MUSIC Organic Scintillators Benchmark

Flynn Darby, R&D Engineer, NEN-2
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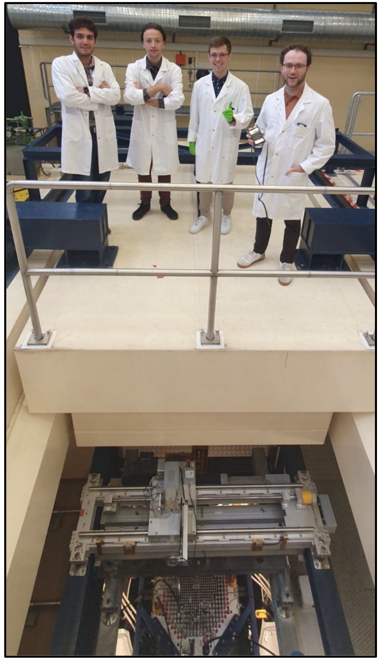
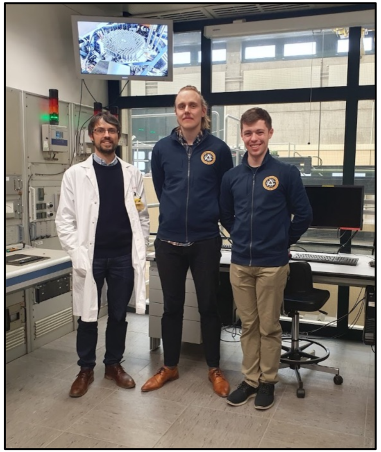
LA-UR-26-25160

Michigan → LANL

- Defended in December 2025
  - Primary Advisor: Prof. Sara Pozzi
- Converted to Staff with NEN-2 and Started at LANL in May 2026





NCERC, NEN-2: Critical Exp.

International Criticality Safety Benchmark Evaluation Project (ICSBEP)
(Critical and Subcritical Measurements)

NEA
NUCLEAR ENERGY AGENCY

- ICSBEP
  - OECD Nuclear Energy Agency (NEA)
- Reactor Pilot Program
- Criticality Safety Training
- Simple and complex, static, fissionable assemblies

NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

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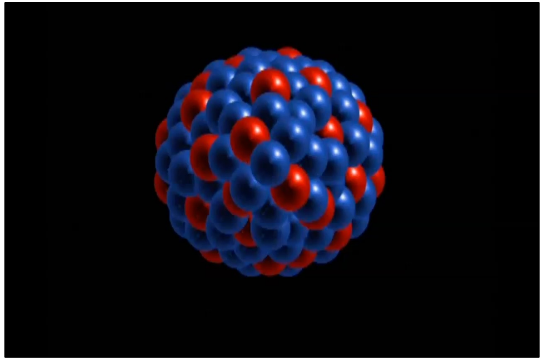
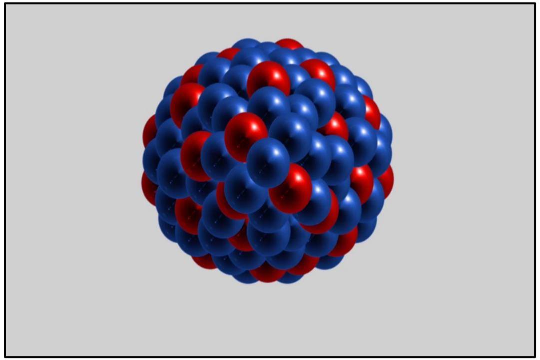
Fission and Fission Chains

- ***Induced Fission***
- Neutron absorbed by ^{235}U nucleus
- Resulting excitation causes ^{235}U to split
- Several fragment possibilities and multiplicities
  - Hundreds of possible radioactive fragment combinations
  - 7-10 gamma-rays and 2-3 neutrons released from each fission on average
- Fission can cause subsequent fission with neutrons resulting in a "chain" of fission events
- Prompt neutrons [femto- (10^{-15}) to pico- (10^{-12}) second time scale]
- Delayed neutrons (millisecond to second time scale)
  - Note: delayed neutrons are not shown in the animations



Single Fission, MTV



Fission chain, MTV

MUSIC – ICSBEP

- **M**easurements of **U**-235 **S**ubcr**i**tical and **C**ritical
- Simulations with MCNP6
- Critical benchmark published with ICSBEP
- Subcritical measurement data evaluation for benchmark in progress, ^{3}He approved, organics next
- Supports nonproliferation with ^{235}U fission and stockpile verification signatures

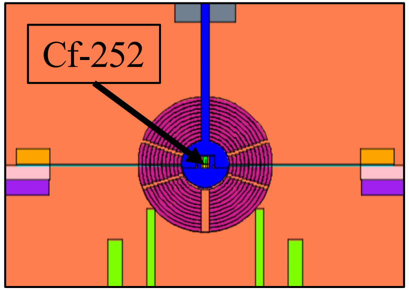
Mass (kg)	k_{eff} KCODE
13.25	0.59
21.95	0.71
29.41	0.78
38.47	0.86
43.50	0.90
49.00	0.93
54.92	0.96
59.85	0.95

Case	Benchmark	MCNP6.2 ENDF8.0	C-E (pcm)
1	1.00072 ± 0.00105	1.00033 ± 0.00001	-39
2	1.00091 ± 0.00105	1.00021 ± 0.00001	-70

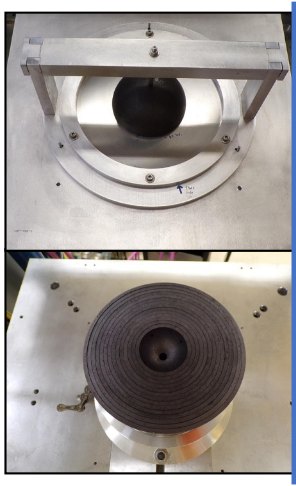
[1] McSpaden, *NSE* ‘24
[2] Weldon, *NCSP*, ‘22.

