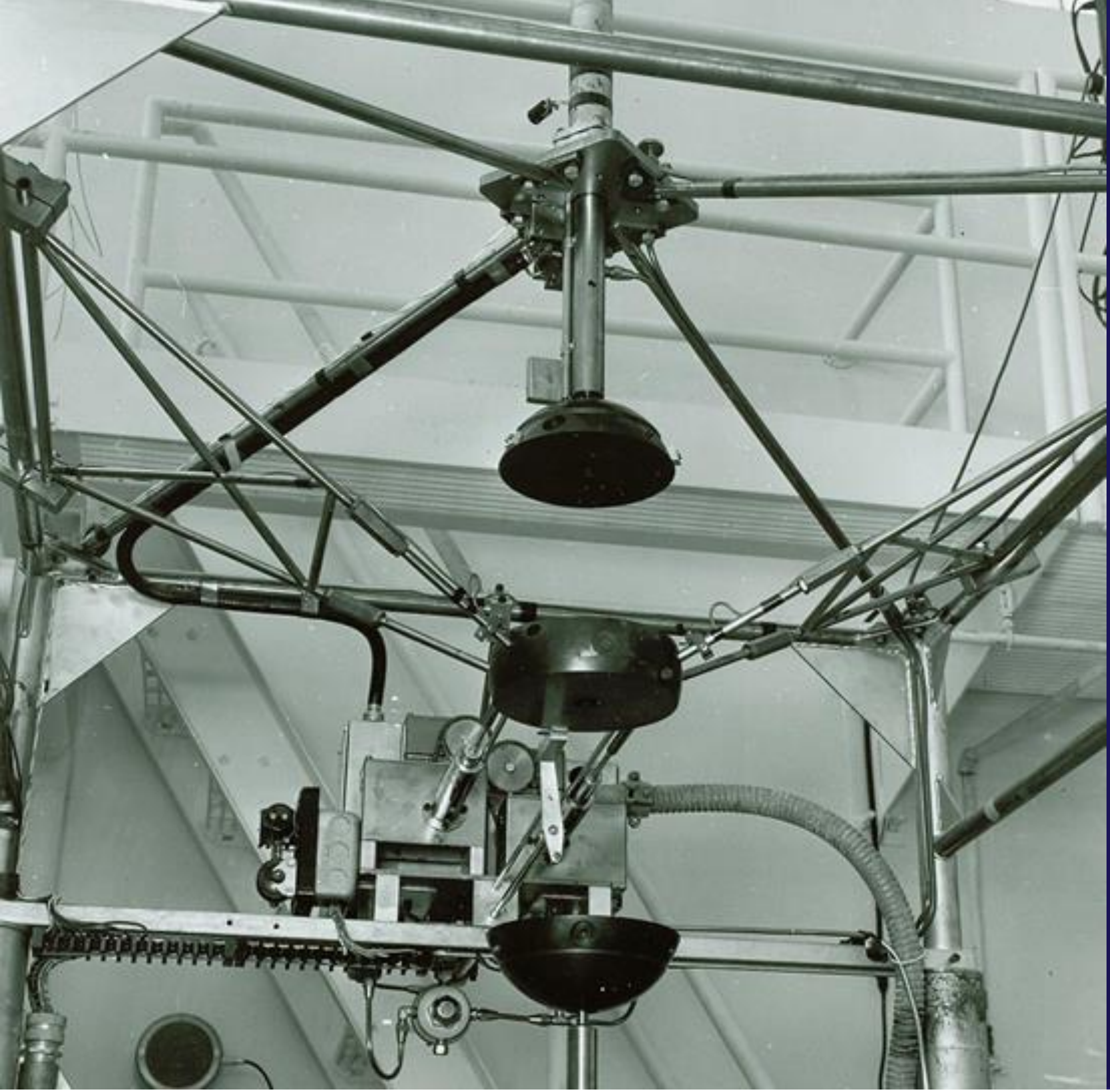

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# Prompt Neutron Decay Constant Measurements on a Polyethylene-Reflected Sphere of HEU

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# Overview

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- Sources measured
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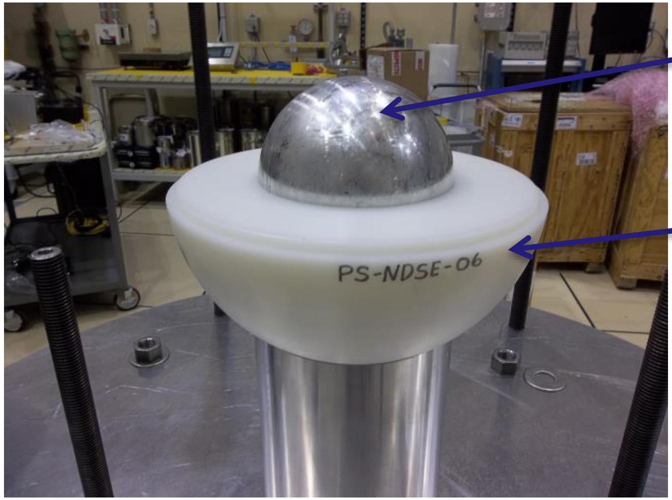
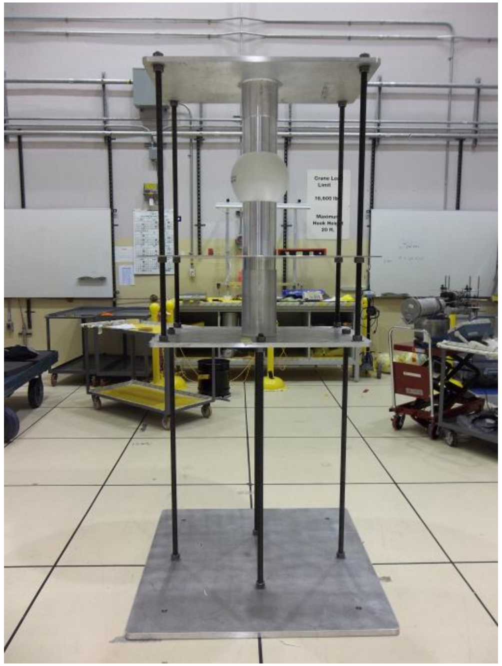
# RTO Information

