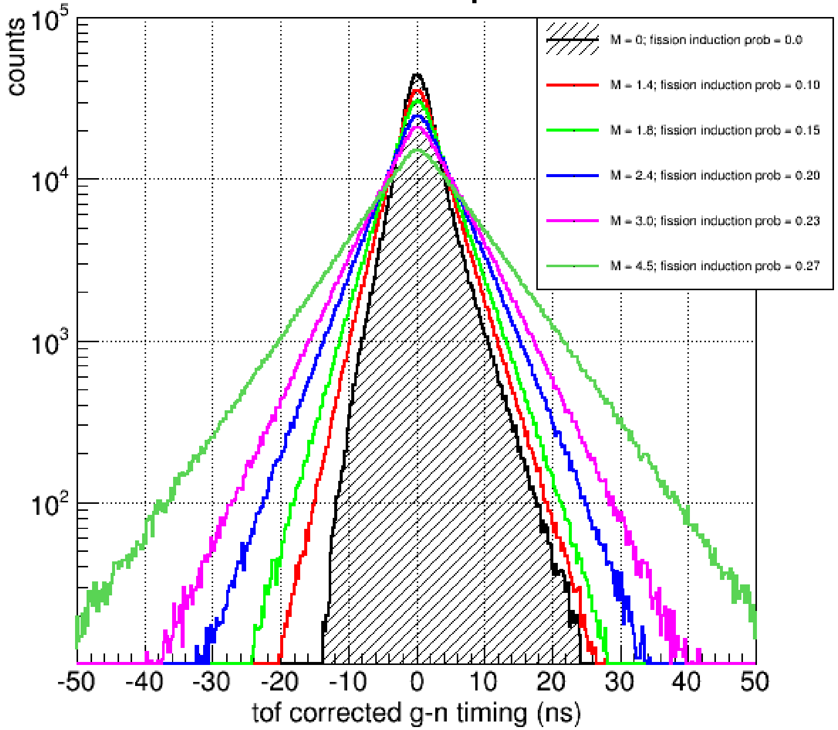
16 independent 3"x3" EJ-309 liquid scintillator cells

$(\Delta t_{n-\gamma} - \Delta t_{En0})$ Distributions

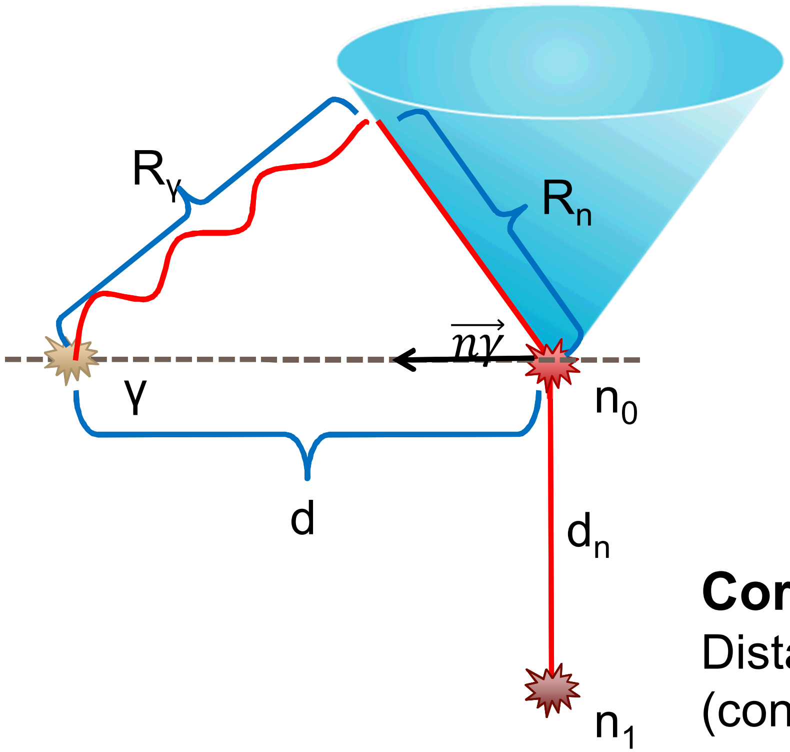
Cf-252 Simulation



Different Multiplications



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)

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

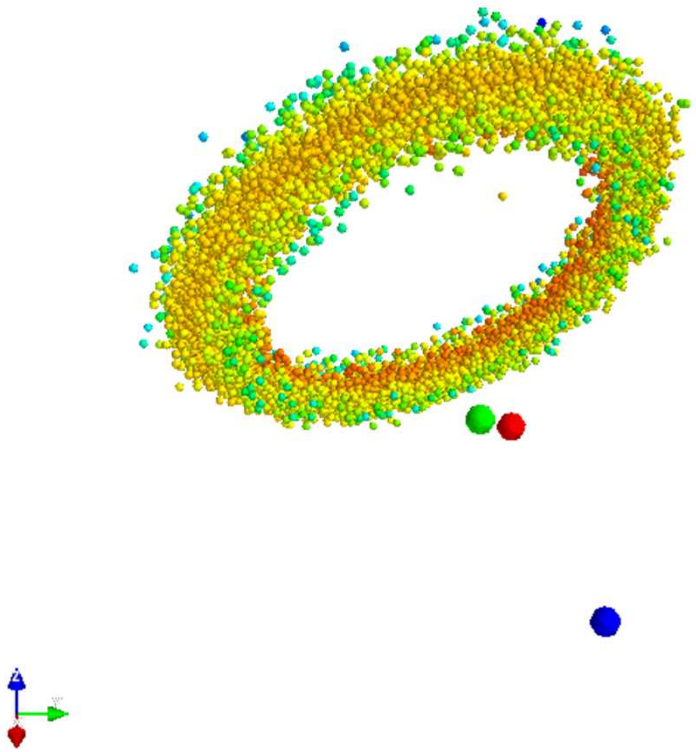
$$R_n = \frac{c^2 \Delta t v_n - d v_n^2 \mu + \sqrt{v_n^2(c^2(\Delta t^2 v_n^2 - 2 d v_n \mu \Delta t + d^2) + v_n^2 d^2(\mu^2 - 1))}}{c^2 - v_n^2}$$

where

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

γ-n-n 3-D reconstruction – single event

Single correlated event back-projection



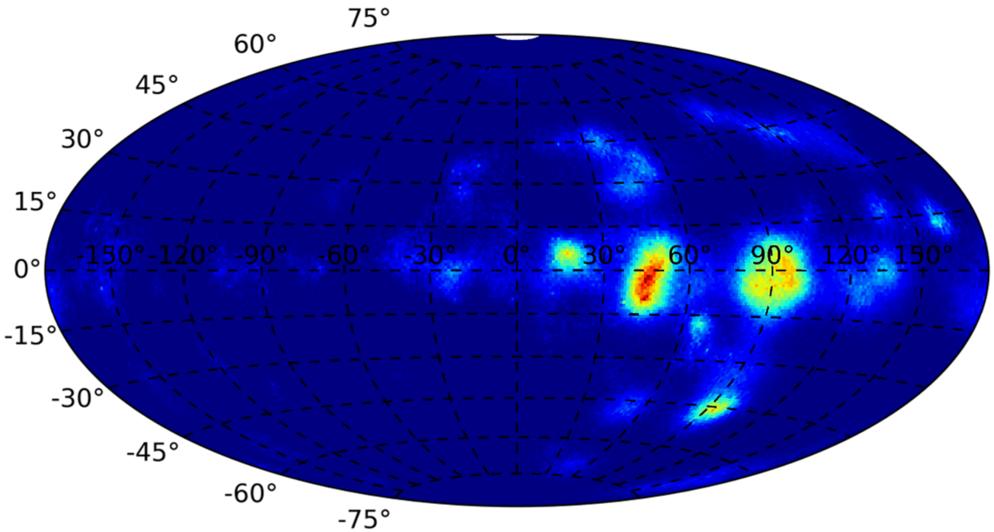
$$cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}}$$

+

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

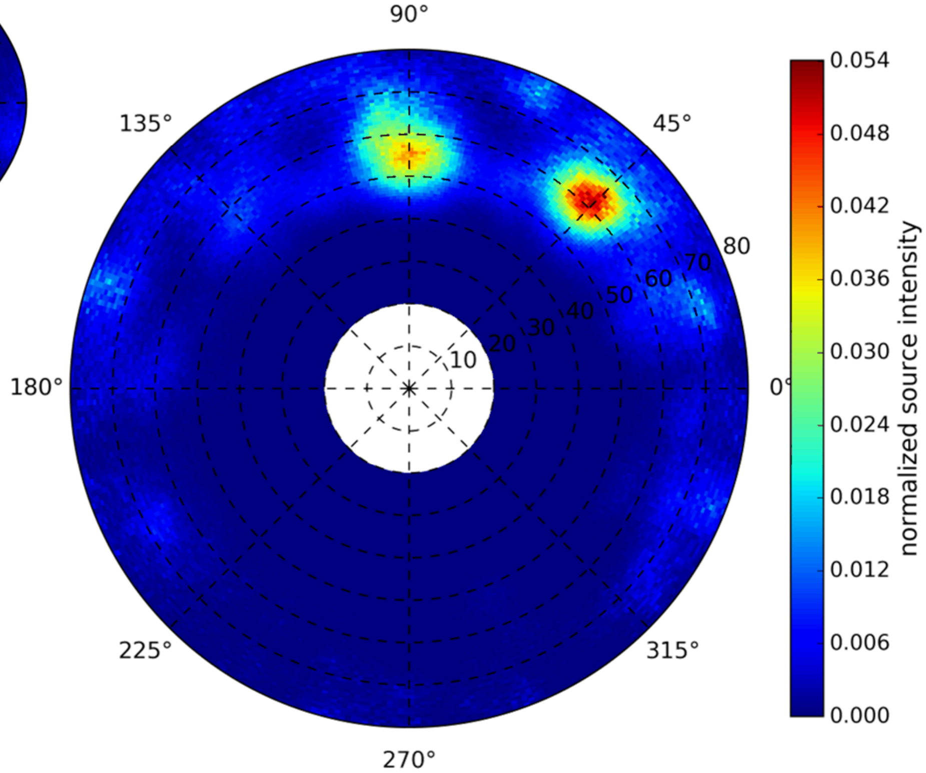
γ-n-n 3-D reconstruction

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



2D angular view

“top down” view



γ-n-n 3-D reconstruction

Sandia National Laboratories

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

Preliminary

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

+

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

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

Conclusions

- Special Nuclear Material can be characterized by fast (ns) timing of correlated gammas and neutrons.

- This can be used to determine:
  1. Geometry (both imaged and through mass-multiplication relation)
  2. Multiplication
  3. Fissile mass
  4. Presence and nature of surrounding reflectors/moderators

- We have demonstrated that the determination of multiplication and the 3-D imaging of SNM is possible using this signature.

Exceptional service in the national interest

Sandia National Laboratories

CONfirmation using a Fast-neutron Imaging Detector with Anti-image NULL-positive Time Encoding (CONFIDANTE)

Peter Marleau

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Certification vs. Authentication: It's not just for hardware

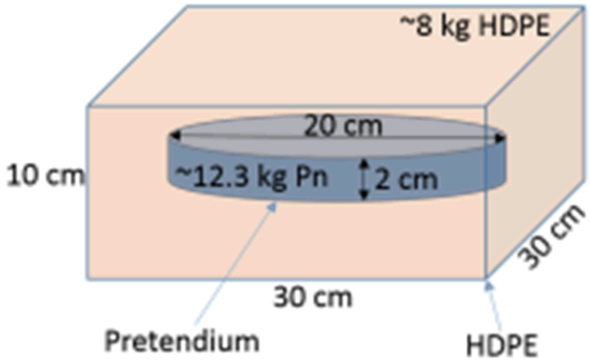
Sandia National Laboratories

Certification – the process by which a host party gains confidence that sensitive information regarding an entity or facility remains secure.

Authentication - the process by which a monitoring party gains confidence that reported characteristics of an entity reflect the true state of that entity

Challenge problem

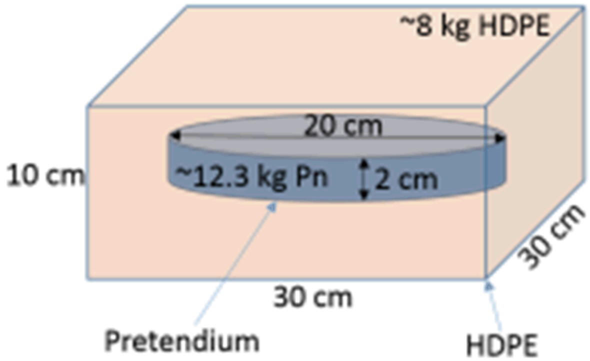
- The inspecting party has or had access to measure item T, which is known to be a valid type 1 treaty accountable item (TAI) through some other mechanism.