MUSiC Kinetics Measurement - Setup

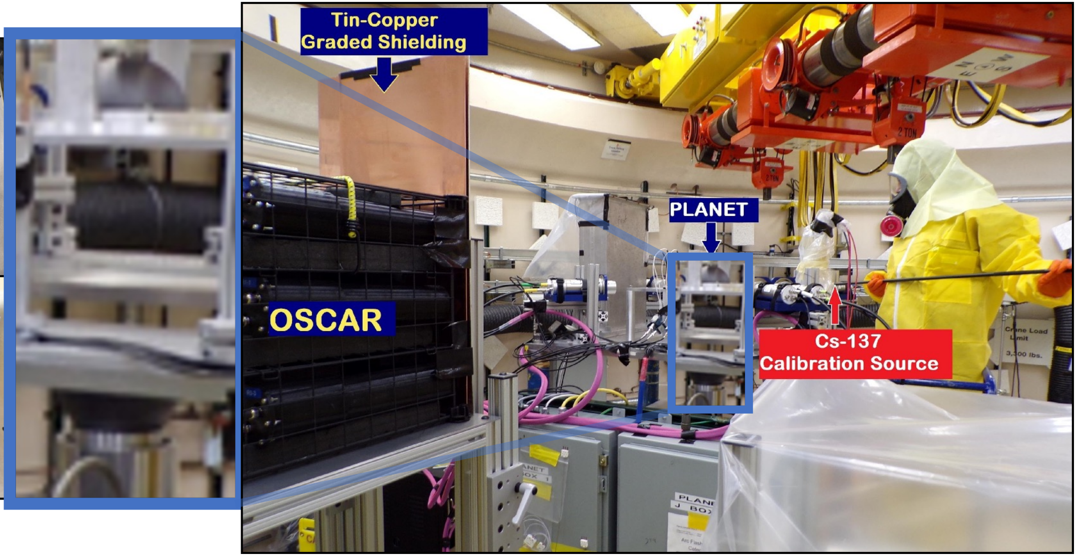
- Rocky Flats hemi-shells (highly enriched uranium, 93% ^{235}U)



- 10 – 60 kg configurations



- k_{eff} of 0.59-0.96
- Driven by a ^{252}Cf point source placed in center



- 3 by 4 array of 5.08 by 5.08 cm trans-stilbene crystals, shielded by tin-copper graded shielding
- 1.66 m offset from center of assembly

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MUSiC Kinetics Measurement – Env. and Data

- Fast neutrons have lower HEU interaction cross section
- Neutron leakage on the ***nanosecond time scale***
- Gamma-ray emissions more easily self-shielded

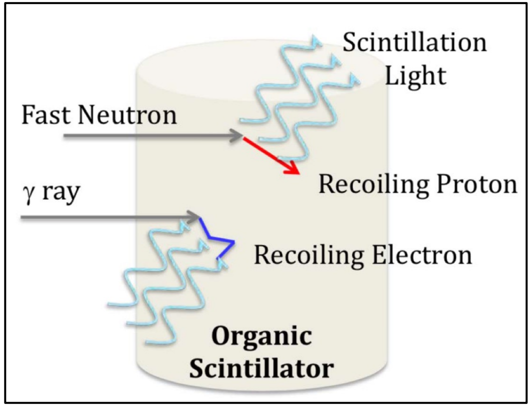
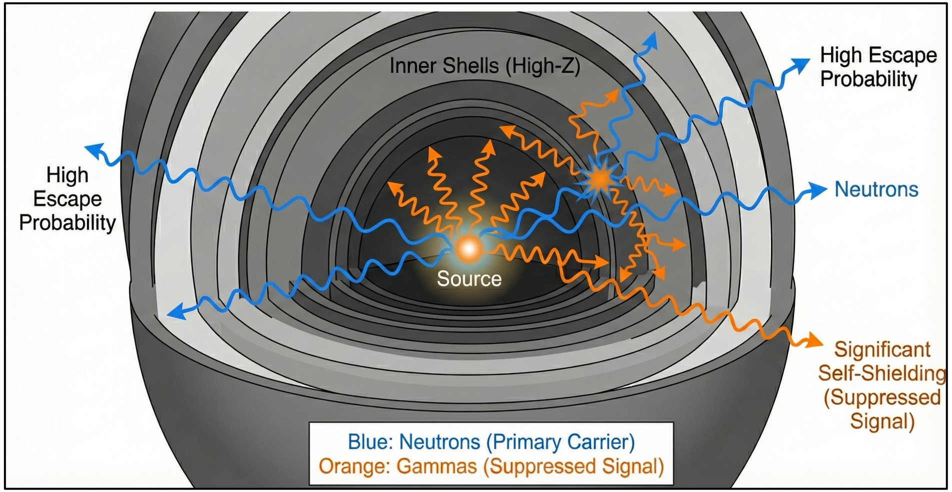
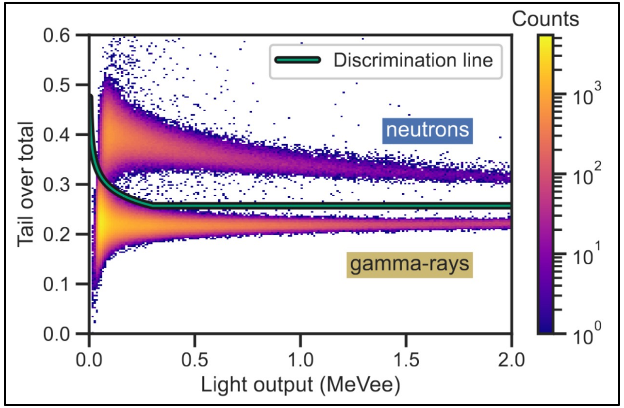


