MUSiC: Reactivity Estimates Using Pulsed Neutron Source Methods

K. Ogren, R. Weldon, G. McKenzie,
J. Hutchinson

Feb 22, 2023
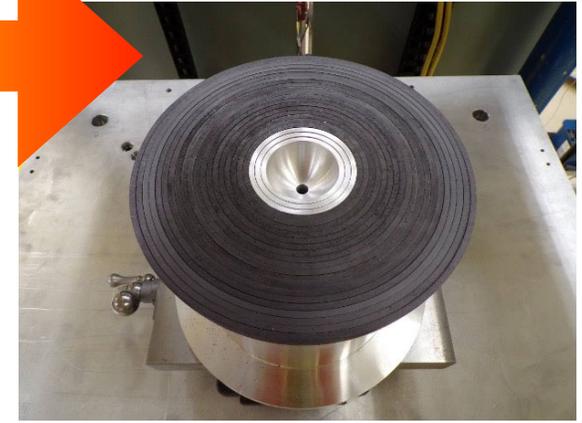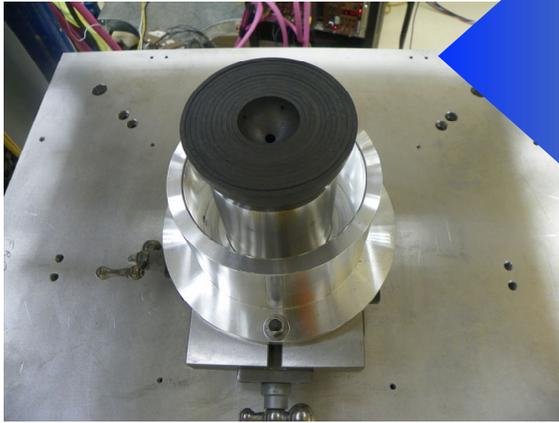
Nuclear Engineering and Nonproliferation
Advanced Nuclear Technology (NEN-2)
kogren@lanl.gov

The MUSiC experiment covers a broad range of subcritical to critical configurations

Deeply Subcritical
k_{eff} 0.64 - 0.8

Nearly Delayed Critical
k_{eff} 0.98 - 0.99

Many Possible Configurations

- Rocky Flats HEU shells can be configured for a variety of masses and reactivities