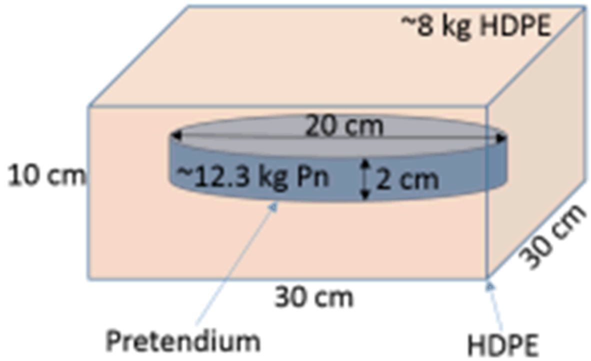
Object T = valid type 1 TAI

Challenge problem

- The inspecting party has or had access to measure item T, which is known to be a valid type 1 TAI through some other mechanism.
- In the course of an inspection, the host presents item X and declares it as a type 1 TAI
- Item X should pass the verification measurement if it is a type 1 TAI, and fail if it is significantly different.



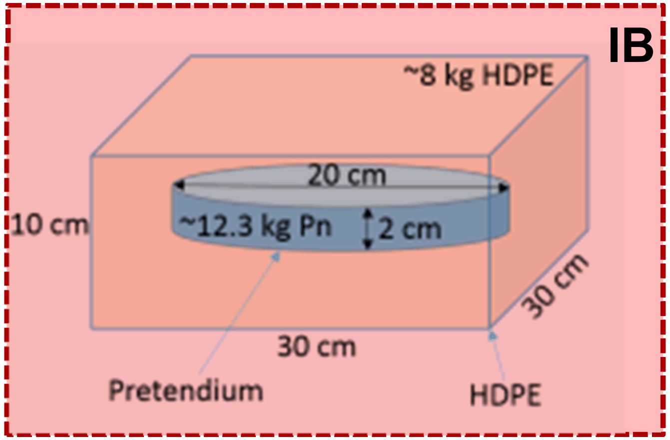
Object T = valid type 1 TAI



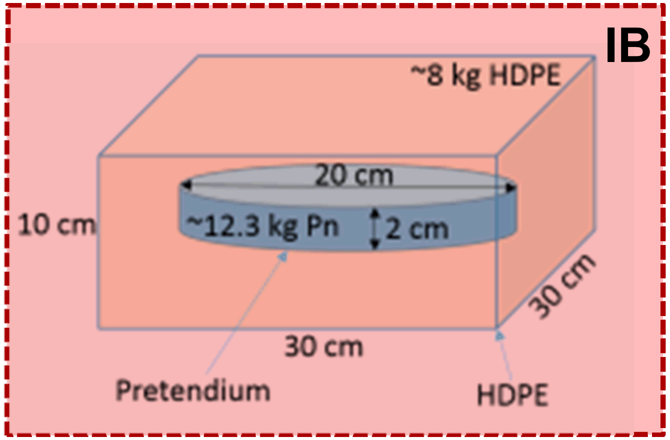
Object X = ?

Challenge problem

- The inspecting party has or had access to measure item T, which is known to be a valid type 1 TAI through some other mechanism.
- In the course of an inspection, the host presents item X and declares it as a type 1 TAI
- Item X should pass the verification measurement if it is a type 1 TAI, and fail if it is significantly different.
- The host must be confident that the inspector has not learned the diameter *d* of the pretendium in item X, or any type 1 TAI



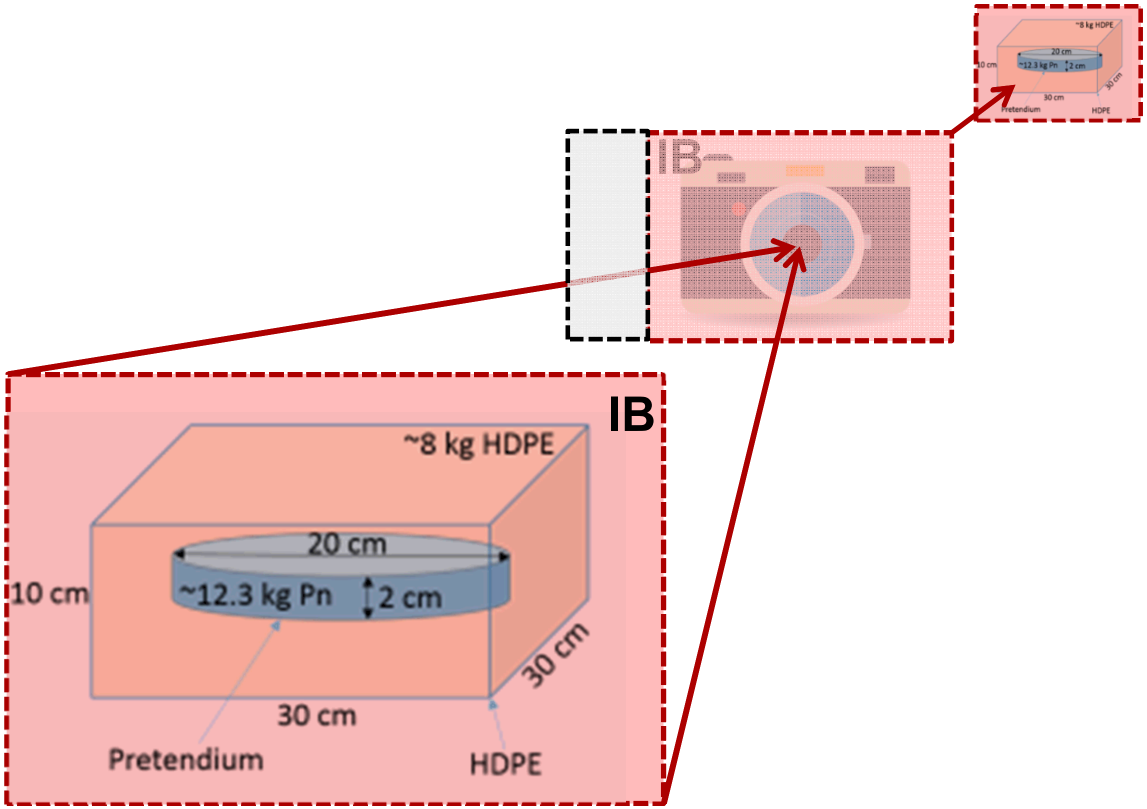
Object T = valid type 1 TAI



Object X = ?

Templates - generation

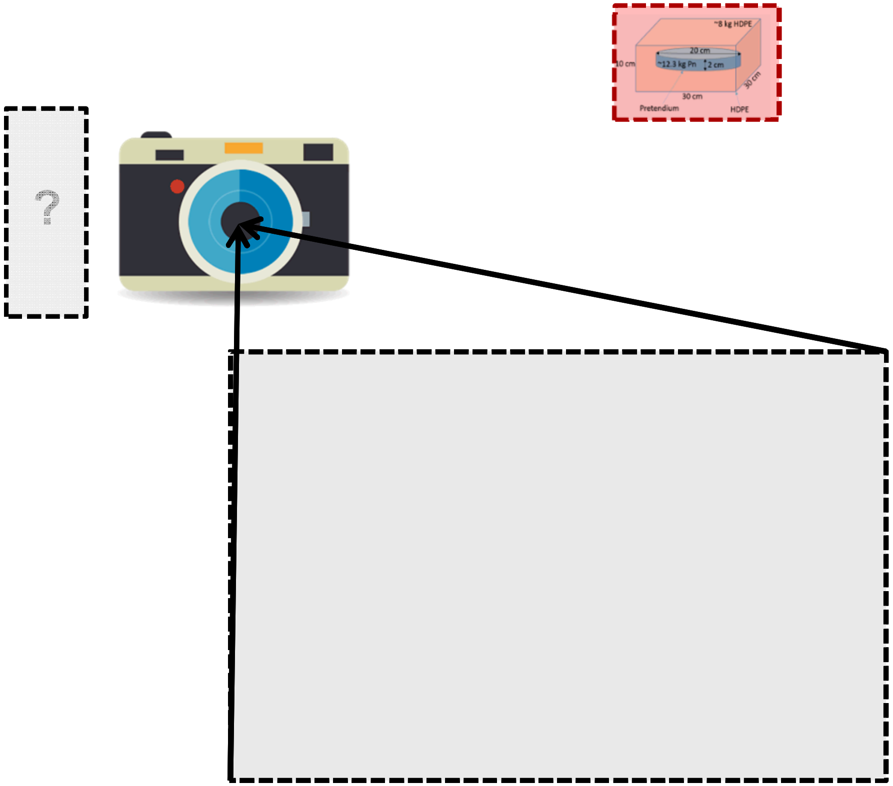
- We could generate a template behind an information barrier (IB) …



Object T = valid type 1 TAI

Templates - authentication

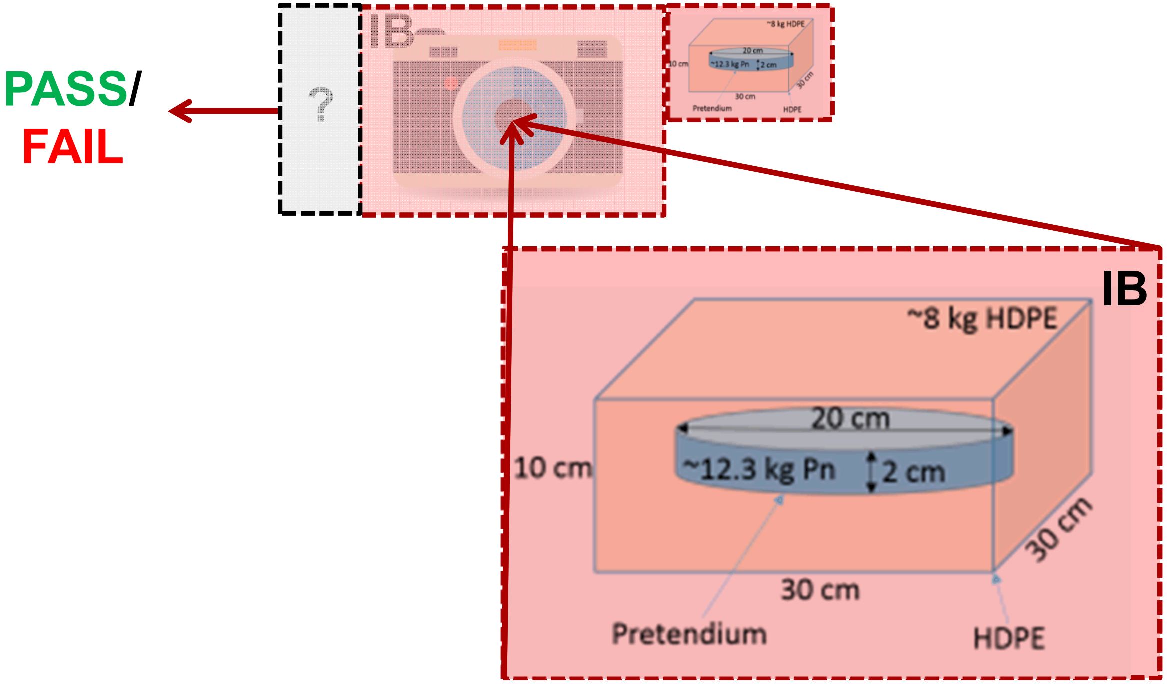
- Authenticate equipment …



Object Z = ?