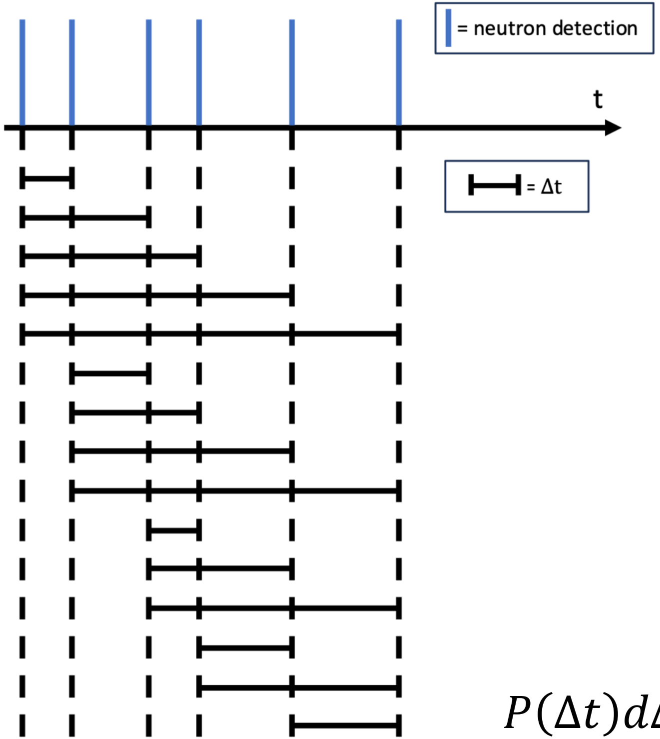
Diagram by Manfredi NSSC UC Berkeley

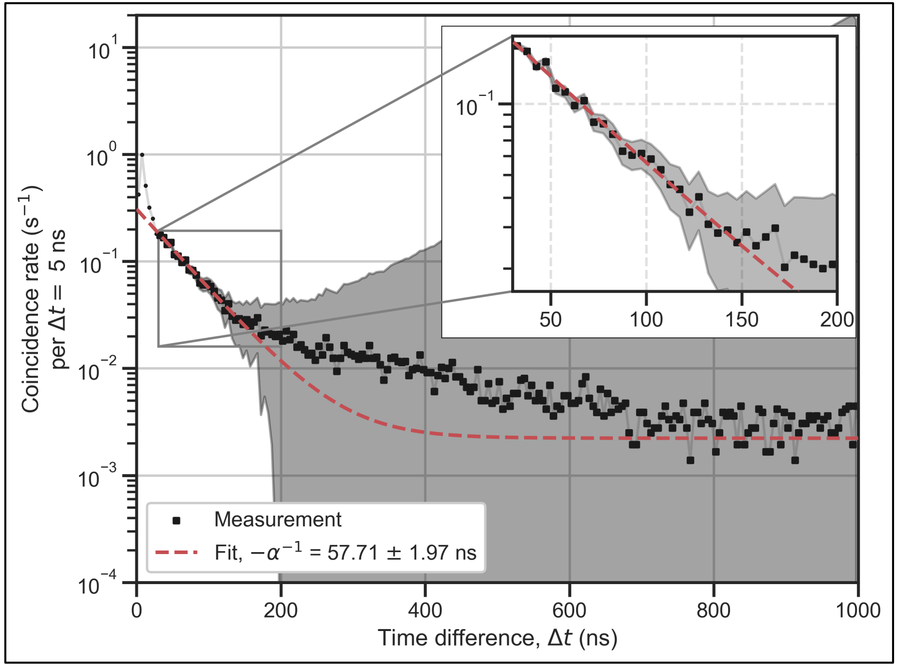


Visualization generated using **DALL-E 3**



MUSiC Kinetics Measurement – Rossi-α

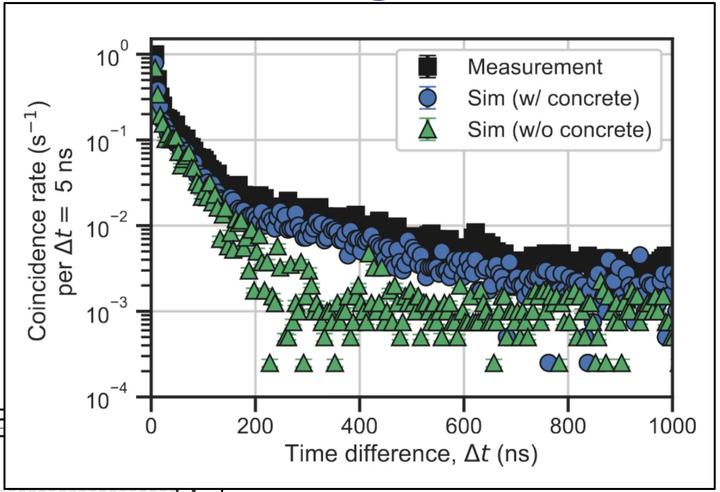


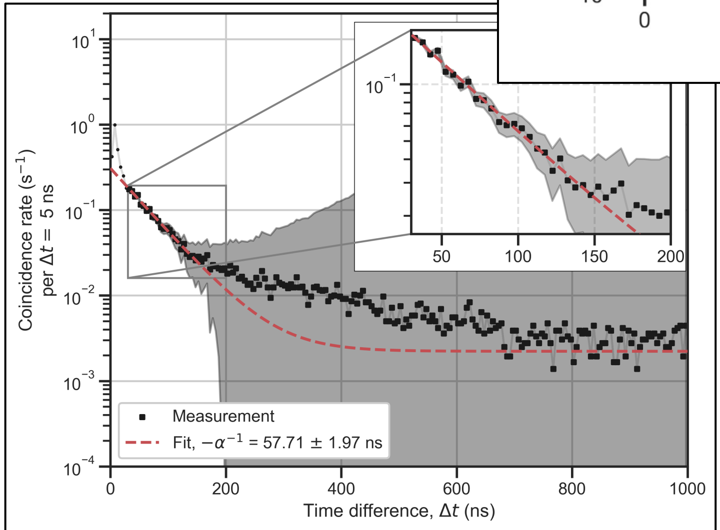


$$P(\Delta t)d\Delta t = \left(Ae^{\alpha\Delta t} + B\right)d\Delta t \rightarrow \ln(P(\Delta t) - B) = \alpha\Delta t$$

MUSiC Kinetics Measurement – Rossi-α – Fitting

- Two modes in RA distribution
- First mode in early time differences is assumed to be true fission chain correlations
- Second mode is from concrete room return
- Fit with non-linear least squares
- Apply deviation scaled uncertainty to bins
- Decrease weight of later time differences with higher deviation