- **This radiation test object (RTO) consists of Rocky Flats shells 3-30 (21.8 kg HEU) inside Al contamination control shells (~1/8 inch-thick) reflected by 2.5 inch-thick High Density Polyethylene (HDPE).**




RF3-30 inside Al hemishells.

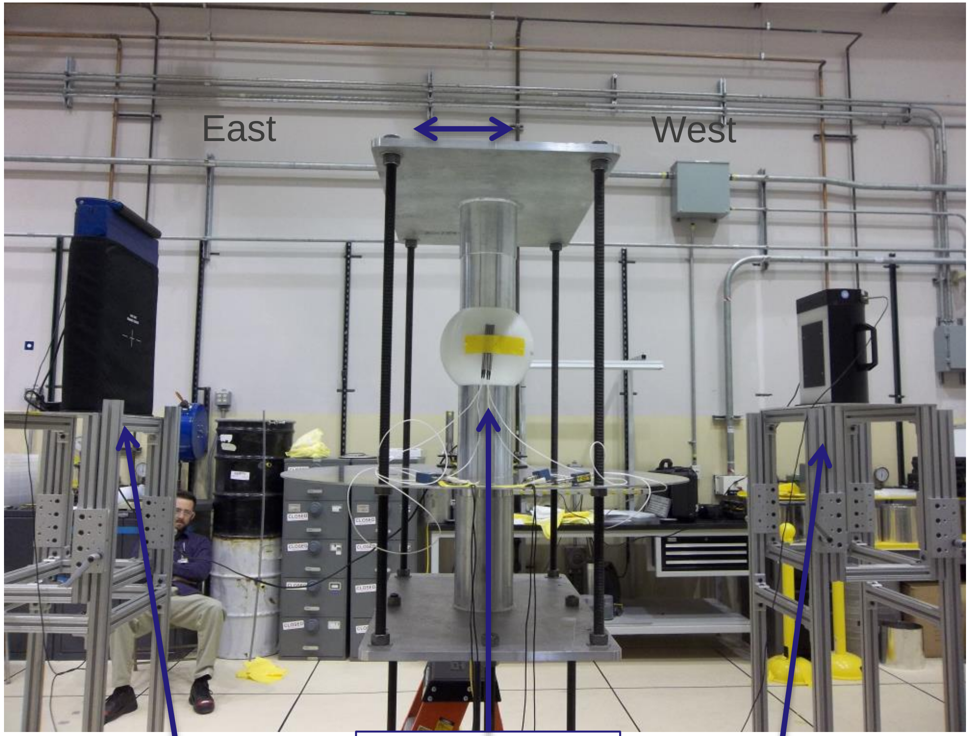
2.5 inch-thick HDPE.



Built on a stand which resulted in the center height being 73.875 inches above the floor.

# Measurement Setup

- **Neutron measurements systems shown setup around the RTO.**




NoMAD

Small He-3 system

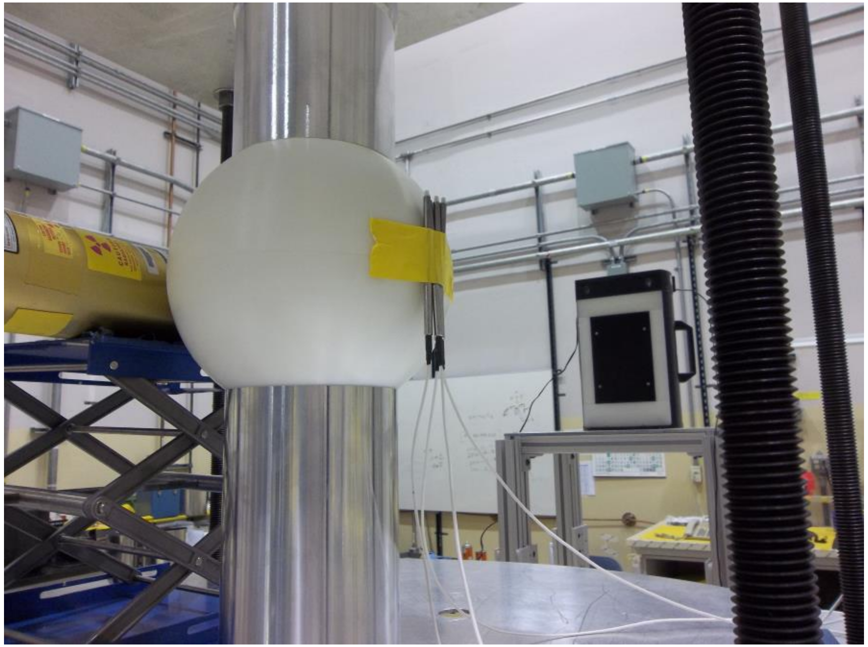
SNAP

Source (Cf-252, AmBe, Pu-240, or DT generator) is centered on the sphere on the opposite side of the small He-3 system (not pictured).

NoMAD and SNAP were 100 cm from the center of the sphere.