Templates - comparison

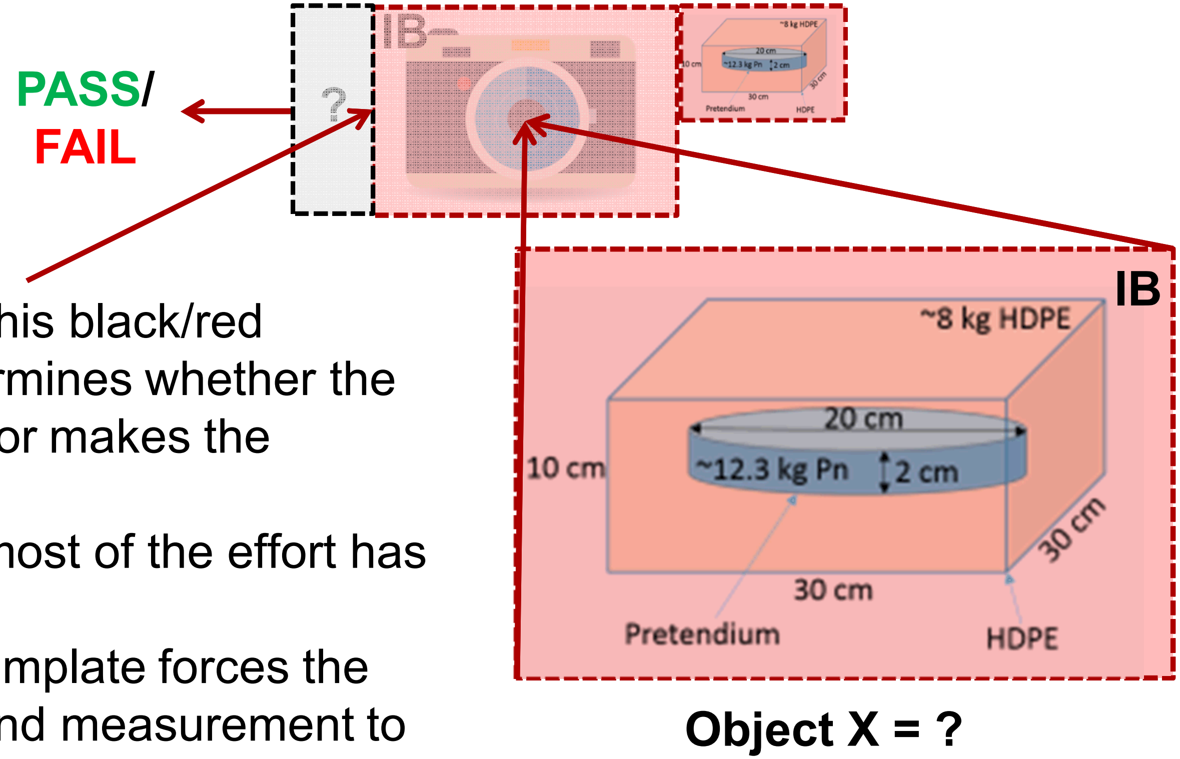
- Make comparison measurement…



Object X = ?

Templates – who measures?

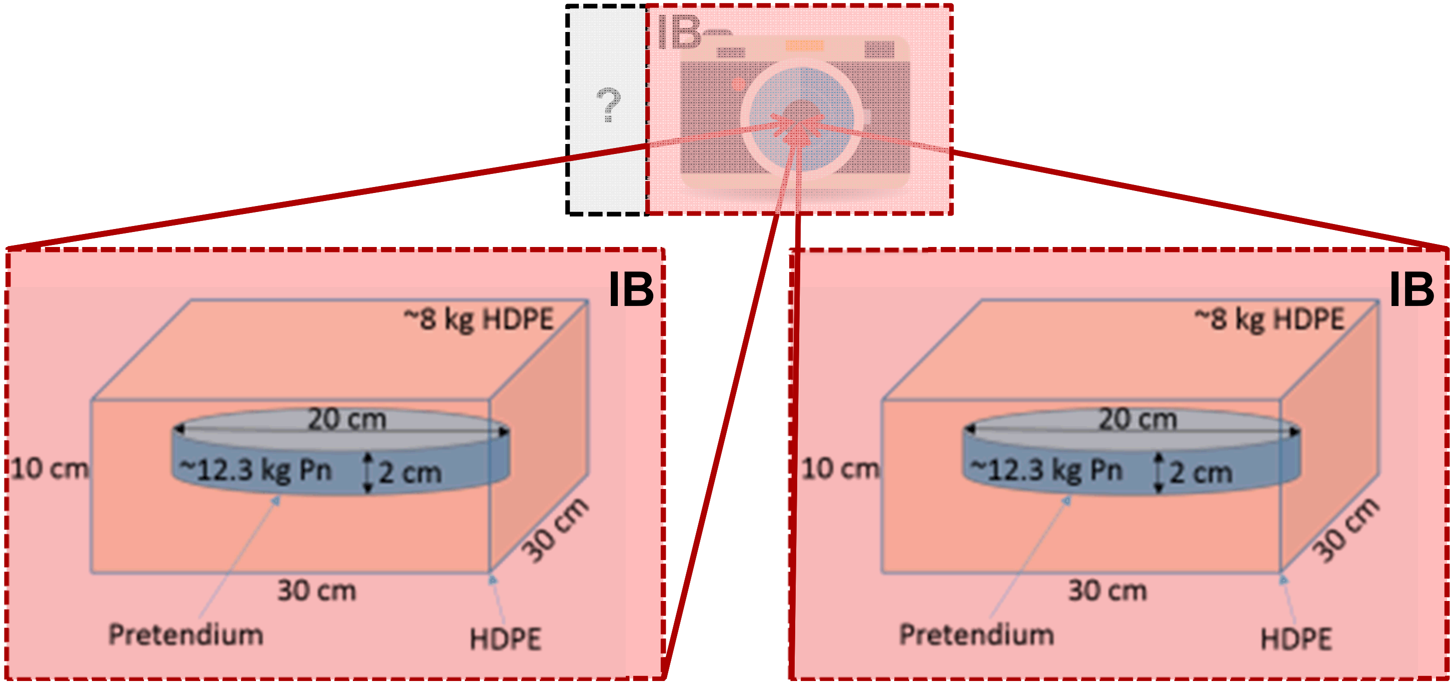
- Who makes the measurement? Is the measurement itself authenticatable?



- The nature of this black/red boundary determines whether the host or inspector makes the measurement.
- This is where most of the effort has gone.
- At worst, the template forces the entire device and measurement to be behind an IB.

Proposal – comparison measurements

- Can we compare two objects directly without generating a template?
- If one object is T, then X is confirmed as a type 1 TAI.
- If neither object is T, then they are confirmed to be identical, but not T.
- If multiple object comparisons are confirmed and even one is T, then all objects are confirmed as type 1 TAIs.

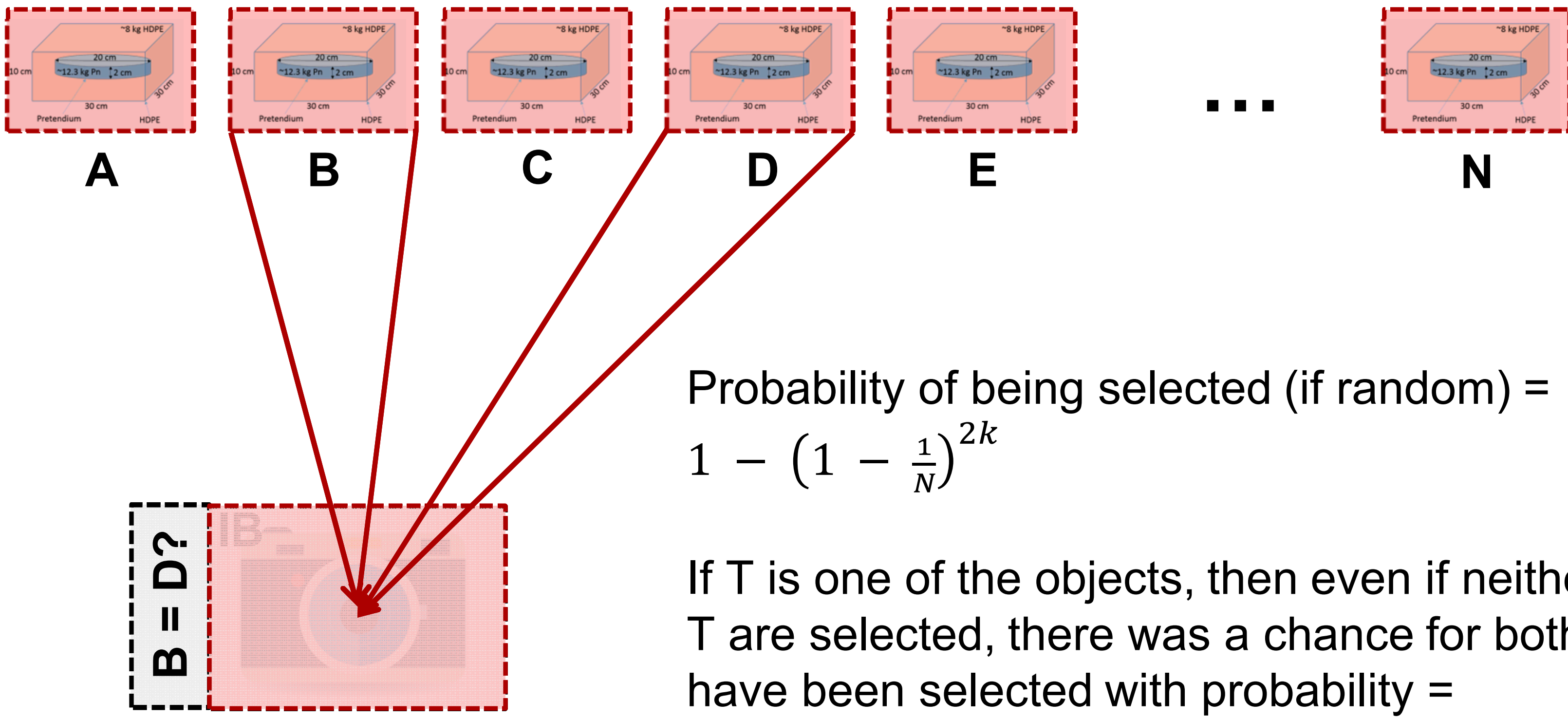


Object T = valid type 1 TAI

Object X = ?

Proposal – CONOPS and Inspector choice

- Presented with N objects and k comparison measurements will be made.



Probability of being selected (if random) =

$$1 - \left(1 - \frac{1}{N}\right)^{2k}$$

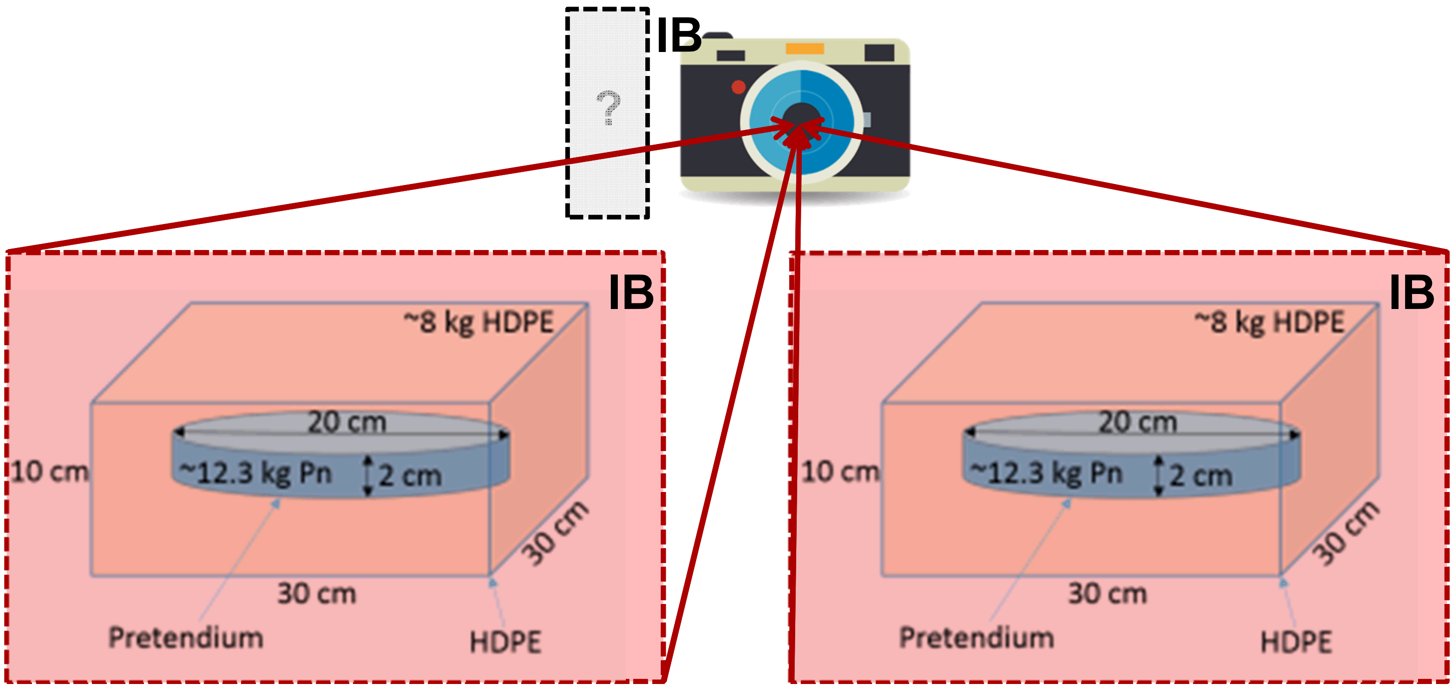
If T is one of the objects, then even if neither X nor T are selected, there was a chance for both to have been selected with probability =

$$\left(1 - \left(1 - \frac{1}{N}\right)^{2k}\right)^2$$

providing some degree of confidence

Proposal – comparison measurements

- Is there a physical implementation of the confirmation measurement that the inspector can watch and authenticate?
- **It would be great if we could get a physical NULL as an indication of positive confirmation at all times, even during the measurement.**