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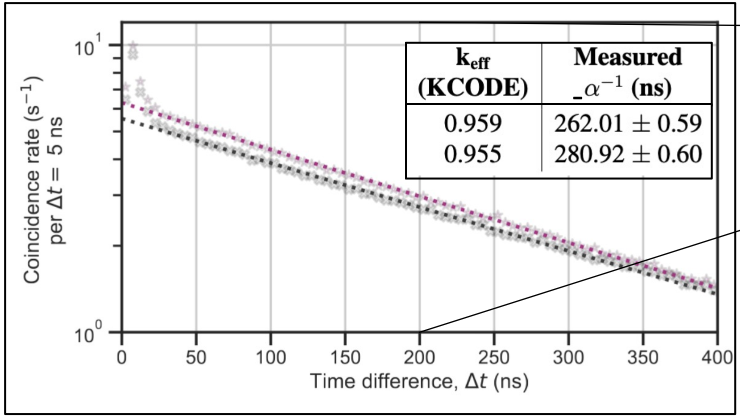
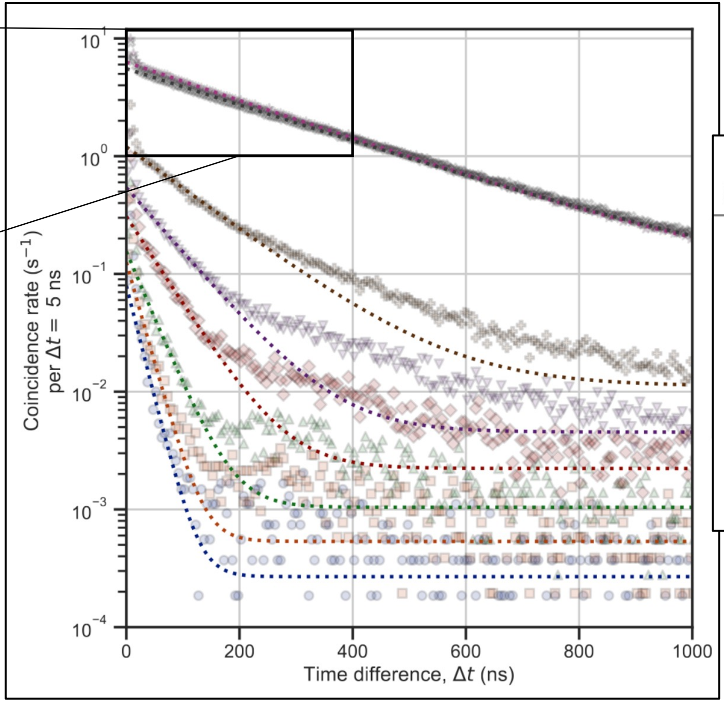
MUSiC Kinetics Measurement – Rossi-α - Neutron





k_{eff} (KCODE)	Measured $\_\alpha^{-1}$ (ns)
0.591	22.62 ± 6.82
0.710	25.12 ± 3.92
0.784	37.89 ± 3.41
0.862	57.71 ± 1.97
0.900	78.20 ± 1.43
0.931	122.23 ± 1.02
0.959	262.01 ± 0.59
0.955	280.92 ± 0.60

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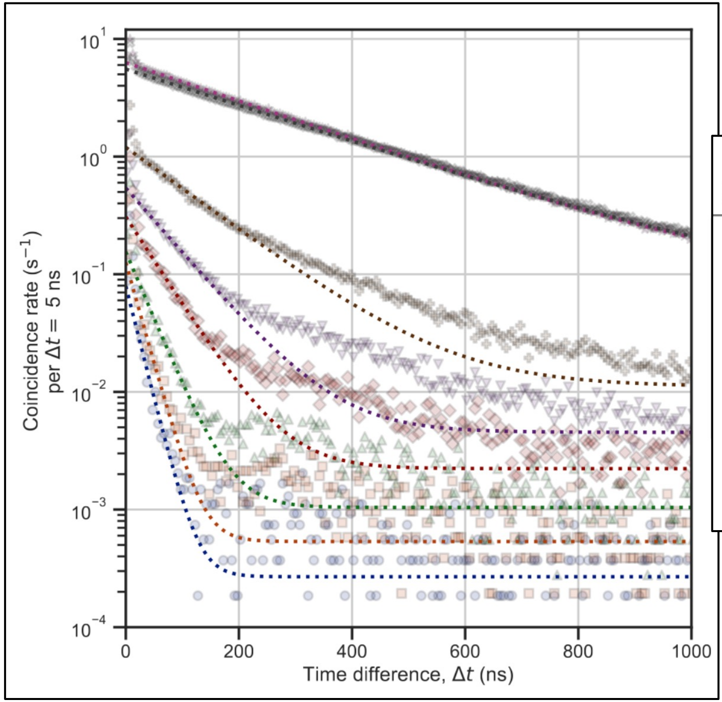
MUSiC Kinetics Measurement – Rossi-α - Neutron

- Prompt neutron period α^{-1} estimates follow increase in criticality
- Organic scintillators allow nanosecond time resolution to resolve fast system
- Traditional He-3 systems cannot resolve time behavior below 4 microseconds
- Other neutron detectors like fission chambers could offer similar timing resolution, but large form factor and inherent special nuclear material pose additional challenges.



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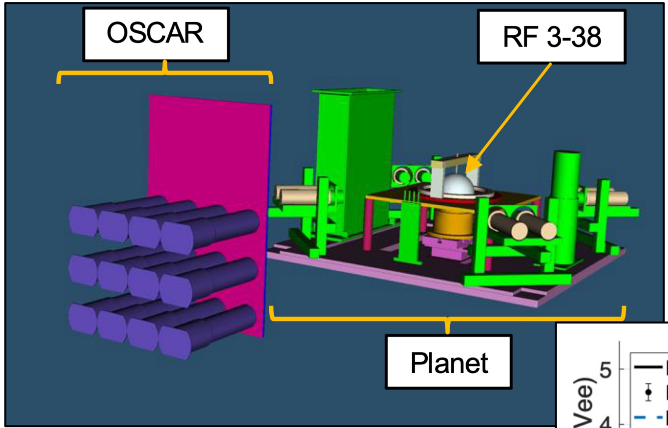
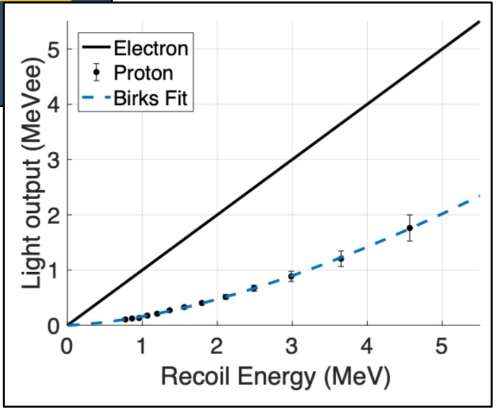
MUSiC Kinetics Simulation – Rossi-α - α^{-1}