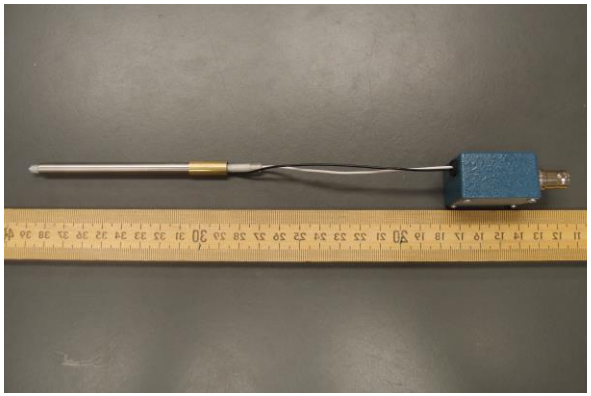
# Sources Measured

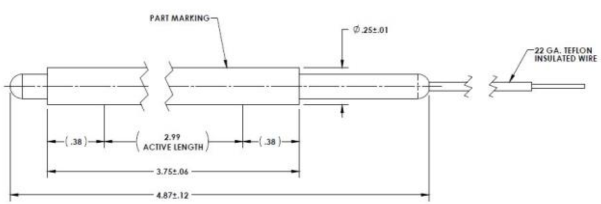
- Cf-252: 9.1e4 n/sec (Source ID: D1-411).
- AmBe: 6.3e4 n/sec (Source ID: RAM 95389).
- Pu-240: 1.0e3 n/sec (Lot ID: LOO435400). 1 g of 100% Pu-240.
- DT generator: gives 1e6 n/pulse at 50 Hz.



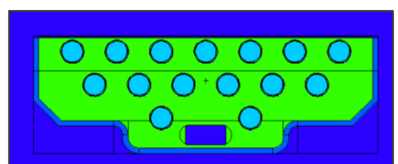
# Detector Information

- **All 3 systems produced list-mode data.  This contains the time and channel of each recorded neutron event.**

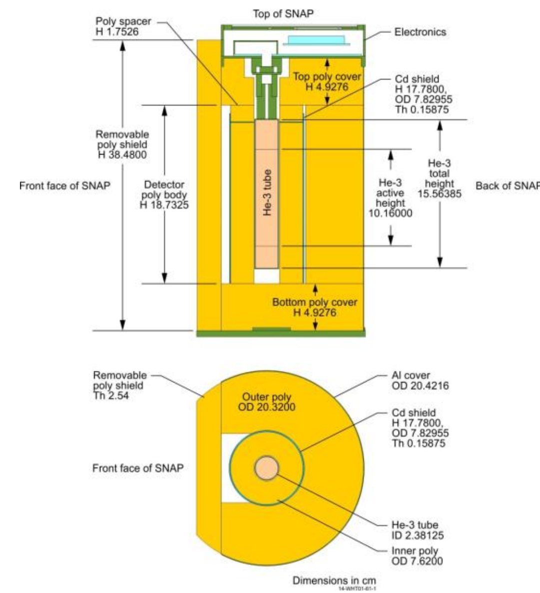





Small He-3 tubes: 4 He-3 tubes (40 atm), ¼” in diameter



Multiplicity Counter (NoMAD): 15 He-3 tubes (10 atm) inside HDPE.




Shielded Neutron Assay Probe (SNAP): 1 He-3 tubes (12 atm) inside HDPE.

# Measurement Techniques Used

- **Rossi-α Technique**
  - Measures prompt neutron decay constant using statistical correlations in a static neutron population.
  - Diagnostic capability that infers nuclear reactivity and prompt neutron lifetime.
  - Listmode data is manipulated into a decay histogram which is fit to determine the value of α.
  - Fit using: $\boldsymbol{p(t) = Ae^{\alpha t} + B}$.

- **Pulsed Source Technique**
  - Same analysis results as the Rossi-α technique.
  - Uses same equation to fit as Rossi-α.
  - Uses a “pulsed” or dynamic neutron source to measure prompt neutron population die-away

- **Feynman Variance-to-Mean**
  - Histograms of the number of neutrons detected in a time interval t are created. The excess variance (deviation from a Poisson distribution, Y), determined from the first ($\bar{c}$, mean) and second ($\overline{c^2}$, variance) moments is
  $$Y = \frac{\overline{c^2} - \bar{c}^2}{\bar{c}} - 1$$
  - This applies to the system being measured using the equation
  $$Y = \frac{\varepsilon\left(\overline{\nu^2} - \bar{\nu}\right)}{\bar{\nu}\left(1 - k_p\right)^2}\left[1 - \frac{\left(1 - e^{-\alpha t}\right)}{\alpha t}\right]$$
  where ε is the detector efficiency (counts per fission), $k_p$ is the prompt multiplication factor, $\bar{\nu}$ is the average number of neutrons produced per induced fission, and $\overline{\nu^2}$ is the second moment (variance) of the distribution of the number of neutrons produced per induced fission.