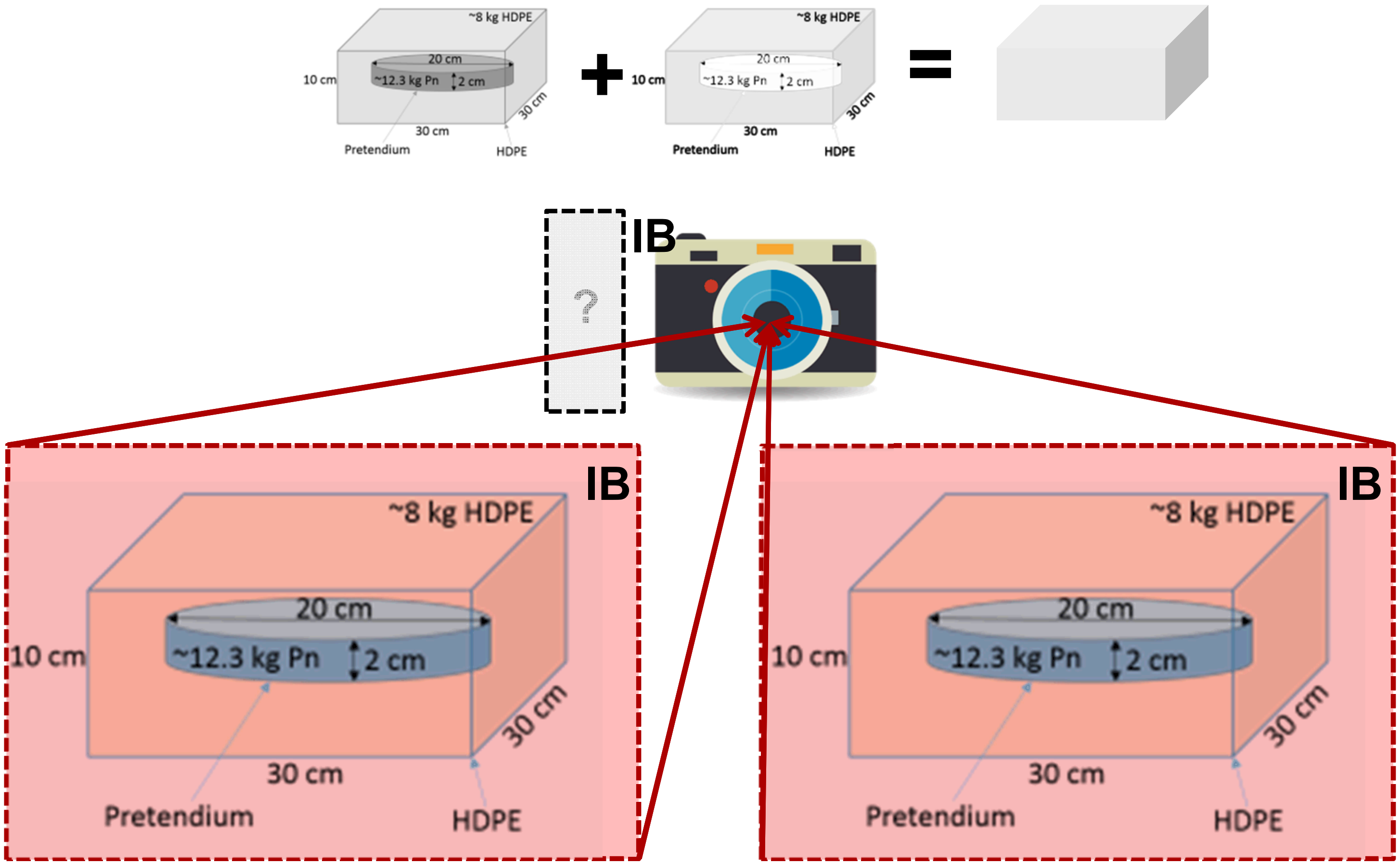


Object T = valid type 1 TAI

Object X = ?

Proposal – complementary comparison

- What we need is to turn one image into the complement of the other ***at all times***.

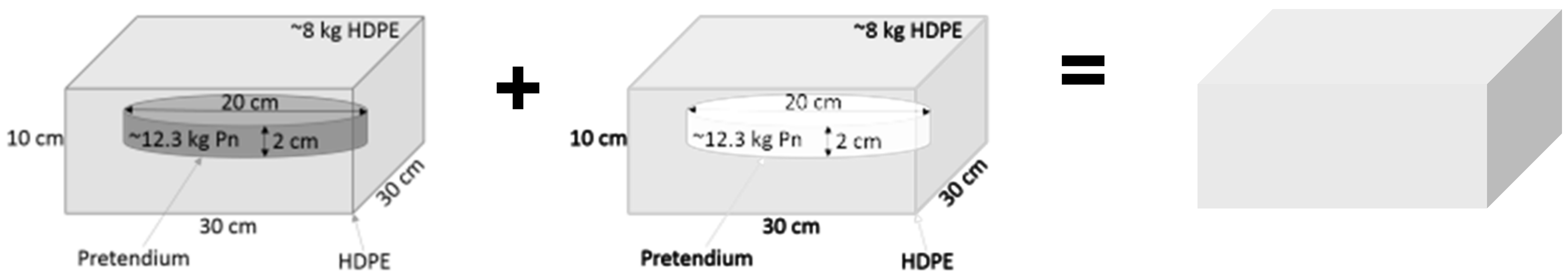


Object T = valid type 1 TAI

Object X = ?

Ok, but how? …

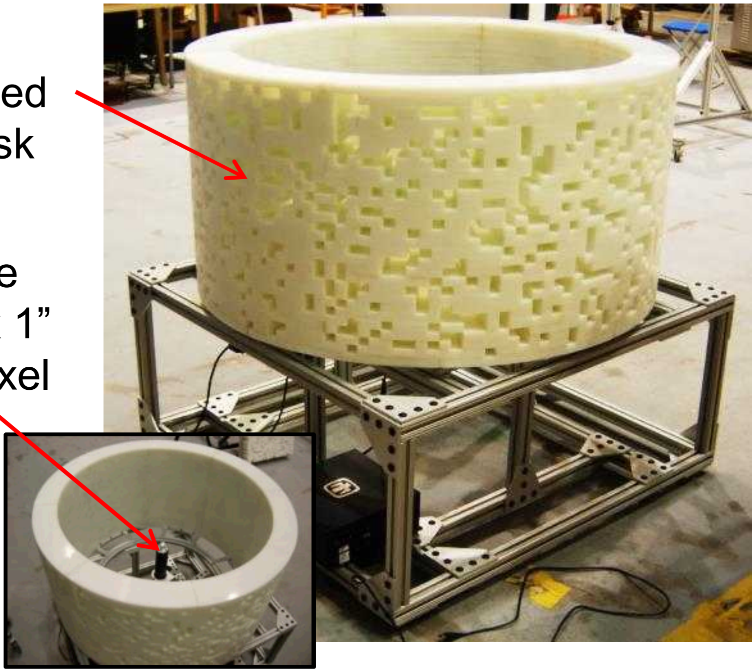
- One image is the complement of the other ***at all times***.



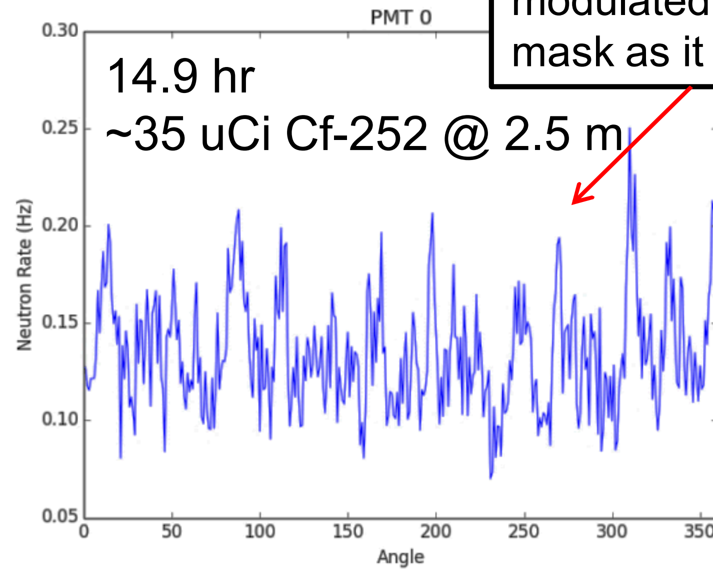
2D Time-encoded Imaging (TEI)

2-d coded mask

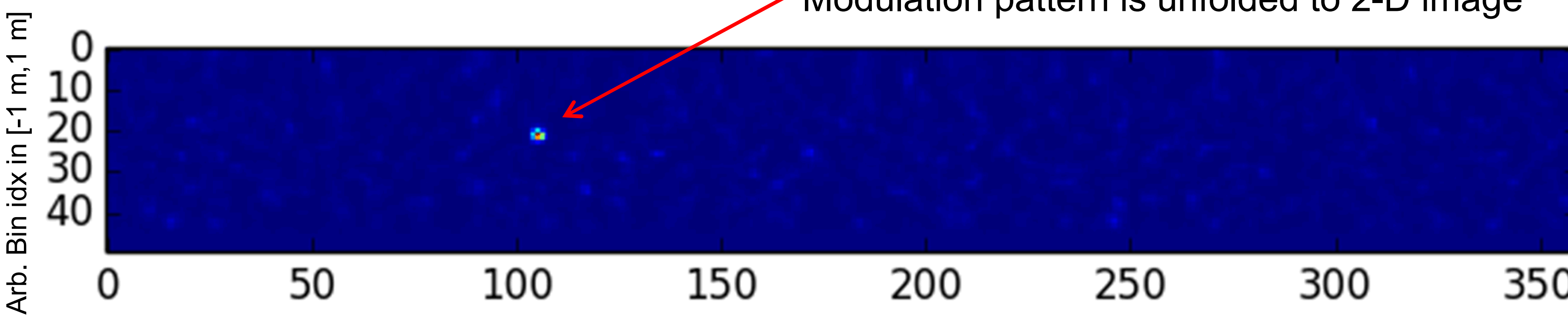
Single 1"D x 1" LS pixel



Single pixel rate is modulated by the mask as it rotates.



Modulation pattern is unfolded to 2-D image

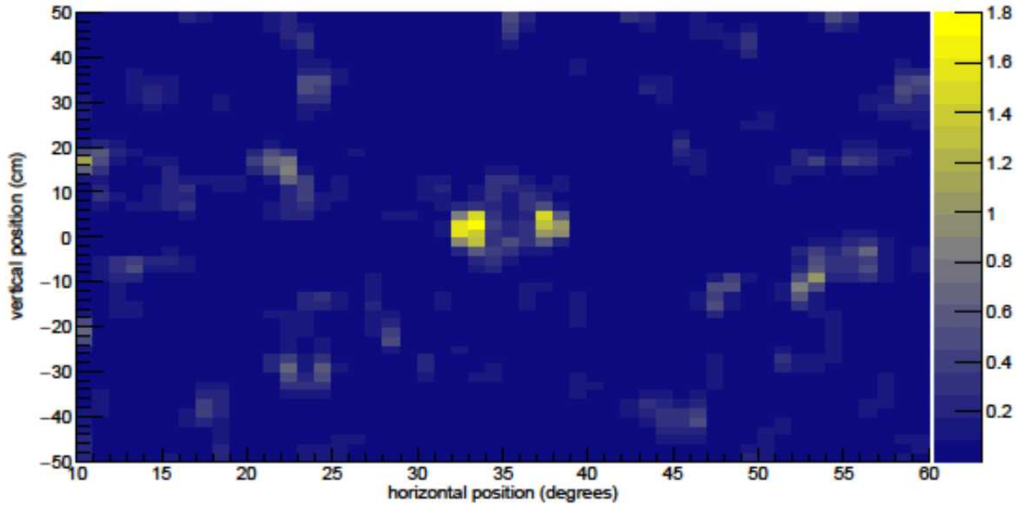


J. Brennan, E. Brubaker, M. Gerling, P. Marleau, K. McMillan, A. Nowack, N. LeGalloudec, M. Sweany, "Demonstration of Two-dimensional Time-encoded Imaging of Fast Neutrons", Nuclear Instruments and Methods A, 2015

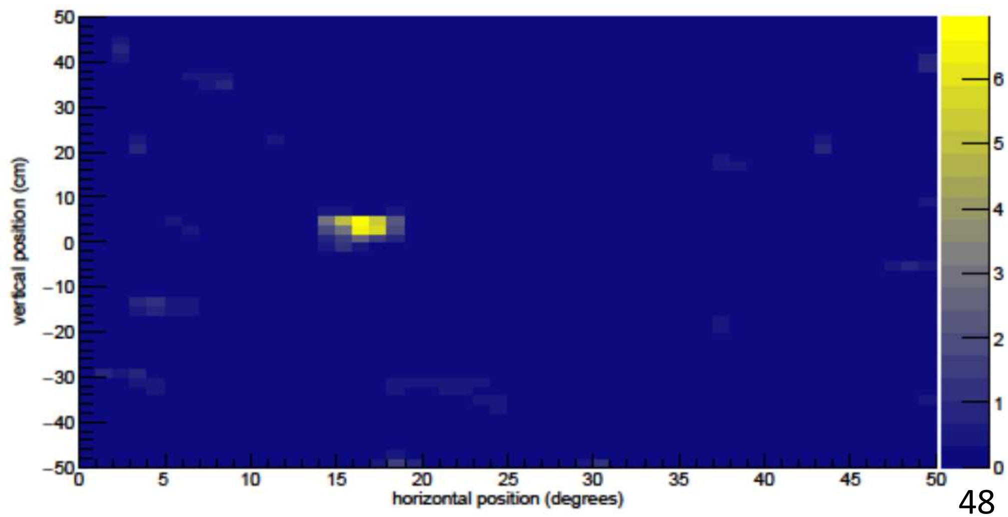
TEI-2D imaging – two point sources

Two 1.4e5 n/s ^{252}Cf point sources at 2.0 meters stand-off.