- Valuable test bed for measurement methods and instrumentation

- Platform for validated subcritical nuclear data benchmarks

One primary goal of MUSiC is to evaluate and compare subcritical system measurement methods
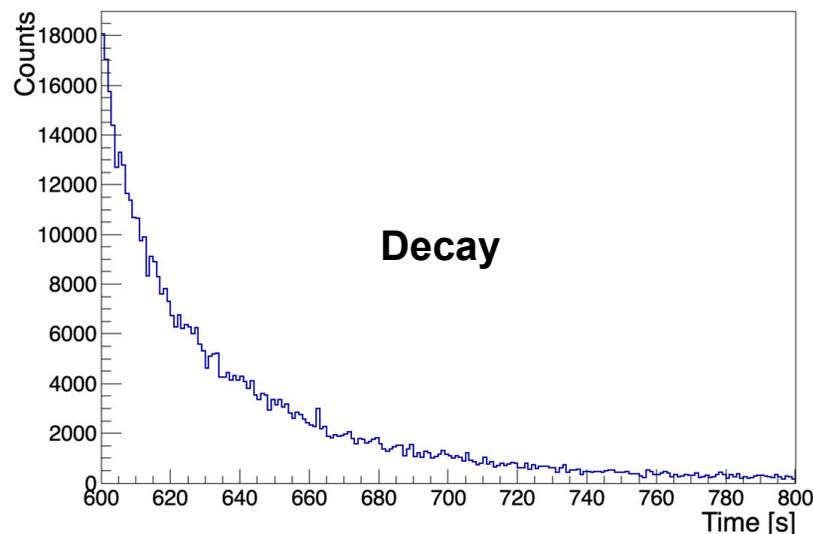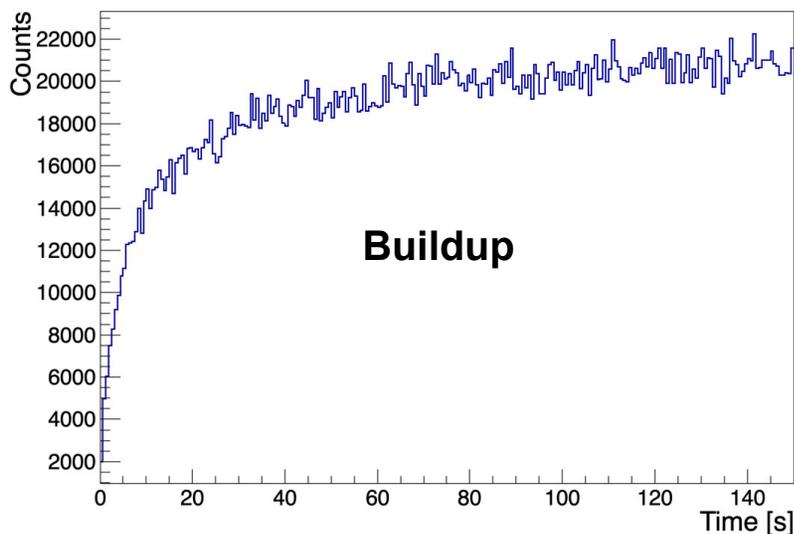
- Instrumentation:
  - ^{3}He detector systems
  - Scintillators
- Broad range of reactivities
- Multiple interrogation sources
- Rich data for analysis methods and parameter studies
- Consistent, repeatable configurations
- All methods are subject to bias → cross-compare and adjust experiments to account for it

- Preliminary results will guide future experimental improvements

- **Focus of this presentation: pulsed neutron method for reactivity analysis, using DT interrogation source and NoMAD detector**
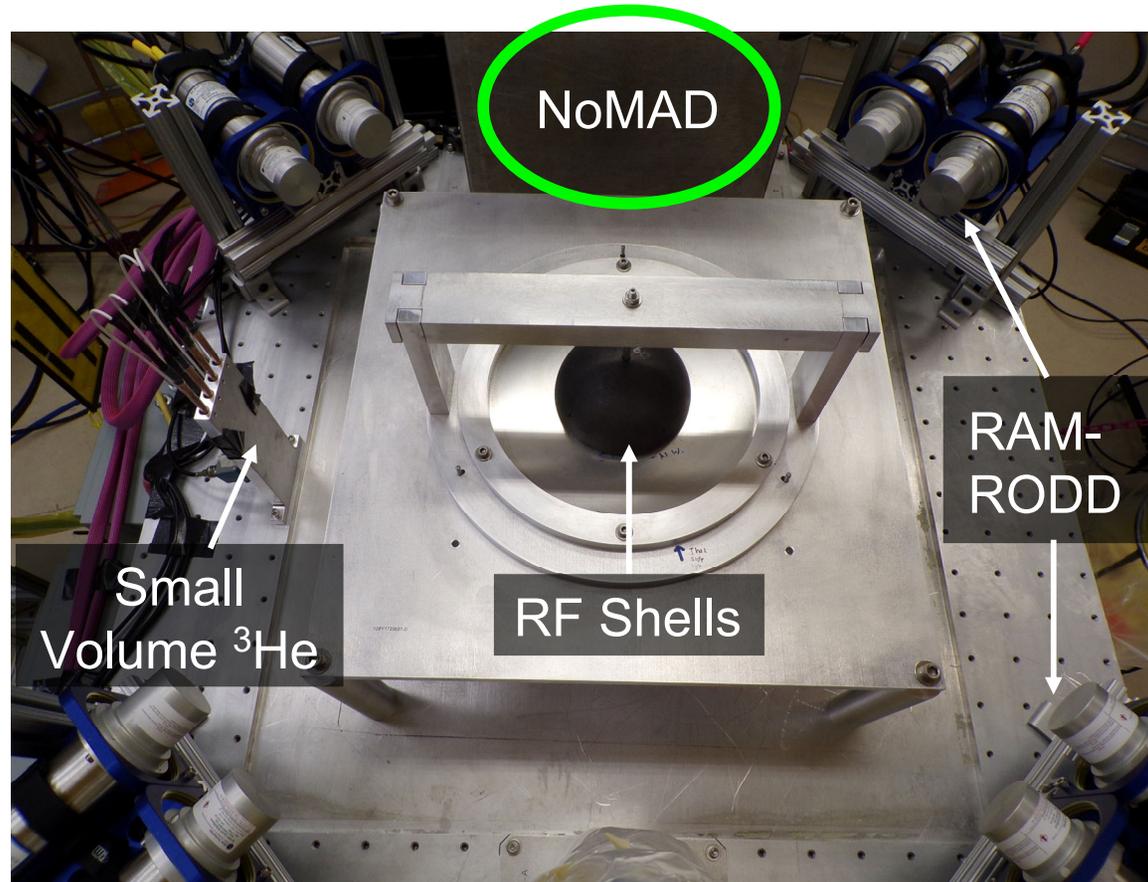
Pulsed neutron active interrogation can reveal characteristic signatures in the time domain