# Results: MC-15, SNAP and small He-3 tubes

- **Count rates:**

SNAP

| Source | Poly off | | | Poly on | | | Off/On |
|---|---|---|---|---|---|---|---|
| Cf-252 | 5.01 | ± | 0.06 | 3.67 | ± | 0.04 | 1.37 |
| AmBe | 2.89 | ± | 0.04 | 2.22 | ± | 0.02 | 1.30 |
| Pu-240 | 0.099 | ± | 0.007 | 0.067 | ± | 0.003 | 1.47 |

NoMAD

| Source | 1st row | | | 2nd row | | | 3rd row | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cf-252_1 | 190.1 | ± | 0.5 | 214.2 | ± | 0.3 | 46.5 | ± | 0.1 | 450.8 | ± | 0.7 |
| Cf-252_2 | 182.8 | ± | 0.3 | 198.6 | ± | 0.6 | 43.1 | ± | 0.2 | 424.5 | ± | 0.6 |
| AmBe_1 | 112.1 | ± | 0.3 | 123.7 | ± | 0.3 | 27.7 | ± | 0.1 | 263.5 | ± | 0.5 |
| AmBe_2 | 111.8 | ± | 0.3 | 122.4 | ± | 0.2 | 27.4 | ± | 0.2 | 261.7 | ± | 0.3 |
| Pu-240_1 | 4.5 | ± | 0.1 | 5.5 | ± | 0.1 | 1.7 | ± | 0.0 | 11.6 | ± | 0.1 |
| Pu-240_2 | 4.4 | ± | 0.0 | 5.3 | ± | 0.0 | 1.6 | ± | 0.0 | 11.4 | ± | 0.1 |

Two different measurements for each source (were taken on different days and have slightly different results.

¼” He-3

| Source | Count Rate | | |
|---|---|---|---|
| Cf-252 | 34.94 | ± | 0.20 |
| AmBe | 27.38 | ± | 0.09 |
| Pu-240 | 0.73 | ± | 0.007 |

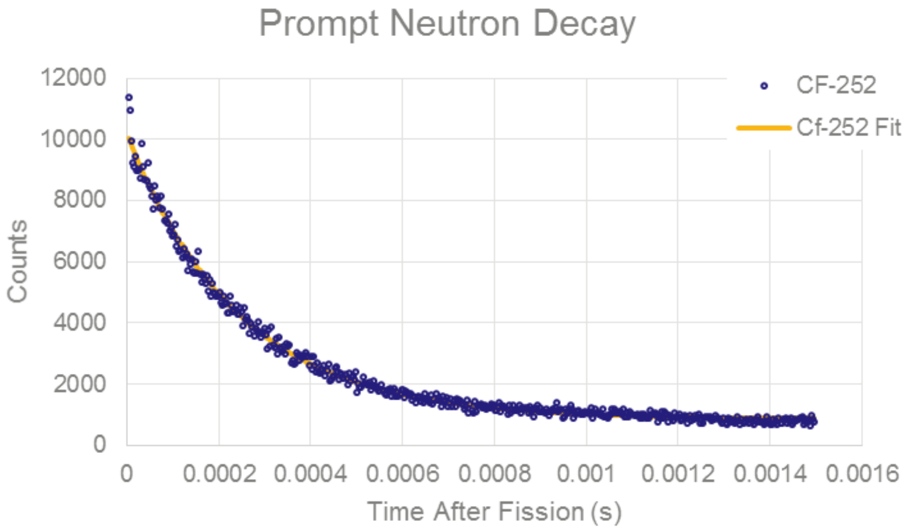
Count rate ratios

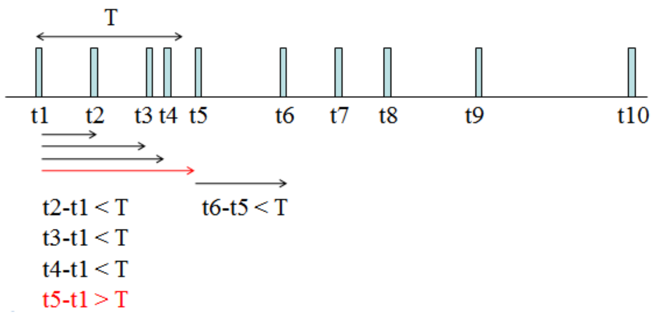
| Detector | | Cf/AmBe | Cf/Pu | AmBe/Pu |
|---|---|---|---|---|
| Source certificates | | 1.4 | 91 | 63 |
| SNAP | Poly off | 1.7 | 50 | 29 |
| | Poly on | 1.7 | 54 | 33 |
| MC-15 | 1st row | 1.7 | 42 | 25 |
| | 2nd row | 1.7 | 38 | 23 |
| | 3rd row | 1.6 | 27 | 17 |
| | Total | 1.7 | 38 | 23 |
| ¼” He-3 | Total | 1.3 | 48 | 38 |

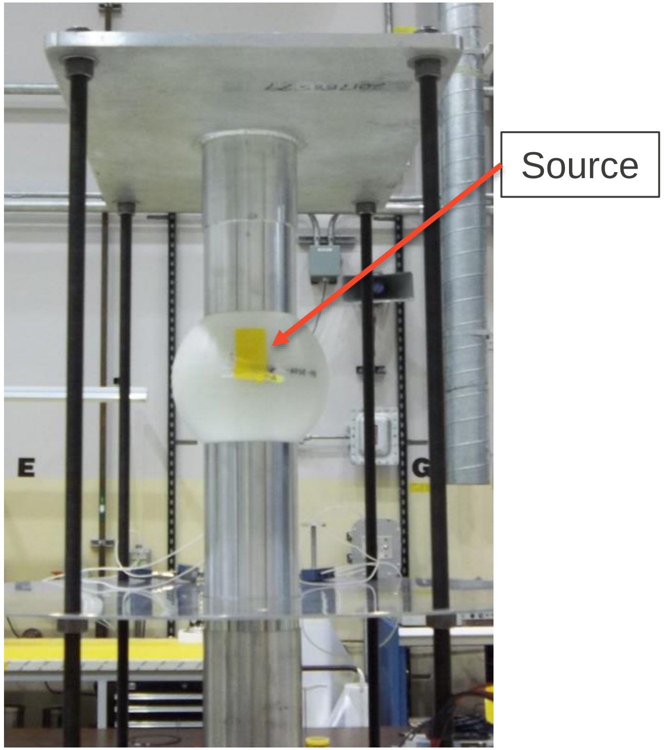
Seems to indicate that the reported Pu-240 neutron emission rate may be incorrect.