5 degree separation in 1 hour (50 mlem iterations)



2 degree separation in 24 hours (250 mlem iterations)

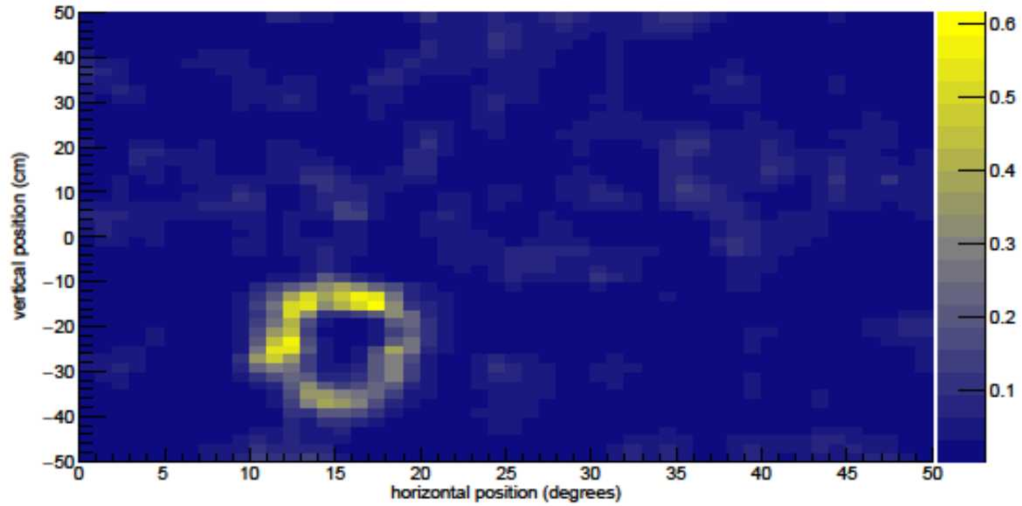


J. Brennan, E. Brubaker, M. Gerling, P. Marleau, K. McMillan, A. Nowack, N. LeGalloudec, M. Sweany, "Demonstration of Two-dimensional Time-encoded Imaging of Fast Neutrons", Nuclear Instruments and Methods A, 2015

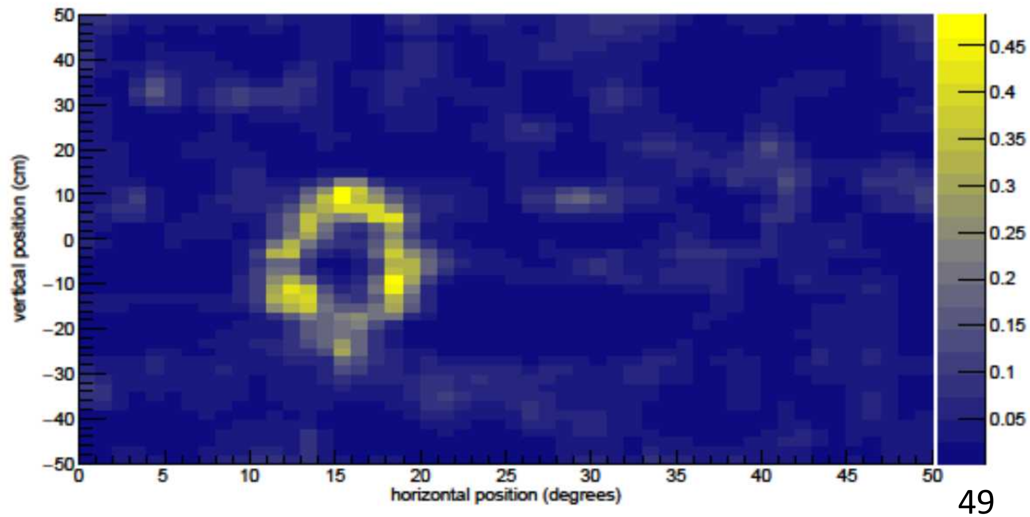
TEI-2D imaging – extended sources

A single 1.4e5 n/s ^{252}Cf source move through an extended pattern at 2 m.

72 hours
(100 mlem iterations)



94 hours
(100 mlem iterations)

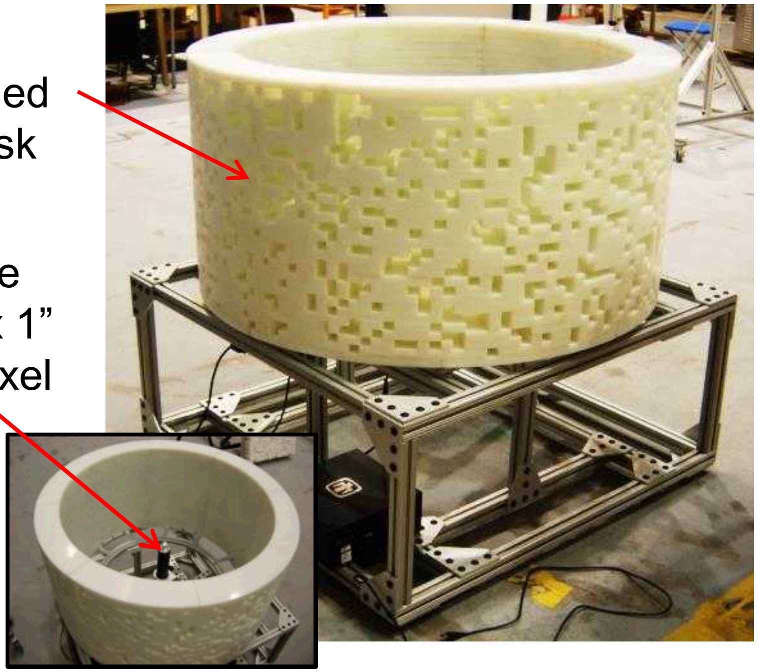


J. Brennan, E. Brubaker, M. Gerling, P. Marleau, K. McMillan, A. Nowack, N. LeGalloudec, M. Sweany, "Demonstration of Two-dimensional Time-encoded Imaging of Fast Neutrons", Nuclear Instruments and Methods A, 2015

2D TEI – confirmation measurements?

2-d coded mask

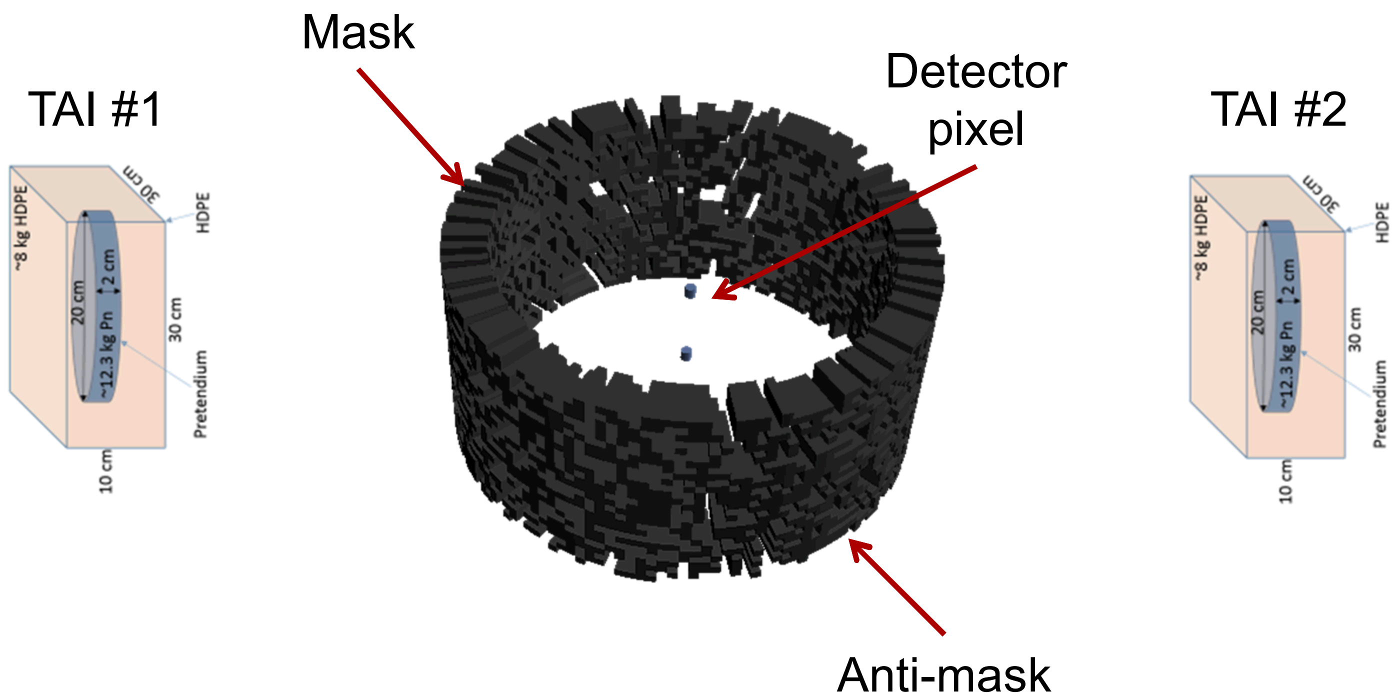
Single 1"D x 1" LS pixel



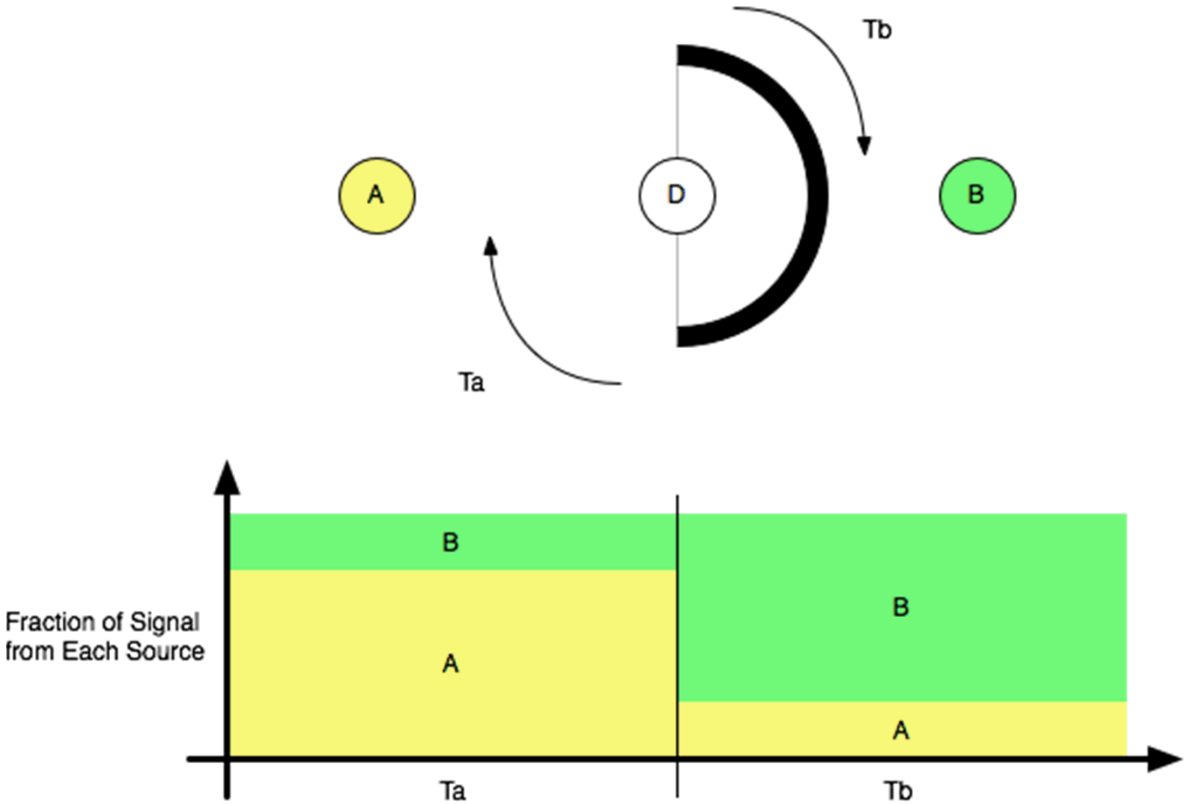
- **TEI is simple**
  1. Only one instrumented channel.
  2. Minimal calibration issues
     a) Information encoded in the relative rate of a single detector.
     b) Absolute gain doesn't matter.
     c) Gain can drift over time.
  3. Potential real-time analysis
     a) Single data stream.
     b) Events can be processed one at a time and update a test statistic.
- **Can we design a TEI confirmation system such that the detection rates can be monitored by an inspector without putting sensitive information at risk?**

Here's where the magic happens …

If the mask is designed such that one side is the anti-mask of the other, then **TAI #2 projects the anti-image of TAI #1 at all times**
if and only if they are identical!