PTRAC-to-PoliMi Public

https://github.com/Umich-DNNG/PTRAC-to-PoliMi

LA-UR-25-30501





k_{eff} (KCODE)	Measured α^{-1} (ns)	MCNP6.3 w/ room α^{-1} (ns)	Ratio (w/ room) /(Meas)
0.591	22.62 ± 6.82	21.51 ± 4.11	0.95 ± 0.34
0.710	25.12 ± 3.92	30.79 ± 2.41	1.23 ± 0.21
0.784	37.89 ± 3.41	37.82 ± 4.24	1.00 ± 0.14
0.862	57.71 ± 1.97	57.06 ± 2.35	0.99 ± 0.05
0.900	78.20 ± 1.43	77.41 ± 1.55	0.99 ± 0.03
0.931	122.23 ± 1.02	107.12 ± 1.13	0.88 ± 0.01
0.959	262.01 ± 0.59	172.49 ± 2.52	0.66 ± 0.01
0.955	280.92 ± 0.60	160.98 ± 2.84	0.57 ± 0.01

DOI: 10.1119/5.0139531

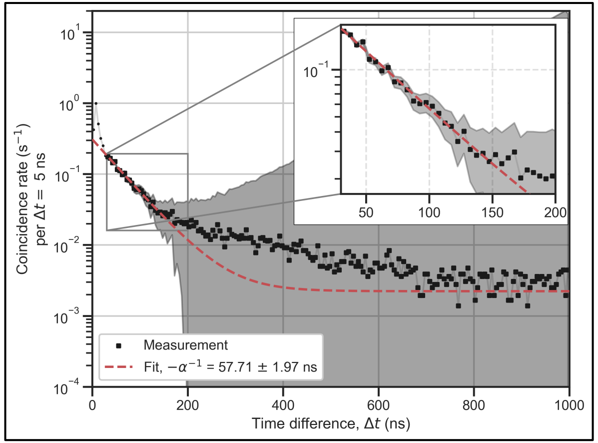
MUSiC Kinetics Simulation – Rossi-α - α^{-1}

PTRAC-to-PoliMi Public

https://github.com/Umich-DNNG/PTRAC-to-PoliMi

LA-UR-25-30501

- Simulated Rossi-alpha detector response and measured Rossi-alpha detector response agree well for prompt period of < 100 ns
- Concrete room is a factor, but effect is limited by weighted fit approach



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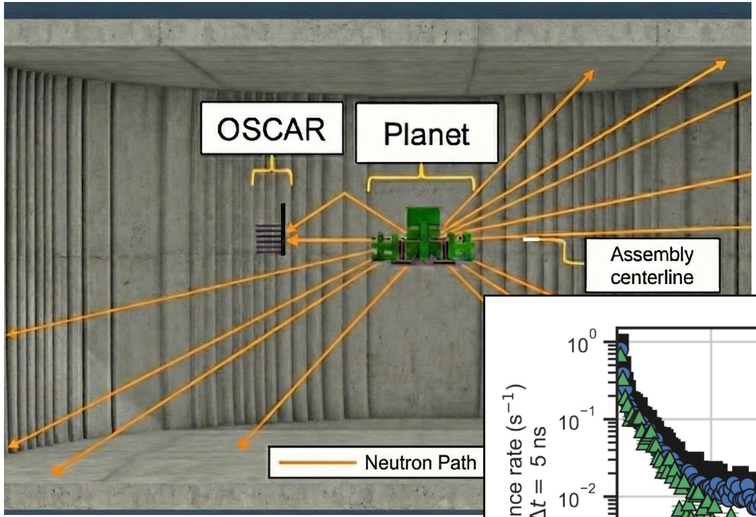
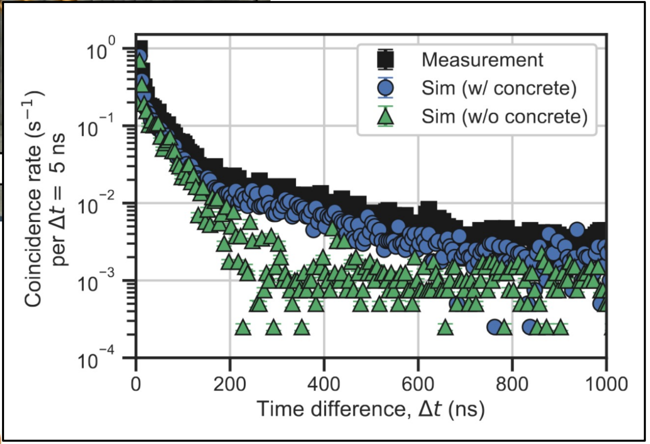
MUSiC Kinetics Simulation – Rossi-α Interference





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0.959	262.01 ± 0.59	172.49 ± 2.52	0.66 ± 0.01
0.955	280.92 ± 0.60	160.98 ± 2.84	0.57 ± 0.01

- Disagreement at prompt period > 100 ns due to overlap of characteristic correlations and concrete room return

MUSiC Kinetics Simulation

- Good agreement between OSCAR measurements and MCNP replicated detector response
- As k_{eff} → 1, divergence of model
- Future work to improve the concrete room model for these experiments outside of this benchmark

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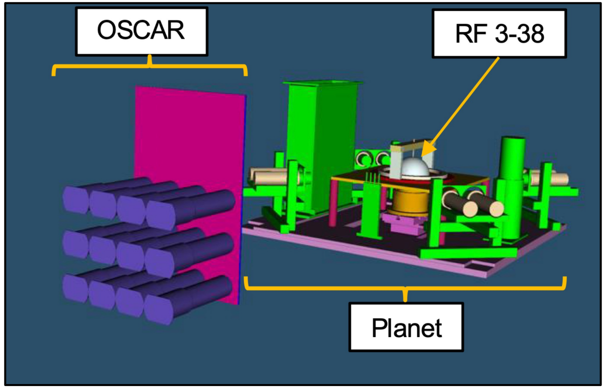
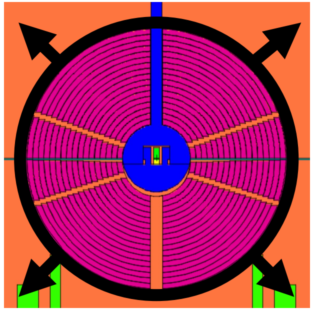
0.955	280.92 ± 0.60	160.98 ± 2.84	0.57 ± 0.01