# Results: small He-3 tubes

## Rossi-α Measurements

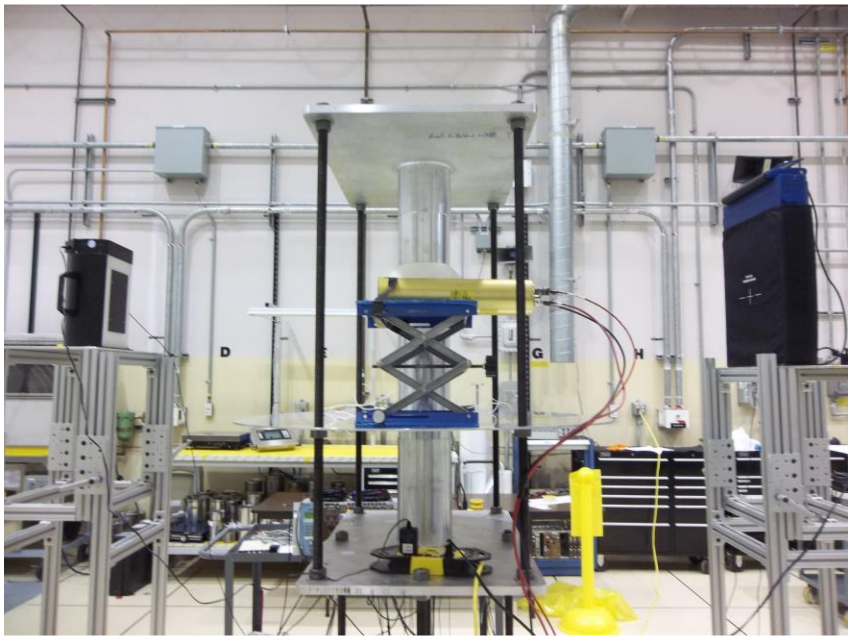


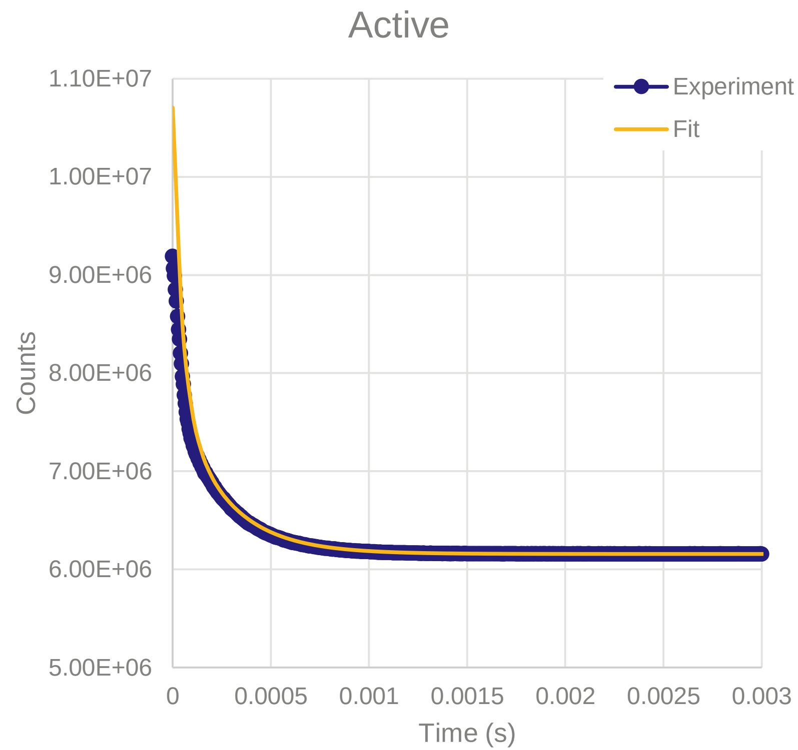



# Results: small He-3 tubes

## Pulsed Source Measurements

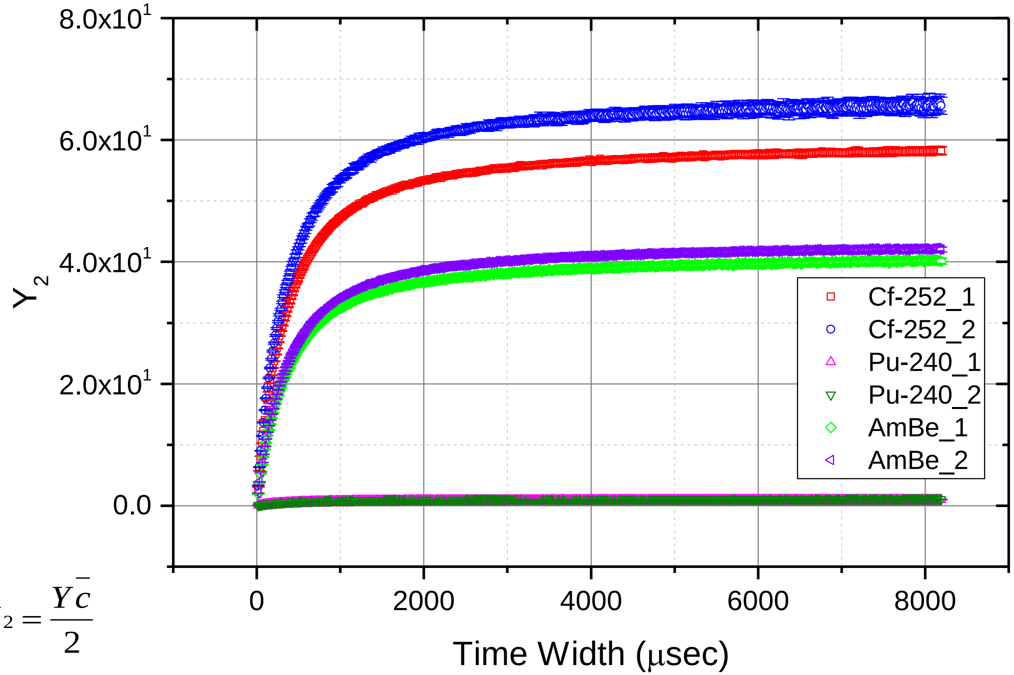




# Results: NoMAD

- **The excess variance (how much the data deviates from Poisson), $Y_2$, can be fit as a function of time width (τ).**
- **This can be fit to the equation** $\omega_2(\lambda,\tau) = 1 - \frac{1-e^{-\lambda\tau}}{\lambda\tau}$ **to determine λ, which is a combination of the system lifetime and the slowing down of neutrons in the HPDE of the MC-15 (known to be 35-40 micro-sec).**

| Source | Tau 1 (μs) | %Lambda 1 | Tau 2 (μs) | %Lambda 2 |
|---|---|---|---|---|
| Cf-252_1 | 44.2 ± 0.4 | 14 | 238.9 ± 0.4 | 86 |
| Cf-252_2 | 47.0 ± 0.7 | 14 | 235.9 ± 0.8 | 86 |
| Pu-240_1 | 63.0 ± 4.1 | 21 | 265.0 ± 5.3 | 79 |
| Pu-240_2 | 52.8 ± 2.2 | 14 | 240.1 ± 2.0 | 86 |
| AmBe_1 | 52.6 ± 0.8 | 14 | 241.7 ± 0.7 | 86 |
| AmBe_2 | 45.8 ± 0.5 | 12 | 237.8 ± 0.4 | 88 |




$$Y_2 = \frac{\overline{Yc}}{2}$$

Two time constants were fit. It can be seen that the first time constant is similar to the expected slowing-down time in the detector system (35-50 μs).

The Pu-240_1 measurement has a very bad fit and the results should be ignored.

# Results: NoMAD

- **After determining the detector count rate, $Y_2$, and $\lambda$, one can solve for the system leakage multiplication.**