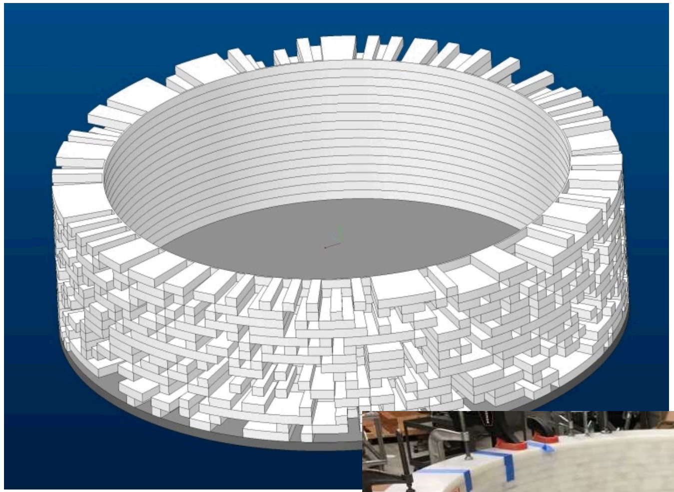


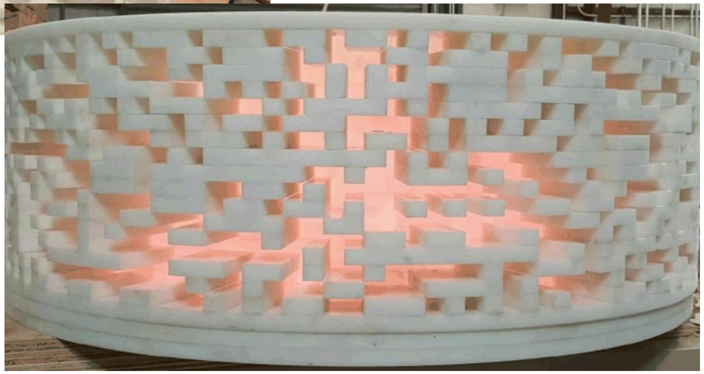
A very simple example



- For example, take a very simple mask: half mask, half aperture.
- The fraction of total count rate coming from A and B is unknown at any given angle.
- In this example, the location (and shape) of the boundary between regions is not revealed.

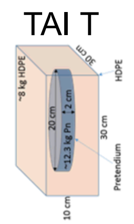
We’re working on it

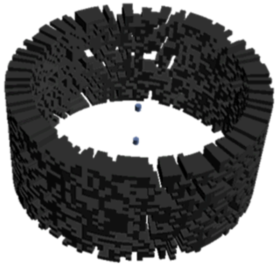


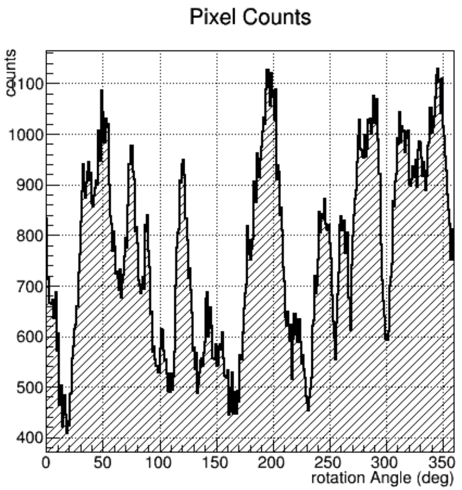


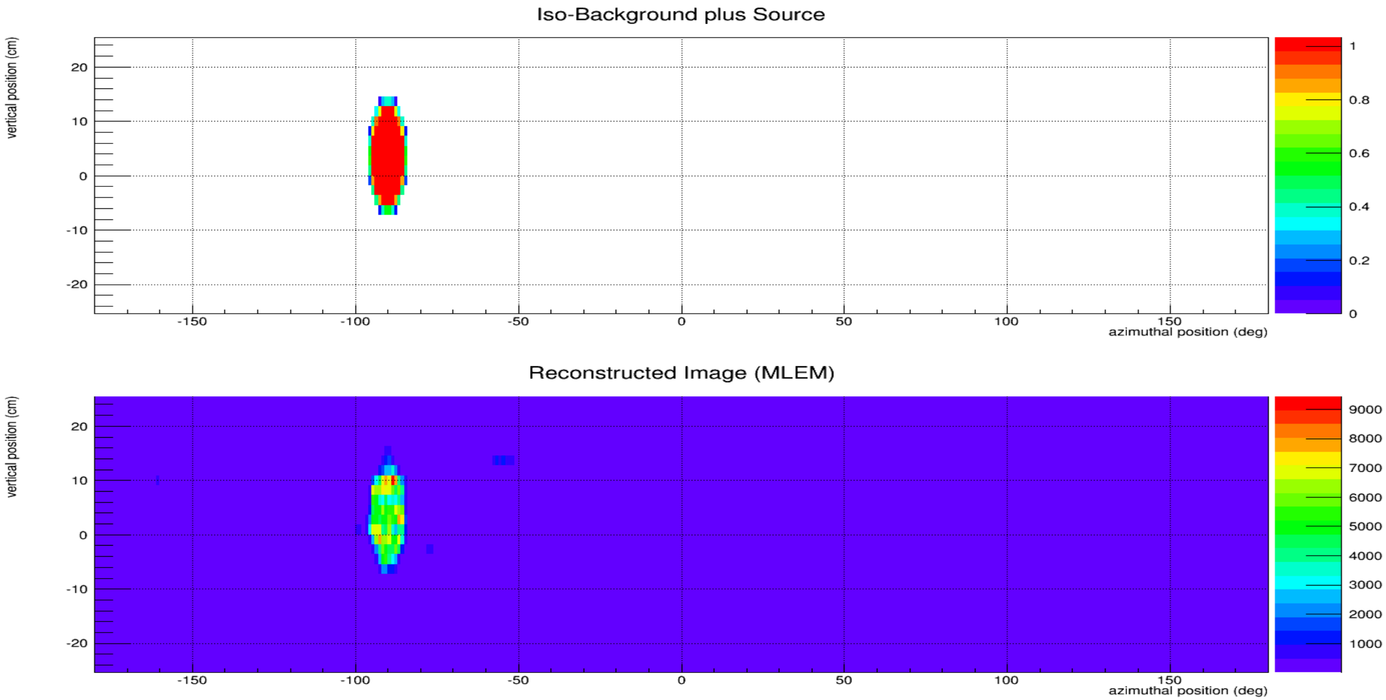
Modeling results - Single type 1 TAI (5e5 counts)

The system still functions as a standard TEI imager for any single object.





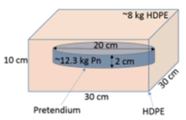


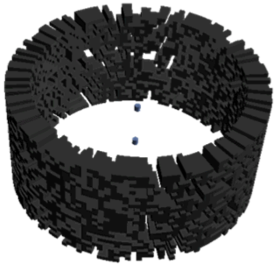


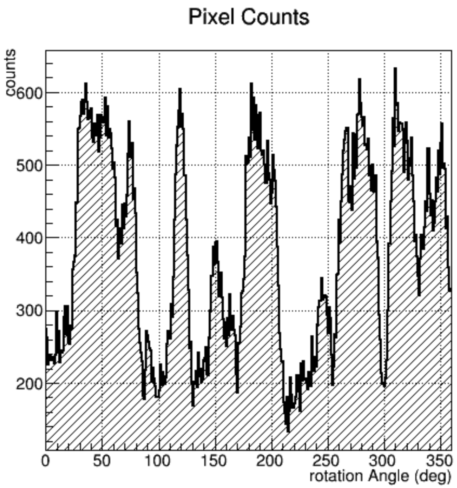
Modeling results - Single type 1 TAI (2.5e5 counts)

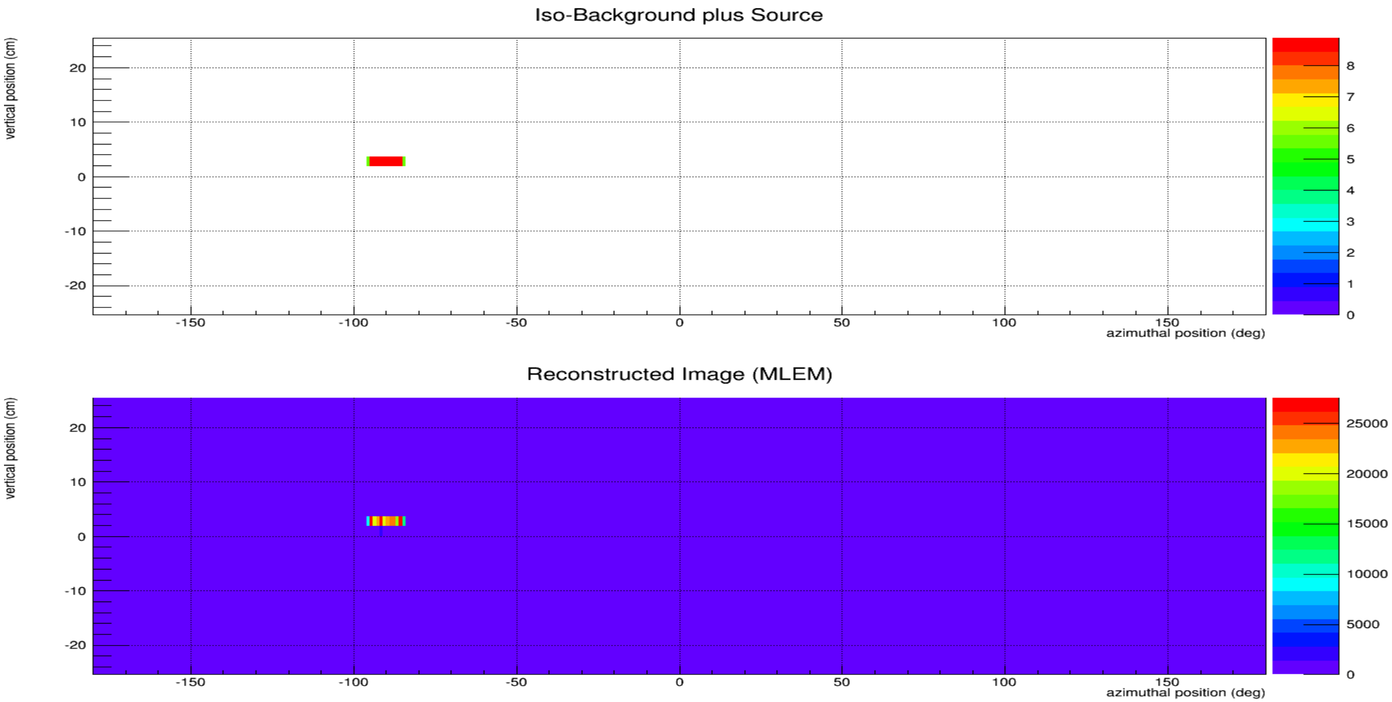
This orientation provides better discrimination between objects T and F.