Interpulse β-Delayed Emission (Buildup)
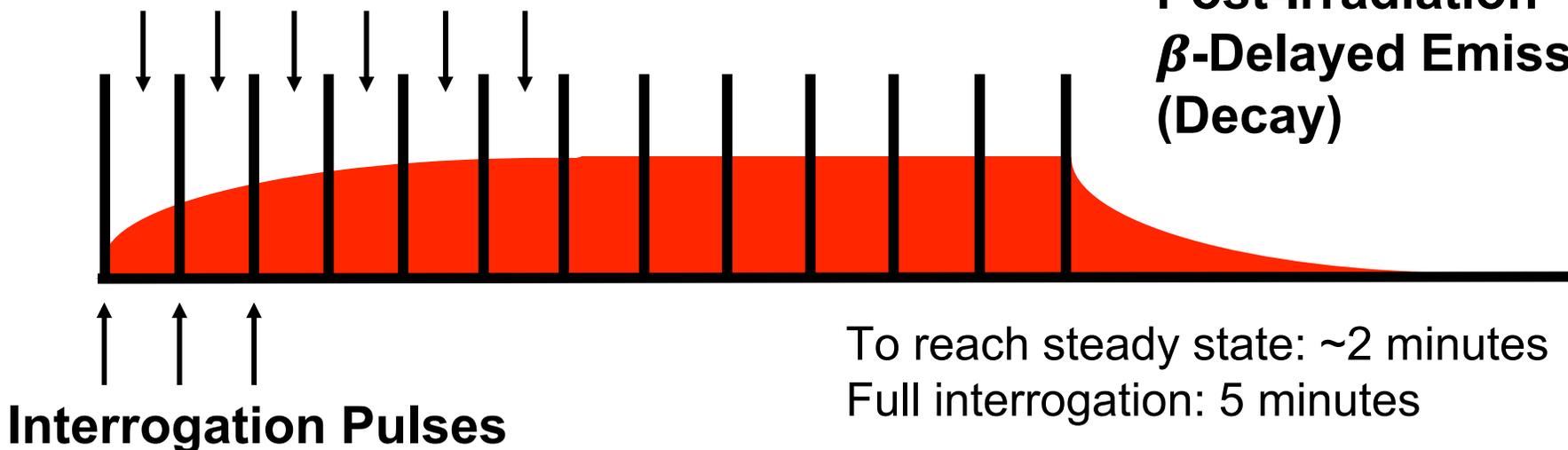
Post-Irradiation β-Delayed Emission (Decay)