- **We have two equations (singles count rate and doubles count rate) with four unknowns (leakage multiplication, spontaneous fission rate, (α,n) neutron emission rate, and detector efficiency). Therefore some parameters must be assumed.**
- **Approach 1: plug in spontaneous fission rate ($F_S$) and assume (α,n) = 0, solve for leakage multiplication ($M_L$) and detector efficiency (ε).**

Leakage multiplication

Total multiplication

Prompt multiplication factor

Multiplication factor

| Config | Ml | dMl | MT | dMT | kp | dkp | keff | dkeff |
|---|---|---|---|---|---|---|---|---|
| Cf-252_1 | 16 | 2 | 31 | 3 | 0.967 | 0.003 | 0.974 | 0.003 |
| Cf-252_2 | 21 | 2 | 39 | 4 | 0.974 | 0.003 | 0.981 | 0.003 |
| Pu-240_1 | 17 | 2 | 32 | 3 | 0.968 | 0.003 | 0.975 | 0.003 |
| Pu-240_2 | 19 | 2 | 36 | 4 | 0.972 | 0.003 | 0.978 | 0.003 |

Leakage multiplication is directly inferred. Additional assumptions as you move to the right.

The detector efficiency values that you get for the results above seem unrealistically low. Additional measurements in the future will investigate this.

# Results: NoMAD

- After determining the detector count rate, $Y_2$, and $\lambda$, one can solve for the system leakage multiplication.
- We have two equations (singles count rate and doubles count rate) with four unknowns (leakage multiplication, spontaneous fission rate, (α,n) neutron emission rate, and detector efficiency). Therefore some parameters must be assumed.
- Approach 2: plug in detector efficiency (ε) and assume (α,n) = 0, solve for leakage multiplication ($M_L$) and spontaneous fission rate ($F_S$).