TAI T



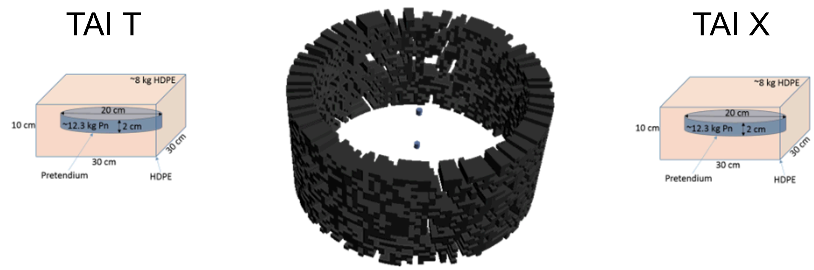


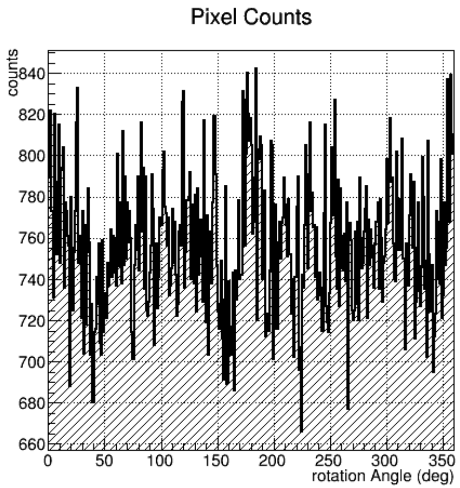


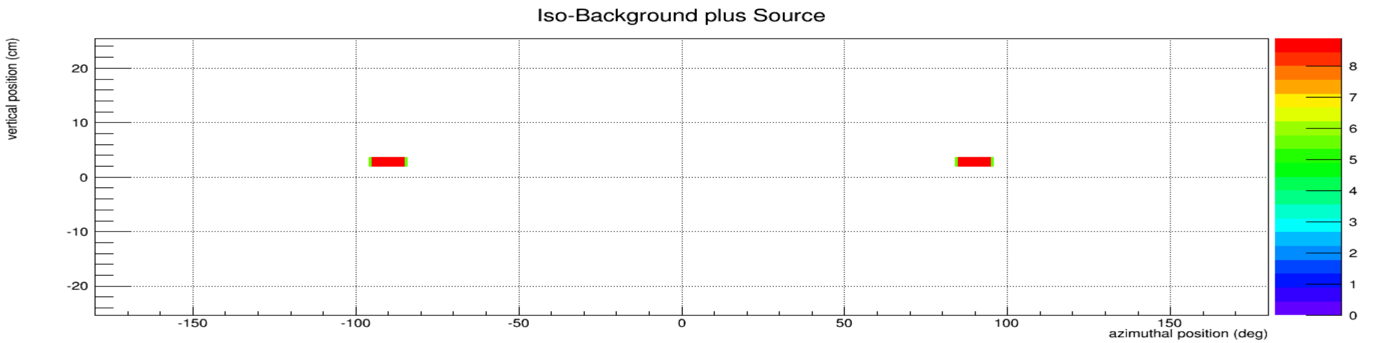


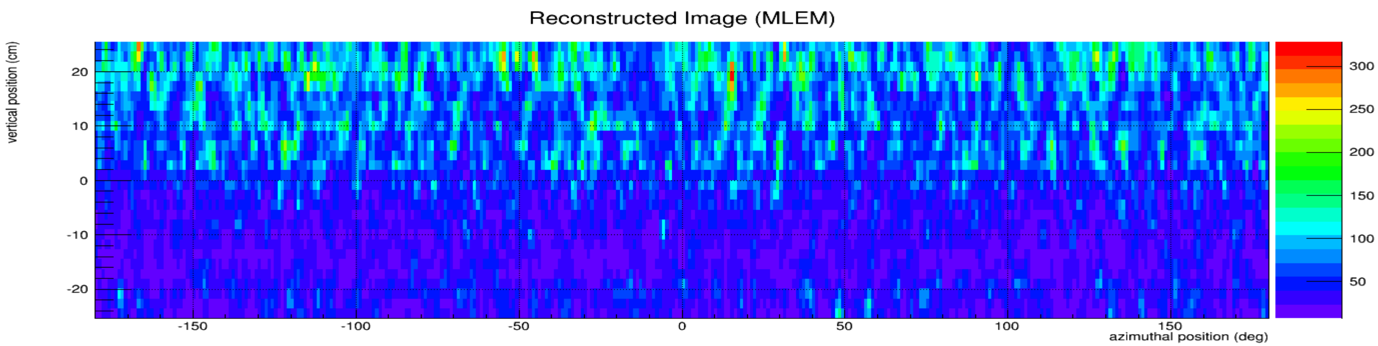
Modeling results – T vs. X (5e5 counts)

True “null”-positive confirmation comparison measurement between two type 1 TAIs.





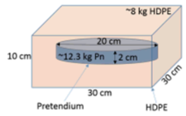


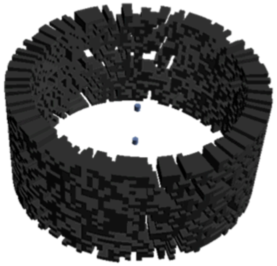


Modeling results – T vs. F (5e5 counts)

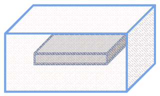
True non-null-negative confirmation comparison measurement between objects T and F.