MUSiC Kinetics Simulation – Source Term Disagreement

- Previous agreement depends on how well we can model concrete
- We want to focus more on the source term than concrete scattering
- Lower expense to simulate response closer to source

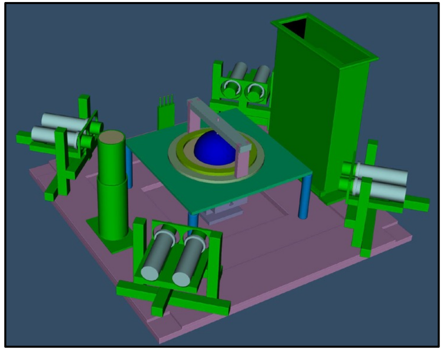
k_{eff} (KCODE)	Measured OSCAR α^{-1} (ns)	MCNP6 F1 α^{-1} (ns)	Ratio OSCAR Meas./ F1
0.59	22.62 ± 6.82	25.46 +/- 1.08	0.89 ± 0.27
0.71	25.12 ± 3.92	26.47 +/- 0.46	0.95 ± 0.15
0.78	37.89 ± 3.41	28.76 +/- 0.11	1.32 ± 0.12
0.86	57.71 ± 1.97	43.90 +/- 0.19	1.31 ± 0.05
0.90	78.20 ± 1.43	57.67 +/- 0.28	1.36 ± 0.03
0.93	122.23 ± 1.02	84.07 +/- 0.48	1.45 ± 0.01
0.96	262.01 ± 0.59	130.03 +/- 1.52	2.01 ± 0.02
0.95	280.92 ± 0.60	123.84 +/- 1.56	2.27 ± 0.03





MUSiC Kinetics Simulation – A New Hope

- Good agreement between RAM-RODD measurements and source term
  - 47 cm offset vs. 166 cm
- RAM-RODD model simulations are being adapted to the OSCAR procedure



k_{eff} (KCODE)	Measured RAM-RODD (RR) α^{-1} (ns)	MCNP6 F1 α^{-1} (ns)	Ratio RR Meas./ F1
0.59	24.75 +/- 0.89	25.46 +/- 1.08	0.97 +/- 0.05
0.71	26.60 +/- 0.72	26.47 +/- 0.46	1.00 +/- 0.03
0.78	32.79 +/- 0.50	28.76 +/- 0.11	1.14 +/- 0.02
0.86	46.95 +/- 0.43	43.90 +/- 0.19	1.07 +/- 0.01
0.9	66.23 +/- 0.41	57.67 +/- 0.28	1.15 +/- 0.01
0.93	85.47 +/- 0.74	84.07 +/- 0.48	1.02 +/- 0.01
0.96	126.58 +/- 0.81	130.03 +/- 1.52	0.97 +/- 0.01
0.95	131.58 +/- 0.81	123.84 +/- 1.56	1.06 +/- 0.01

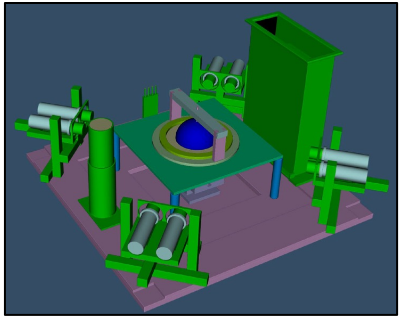
Weldon, et. al., "MUSiC IER-568: Subcritical Neutron Noise Benchmark Results", LA-UR-24-32339

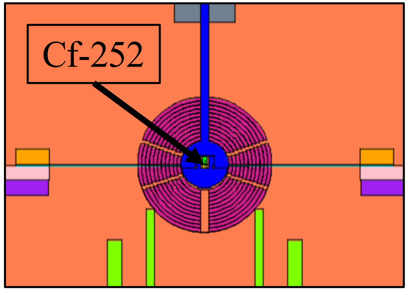
Conclusions

- ICSBEP benchmarks for MUSIC
  - Critical benchmark complete
  - ^{3}He subcritical approved and in final comments
  - Organic scintillator benchmark baseline simulations and drafting
    - Goal for ICSBEP 2027
    - Would be first organics benchmark w/ ICSBEP

International Criticality Safety Benchmark Evaluation Project (ICSBEP)
(Critical and Subcritical Measurements)

NEA NUCLEAR ENERGY AGENCY





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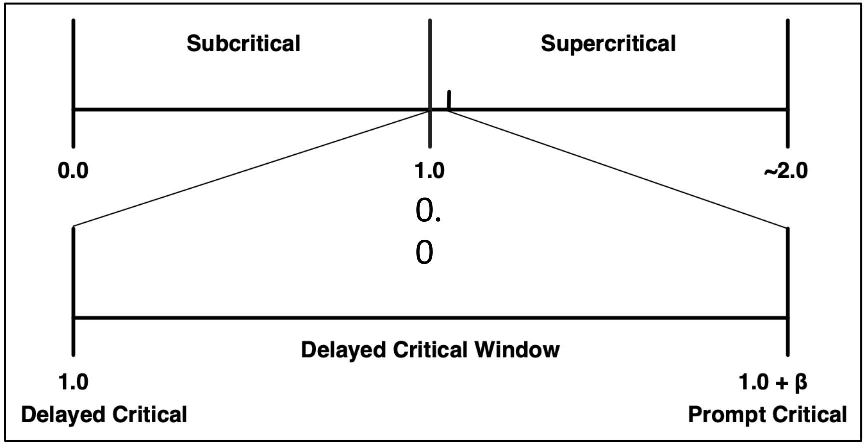
Acknowledgements

This work is supported by the National Criticality Experiments Research Center through the Department of Energy (DOE) Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration (NNSA), the Consortium for Monitoring, Technology, and Verification under DOE NNSA award number DENA0003920, and the DOE through the Los Alamos National Laboratory (LANL) operated by Triad National Security, LLC, for the NNSA under Contract No. 89233218CNA000001.