Interrogation Pulses

To reach steady state: ~2 minutes
Full interrogation: 5 minutes

The reactivity of a subcritical system can be estimated using the pulsed neutron method

Basic method: a burst of neutrons is injected into a subcritical multiplying system and the decay of the neutron population is observed over time

The measured fundamental decay constant of the system, α_0, and the decay constant at delayed critical, α_{DC}, are related to the reactivity ($) by

$$\alpha_0 = \alpha_{DC}\left(\$ - 1\right)$$

Thus, the reactivity is directly proportional to α_0, and can be obtained by measurement of the decay constant at delayed critical.
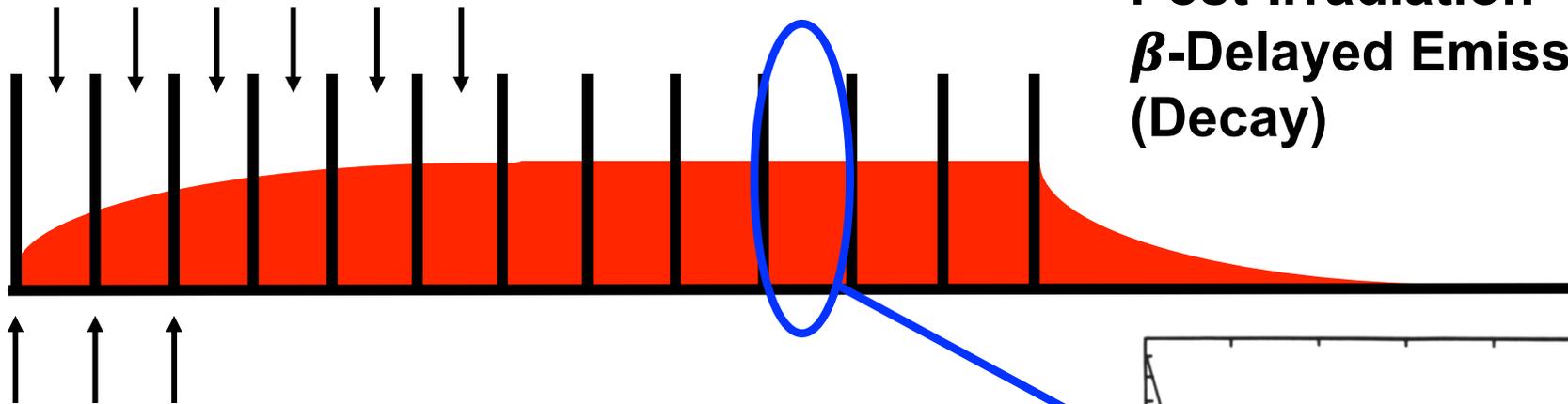
Measuring α_{DC} can be difficult for subcritical systems.

Neutron Pulse

Exponential Decay
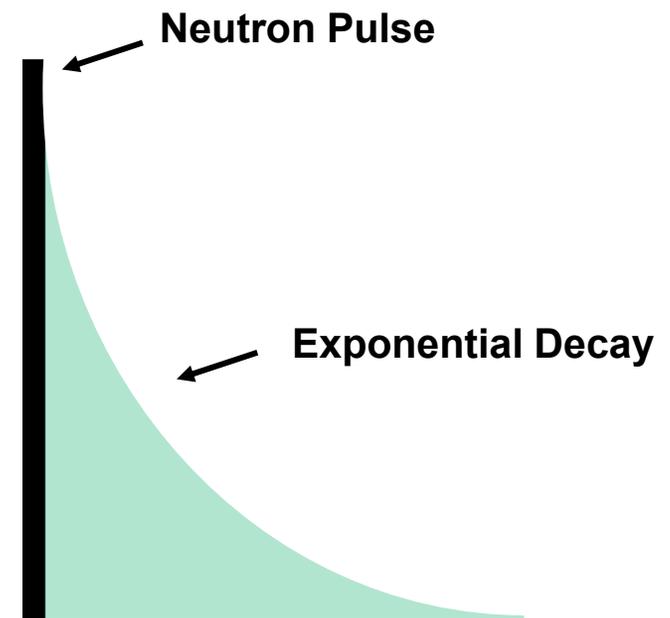
G. Keepin, *Physics of Nuclear Kinetics (Addison-Wesley, 1965)*, 273-277