Leakage multiplication

Total multiplication

Prompt multiplication factor

Multiplication factor

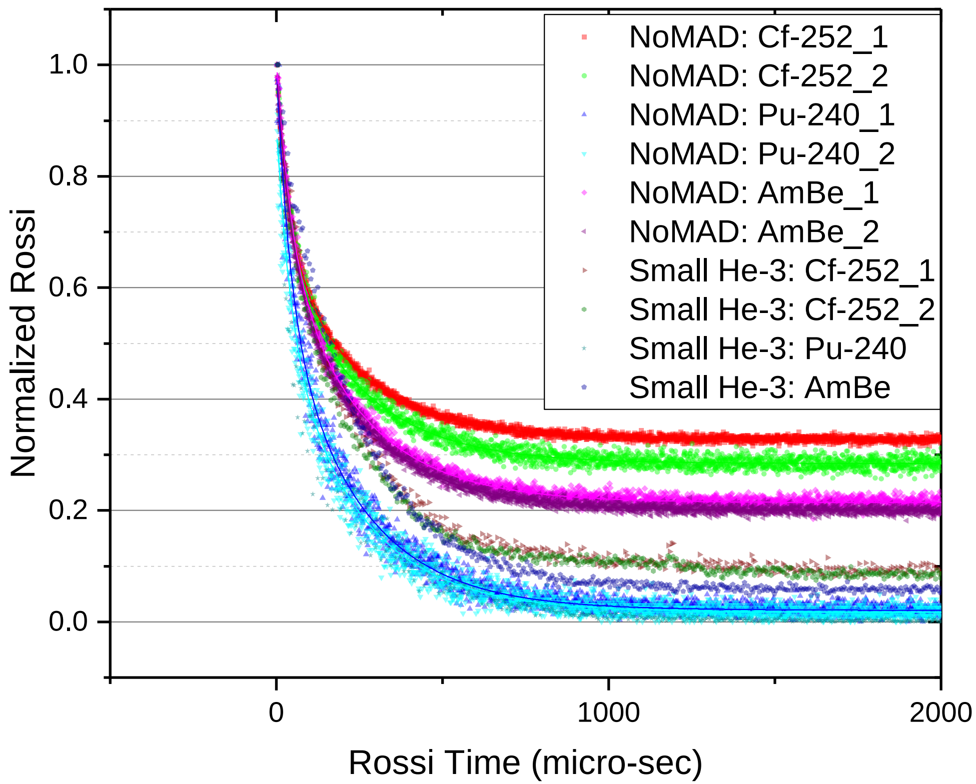
| Config | Ml | dMl | MT | dMT | kp | dkp | keff | dkeff |
|---|---|---|---|---|---|---|---|---|
| Cf-252_1 | 5.9 | 2.9 | 10.5 | 5.7 | 0.90 | 0.05 | 0.91 | 0.05 |
| Cf-252_2 | 6.4 | 3.2 | 11.5 | 6.2 | 0.91 | 0.05 | 0.92 | 0.05 |
| Pu-240_1 | 4.7 | 2.4 | 8.2 | 4.6 | 0.88 | 0.07 | 0.88 | 0.07 |
| Pu-240_2 | 5.0 | 2.5 | 8.7 | 4.8 | 0.88 | 0.06 | 0.89 | 0.06 |

Leakage multiplication is directly inferred. Additional assumptions as you move to the right.

Huge uncertainties because the detector efficiency is not quantified well at the moment.

# Overall/Combined Results

- **The figure to the right shows a normalized version of the results using the Rossi-α method for each source and detection system.**
- **The figure shows that the prompt decay (the high point on the left of the chart) is very similar for all sources and each detection system.**
- **The fit results are compared on the next slide.**



# Overall/Combined Results

## Experimental Values of τ (micro-sec) (τ=1/α)

<table>
<tr><th colspan="2">System</th><th colspan="3">Small He-3 tubes</th><th colspan="6">NoMAD</th></tr>
<tr><th colspan="2">Method</th><th colspan="3">Rossi-α</th><th colspan="3">Rossi-α</th><th colspan="3">Feynman</th></tr>
<tr><td rowspan="7">Neutron Source</td><td>Cf-252_1</td><td>232.0</td><td>±</td><td>1.5</td><td>228.4</td><td>±</td><td>1.3</td><td>238.9</td><td>±</td><td>0.4</td></tr>
<tr><td>Cf-252_2</td><td>212.0</td><td>±</td><td>8.2</td><td>232.2</td><td>±</td><td>2.6</td><td>235.9</td><td>±</td><td>0.8</td></tr>
<tr><td>AmBe_1</td><td rowspan="2">227.0</td><td rowspan="2">±</td><td rowspan="2">5.5</td><td>232.2</td><td>±</td><td>1.9</td><td>241.7</td><td>±</td><td>0.7</td></tr>
<tr><td>AmBe_2</td><td>235.4</td><td>±</td><td>1.5</td><td>237.8</td><td>±</td><td>0.4</td></tr>
<tr><td>Pu-240_1</td><td rowspan="2">196.0*</td><td>±</td><td rowspan="2">17.9</td><td>231.1</td><td>±</td><td>3.1</td><td>265.0</td><td>±</td><td>5.3</td></tr>
<tr><td>Pu-240_2</td><td>±</td><td>230.3</td><td>±</td><td>3.9</td><td>240.1</td><td>±</td><td>2.0</td></tr>
<tr><td>DT</td><td>248.0</td><td>±</td><td>14.2</td><td colspan="3">-</td><td colspan="3">-</td></tr>
</table>

* Poor statistics on measurement, fits had infinite chi-square values.

# Conclusions

- **Measurements with 4 different neutron sources were performed on this RTO.**
  - All had very similar results.
- **Count rate results indicate that perhaps the reported Pu-240 strength is incorrect.**
- **$\tau$ was determined to be 229.0 +/- 6.7 (s) for the RTO using the Rossi-$\alpha$ method.**
- **$\tau$ was determined to be 243.2 +/- 8.6 (s) for the RTO using the Variance-to-Mean Method.**
- **T was determined to be 248.0 +/- 14.2 (s) for the RTO using the pulsed source method.**
- **NoMAD multiplication results still need work but are in the ballpark with the simulations (0.9534 +/- 0.0003 from T. Goorley on 1/27/17).**

# Future work

- **Finish NoMAD analysis: DT.**
- **Perform additional measurements (sources without HEU present) and analyze these measurements.**
- **Perform additional measurements with source centrally located (only Cf-252 is small enough out of those presented here) to determine the difference source geometry makes for this system.**