Additional Slides

Multiplication factor

- Effective multiplication factor k_{eff}
- k_{eff} is # of neutrons from one gen. of fission that cause fission in next gen.
  - The "multiplication factor"
  - $k_{eff} < 1$, subcritical
    - Neutron population drops from gen. to gen.
  - $k_{eff} = 1$, delayed critical
    - Neutron population is constant through each gen.
  - $k_{eff} > 1$, supercritical
    - Neutron population increases from gen. to gen.



Sanchez et. al., "Reactor Physics", LA-UR-21-20178

Nuclear Reactors – Point kinetics approximation

$$\frac{dn(t)}{dt} = \boxed{\frac{\rho(t)-\beta_{\text{eff}}}{\Lambda}\, n(t)} + \boxed{\sum_i \lambda_i c_i} + S$$

Time-dependent change in neutron population

Prompt fission neutrons

Delayed fission neutrons

Additional external source neutrons

$$\boxed{\boldsymbol{\alpha = \frac{\rho(t)-\beta_{\text{eff}}}{\Lambda}}}$$

$$\boxed{\frac{dc_i}{dt} = -\lambda_i c_i + \frac{\beta_i}{\Lambda}\, n(t)}$$

Nuclear Reactors – Point kinetics approximation

$$\frac{dn(t)}{dt} = \boxed{\frac{\rho(t) - \beta_{\text{eff}}}{\Lambda} n(t)} + \boxed{\sum_i \lambda_i c_i} + S$$

Prompt fission neutrons

Prompt neutron decay constant

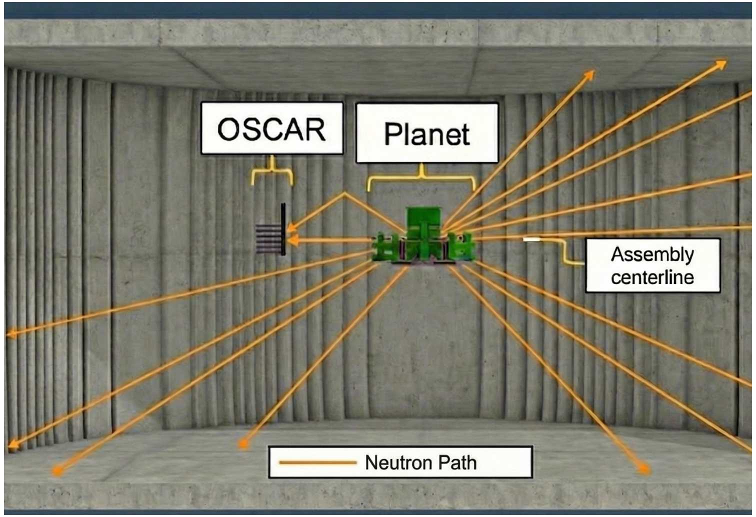
Reactivity

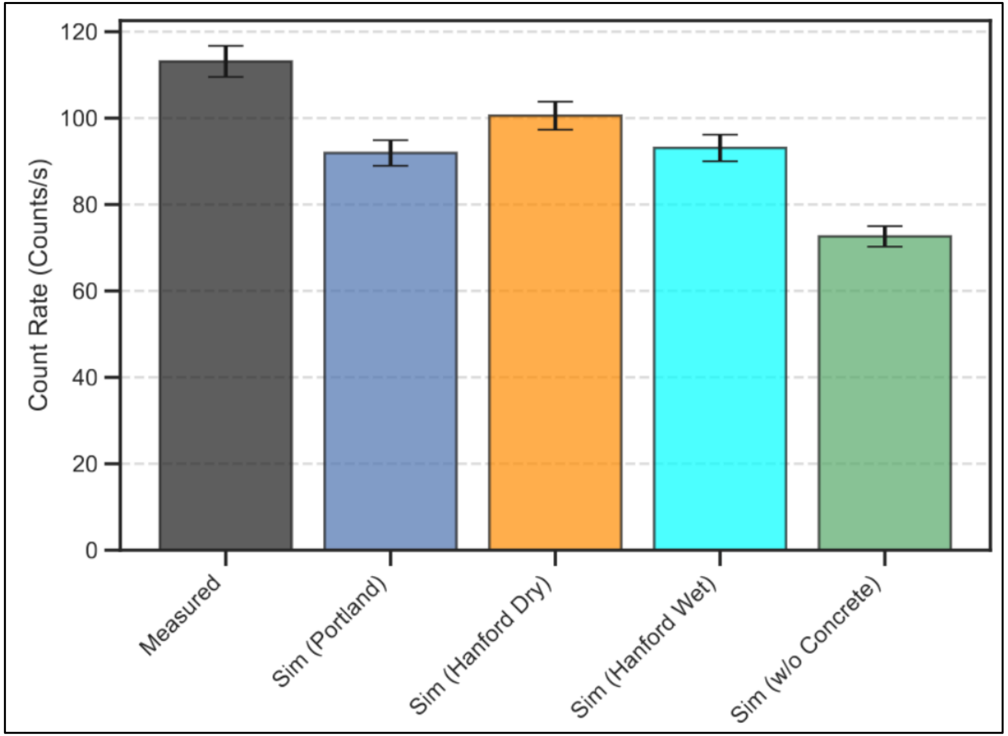
$$\boxed{\alpha = \frac{\rho(t) - \beta_{\text{eff}}}{\Lambda}}$$

Mean generation time (diffusion)