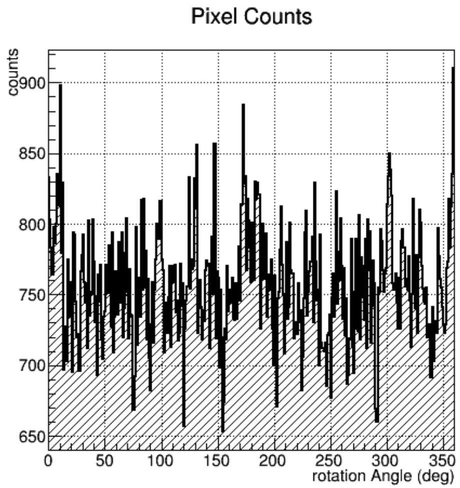
TAI T

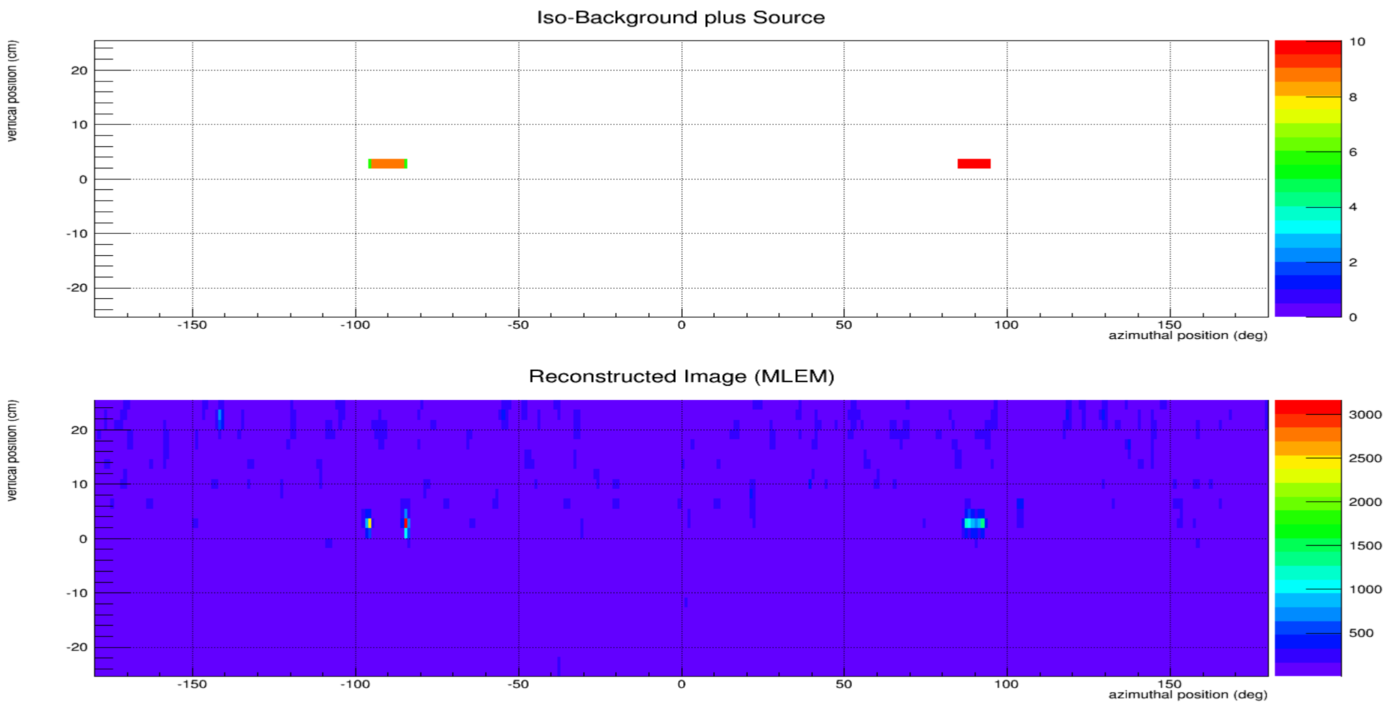




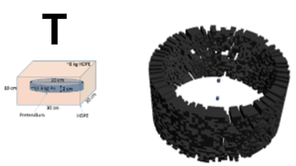
TAI F

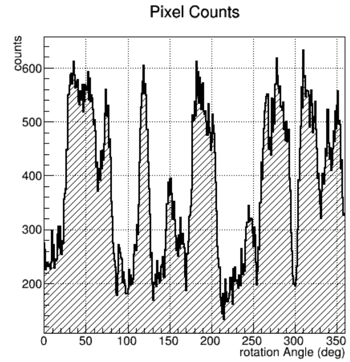


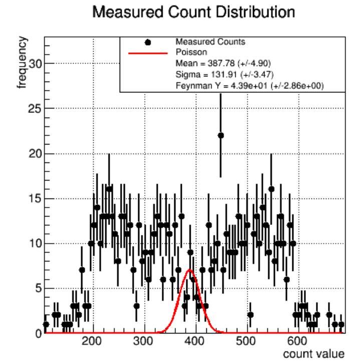




Single Test Statistic – Feynman Y



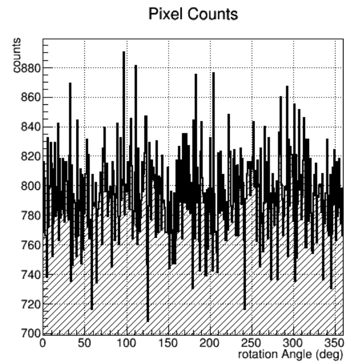


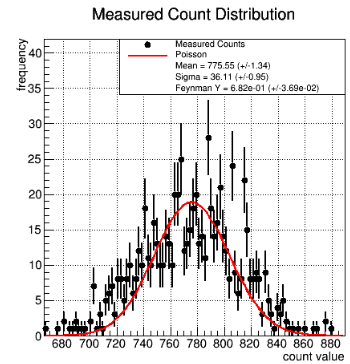


Feynman Y

$$= \left(\frac{variance}{mean} - 1\right)$$

= 86.8 (+/-5.7)→
Far from Poisson

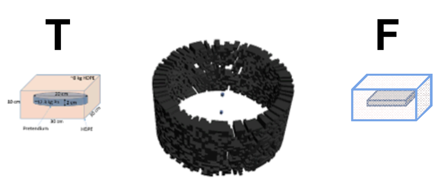


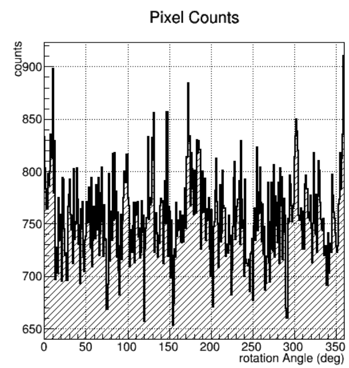


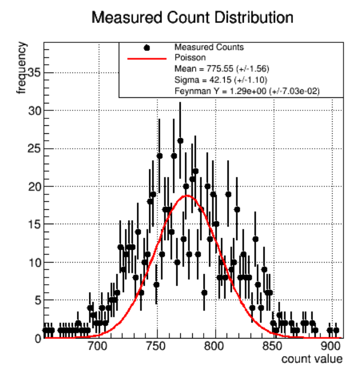
Feynman Y

$$= \left(\frac{variance}{mean} - 1\right)$$

= 0.68 (+/-0.04)→
Fairly Poisson





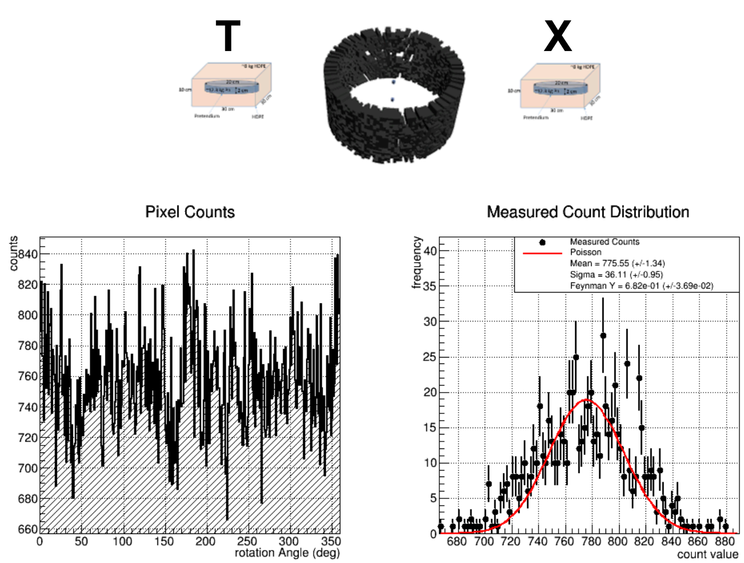


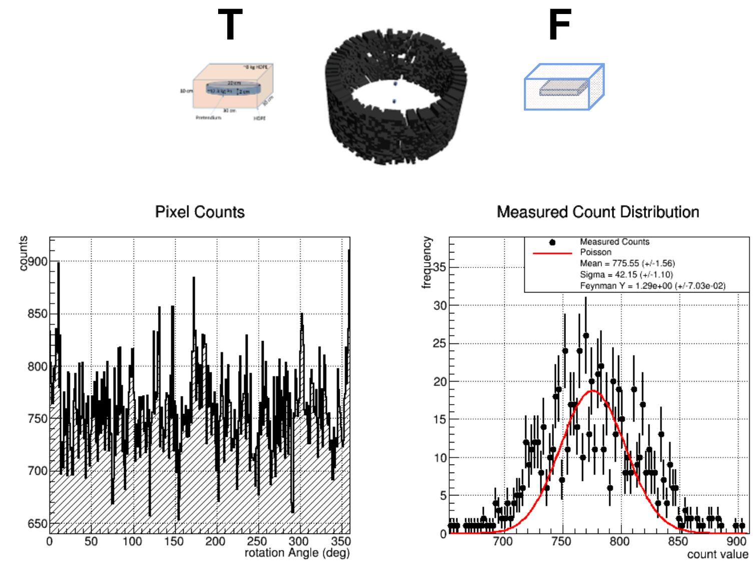
Feynman Y

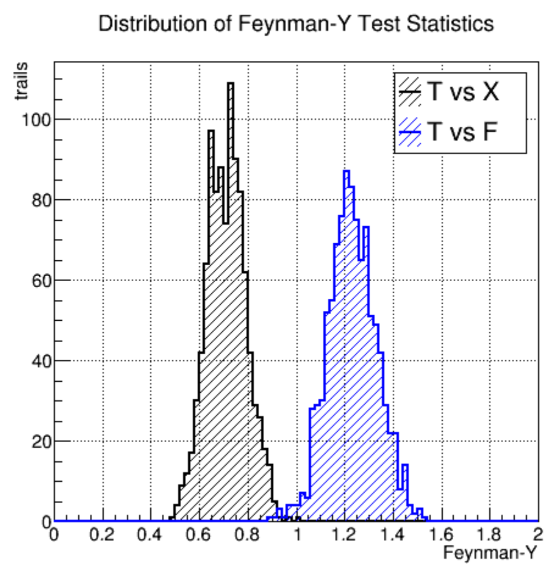
$$= \left(\frac{variance}{mean} - 1\right)$$

= 1.3 (+/-0.07)
→ Less Poisson

Feynman Y Test Statistic – 1000 trials of 5e5 counts







Modeling results – T vs. X (1000 trials of 5e5 counts)

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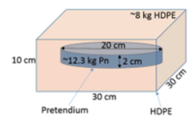
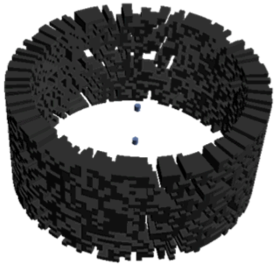
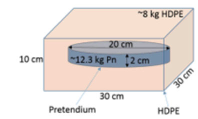
Even after summing 1000 trials worth of data, there isn't much evidence that sensitive information is present. This must be made more rigorous.

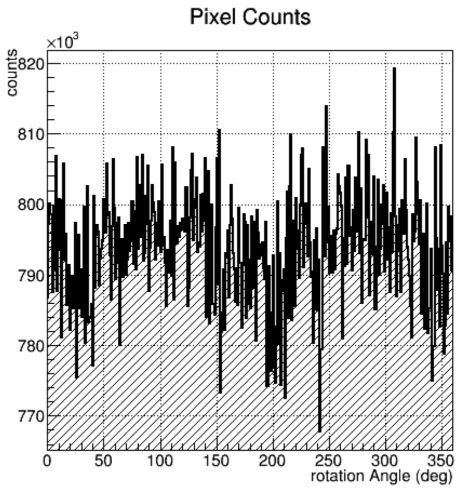
TAI T

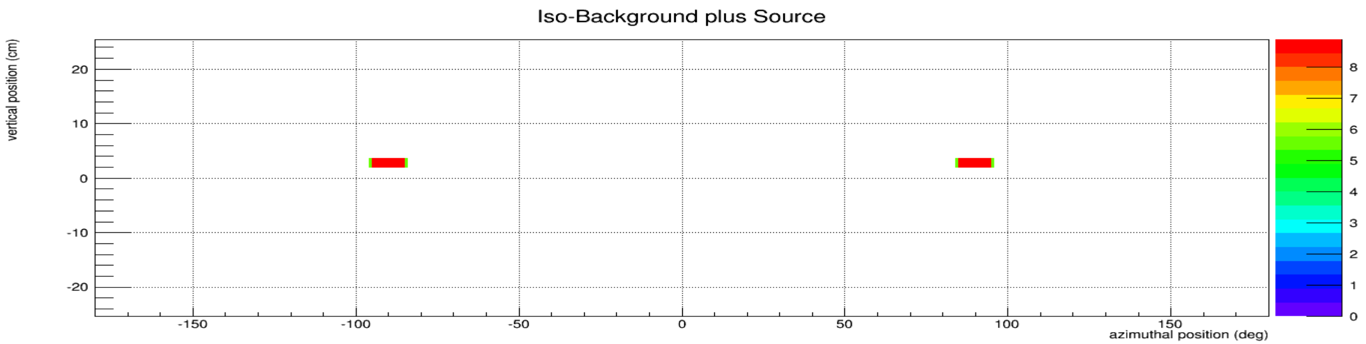


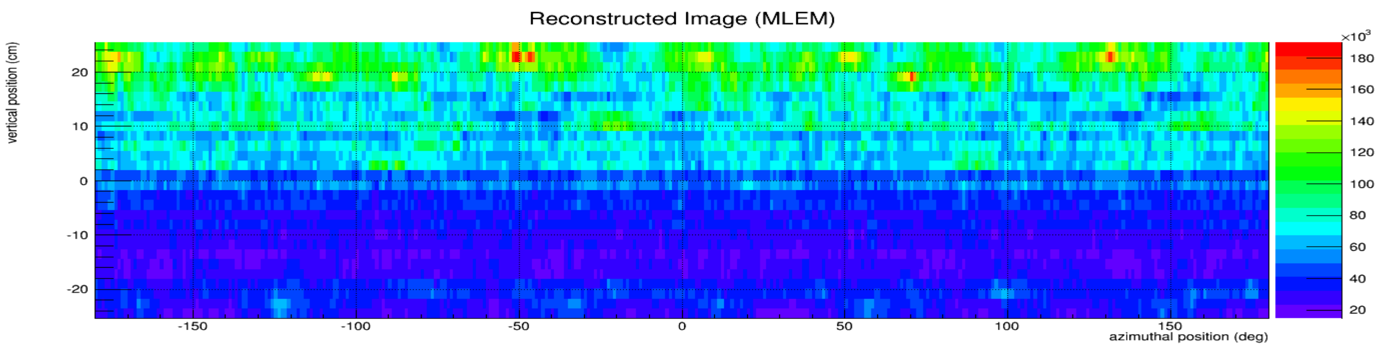


TAI X





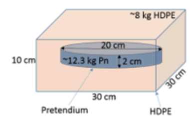


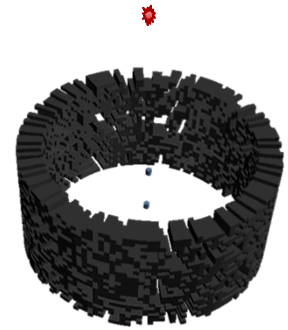


Modeling results – T vs. X plus point source (8e5 counts)

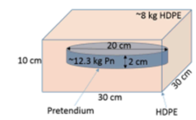
If (and only if) the TAIs are identical, only the third source is visible!

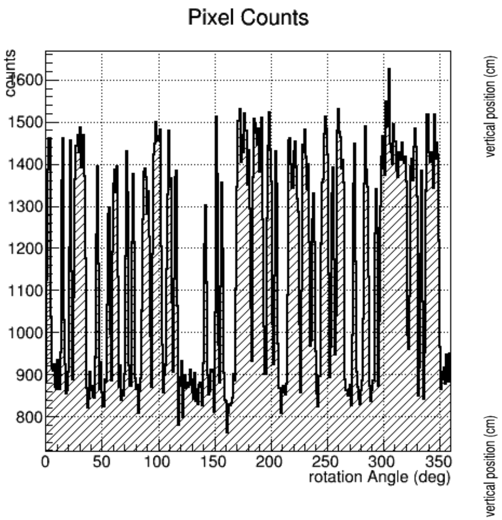
TAI T

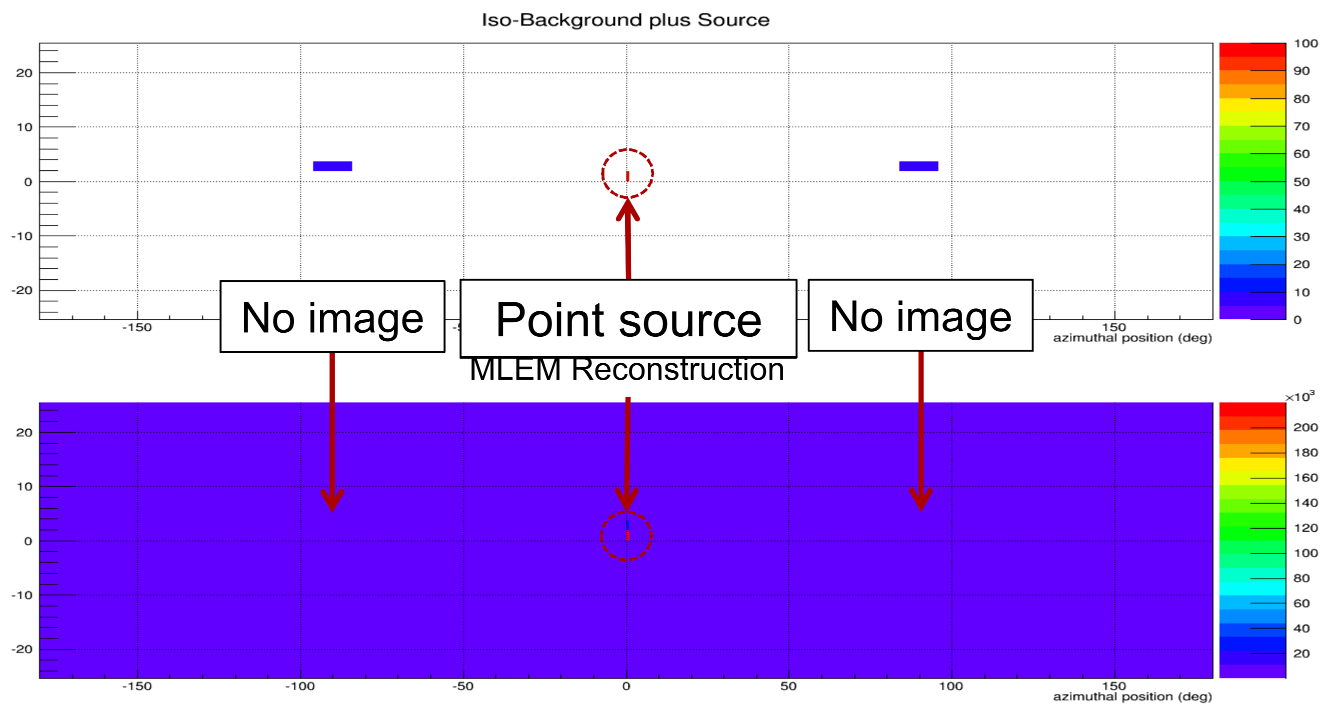




TAI X







Conclusions

A properly designed two-dimensional time-encoded imager can:

1. Confirm that two objects are identical in a single measurement with NULL (constant rate) indicating a positive result.
2. Because a NULL (constant rate) is present at all times, the inspecting party might be allowed full access to the measurement and data.
3. The Feynman-Y test statistic can be updated to further protect against sensitive information loss.
4. Can image any third inspector provided object during the confirmation measurement without revealing the first two objects as an authentication measure.

Extra Slides

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