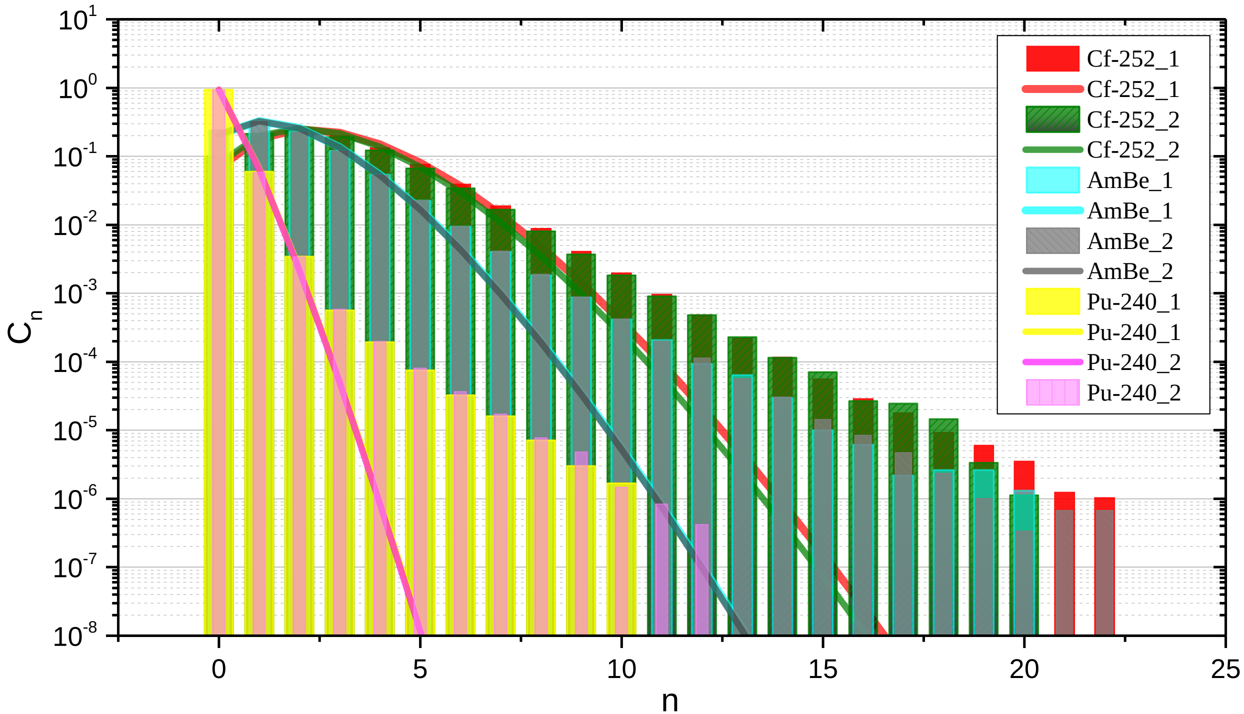
# Acknowledgments


- **This work was supported in part by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.**
- **This work was also supported by the Los Alamos LDRD process and has collaborations across the laboratory.**

# Extra Slides

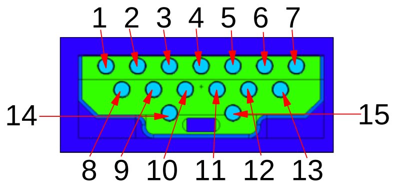
# Results: NoMAD

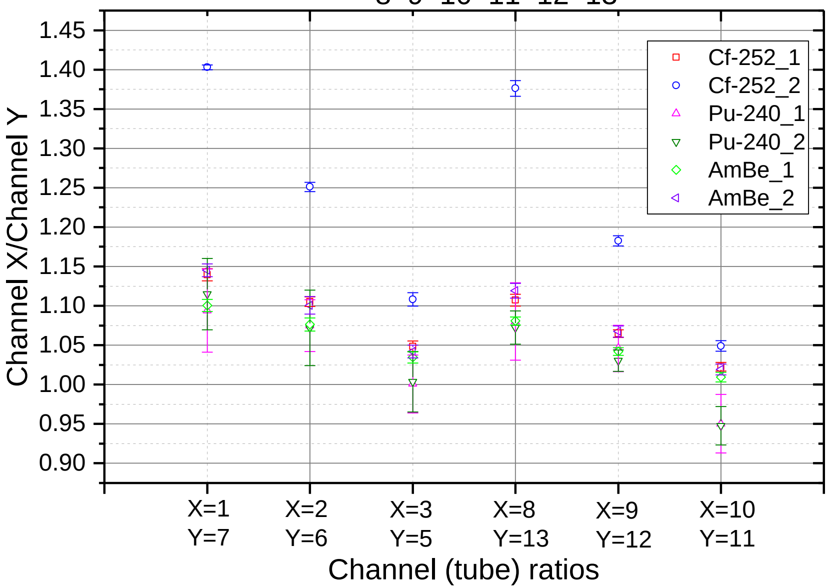
- **Feynman histograms are created by going through the data and recording how many neutrons were detected in each time gate (1024 micro-sec for this graph).**
- **As the multiplication of a system increases, the histogram deviates more from a Poisson distribution (shown by the curves).**
- **It was observed that these histograms all deviated from a Poisson distribution (as expected).**



# Results: NoMAD

- **The setup (with the source on the outside of the polyethylene) was not ideal.**
- **Having the NoMAD at 90º also resulted in some neutrons being absorbed from the source directly. This can negatively influence the results.**
- **To attempt to estimate this, a ratio of count rates in different channels is plotted.**




It can be seen that the count rate on the side closer to the source is 5-15% higher than on the opposite side (these would be equal for an external source). The 2nd Cf-252 measurement was by far the worst.