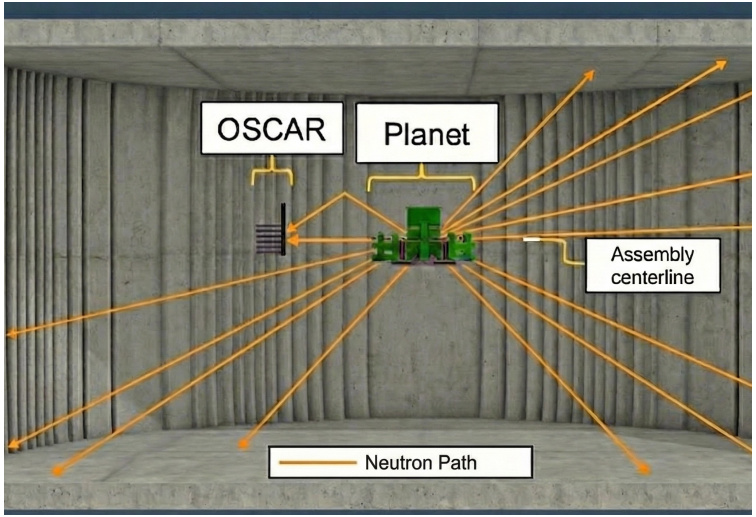
Delayed neutron fraction

MUSiC Kinetics Simulation – Conc. Rossi Neutron





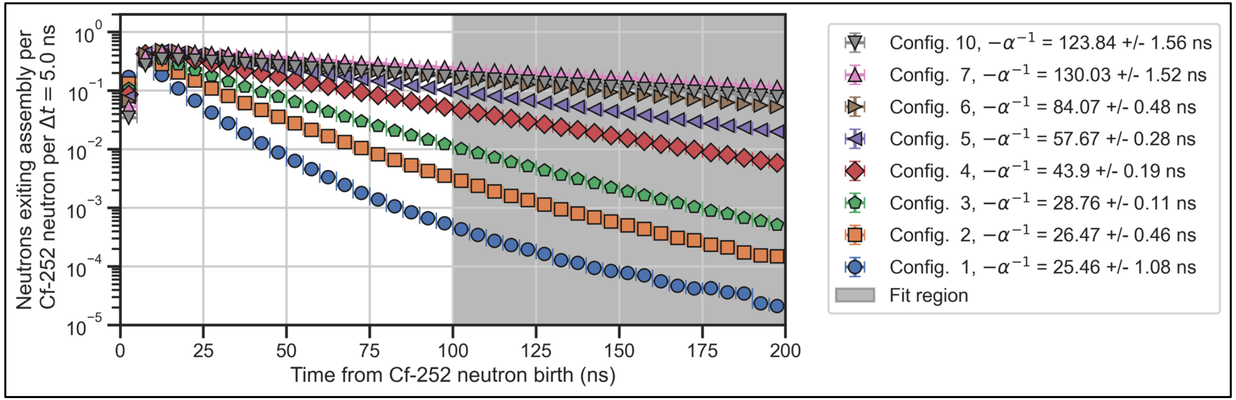
MUSiC Kinetics Simulation – Conc. Neutron counts

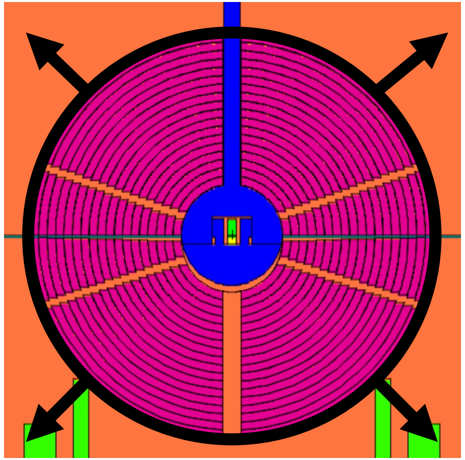


- Hydrogen content of concrete has a significant effect on the “concrete room return”
- Expected for fast neutron, organic scintillator detectors

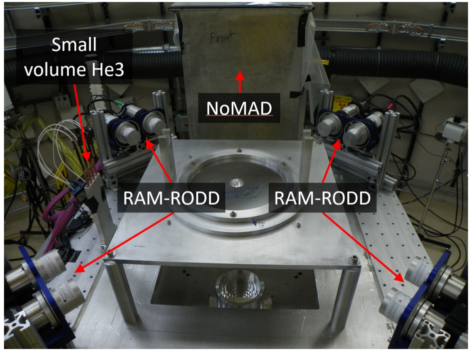
Config. 7 Result	wt% hydrogen	$-\alpha^{-1}$ Estimate (ns)	Estimate / Measurement
Measurement	Unknown	262.01 ± 0.59	N/A
Hanford Dry	0.4	181.57 ± 2.61	0.69 ± 0.01
Portland	1.0	172.49 ± 2.52	0.66 ± 0.01
Hanford Wet	1.2	166.24 ± 2.55	0.63 ± 0.01
No Concrete	N/A	135.86 ± 2.55	0.52 ± 0.01

F1 Time-binned leakage tally Rossi-alpha fit results

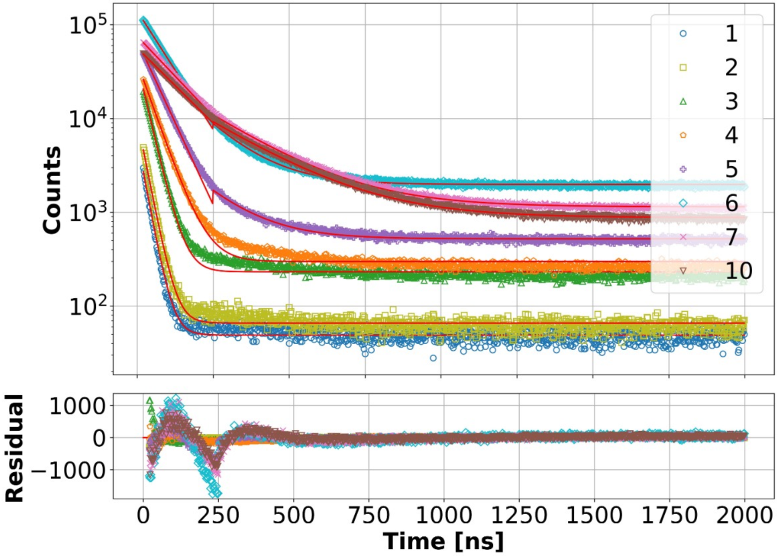




RAM-RODD Experiment results



- Detectors were positioned close to the system
  - Offset of ~45 cm from detector faces to center of RF shells
  - Resulted in high count rates for most configurations
- Configurations 3 – 7 and 10: digitizer throughput issues
  - Correlation was intact but biased due to losses
  - Issues can be corrected in post



Weldon, et. al., “MUSiC IER-568: Subcritical Neutron Noise Benchmark Results”, LA-UR-24-32339

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