The reactivity of a subcritical system can be estimated using the pulsed neutron method
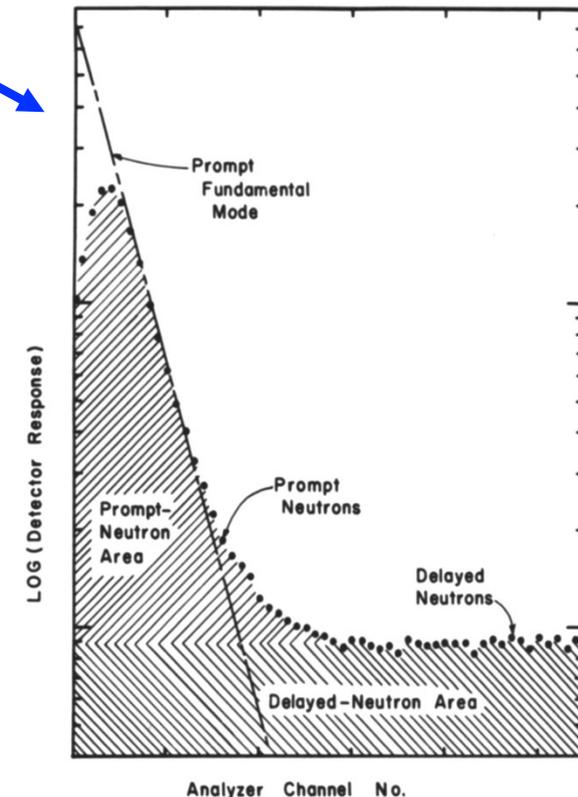
Interpulse β-Delayed Emission (Buildup)

Post-Irradiation β-Delayed Emission (Decay)

Interrogation Pulses

- For subcritical systems, it may not be feasible to directly measure α_{DC}

- The need to measure α_{DC} can be circumvented by measuring pulsed response once delayed neutron equilibrium is reached

- This is possible when the pulse rate R satisfies $\alpha_0 >> R >> \lambda$

LOG (Detector Response)

Prompt Fundamental Mode

Prompt Neutrons

Prompt–Neutron Area

Delayed Neutrons

Delayed–Neutron Area

Analyzer Channel No.

Los Alamos
NATIONAL LABORATORY

The Sjöstrand Method uses a simple area ratio to estimate reactivity

Prompt Neutron Area

Delayed Neutron Area

$$\$_{SJ} \equiv \frac{\text{Prompt Neutron Area}}{\text{Delayed Neutron Area}}$$

[1]N. G. Sjöstrand, *Arkiv Fysik,* 11, 233, 1956
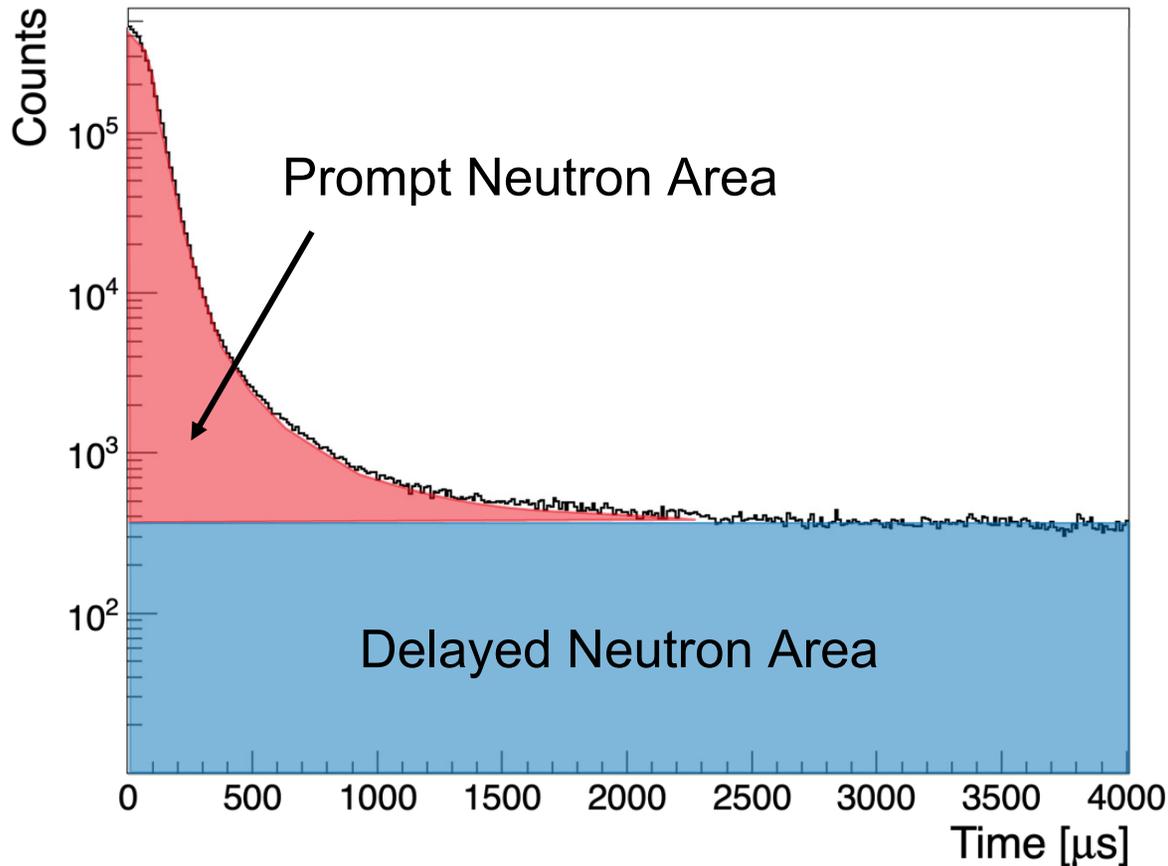
- **Sjöstrand method[1]**
  - Simplest method to apply
  - Reactivity estimated by ratio of prompt/delayed neutron areas
  - Assumes point kinetic model (ignores spatial harmonics)

- **More complex analysis methods are also being pursued**
  - Account for some spatial effects
  - Involve fitting prompt decay modes, alternative calculations of characteristic constants

Los Alamos
NATIONAL LABORATORY

Pulsed neutron method preliminary results

Prompt Neutron Die Away Profile

- Proportion of delayed neutron area increases with increasing reactivity
- Smaller prompt/delayed ratio → closer to critical

Pulsed neutron method preliminary results

Configuration	Mass (kg)	Multiplication	Feynman-α Reactivity ($)	Sjöstrand Reactivity ($)	Sjöstrand k_{eff}
4	37.9617	8.3	-22.71	**-15.76**	0.907
5	42.9722	11.4	-16.90	**-8.60**	0.947
6	48.4099	18.4	-10.26	**-3.68**	0.977
7	54.2785	46.6	-4.81	**-0.764**	0.995
10	59.2075	>150	N/A	**-0.713**	0.995

- Pulsed (Sjöstrand) results higher than expected
- Feynman-α results somewhat lower than expected
- Sources of significant systematic error exist (dead time, integration windows), yet to be fully quantified


Sjöstrand Reactivity
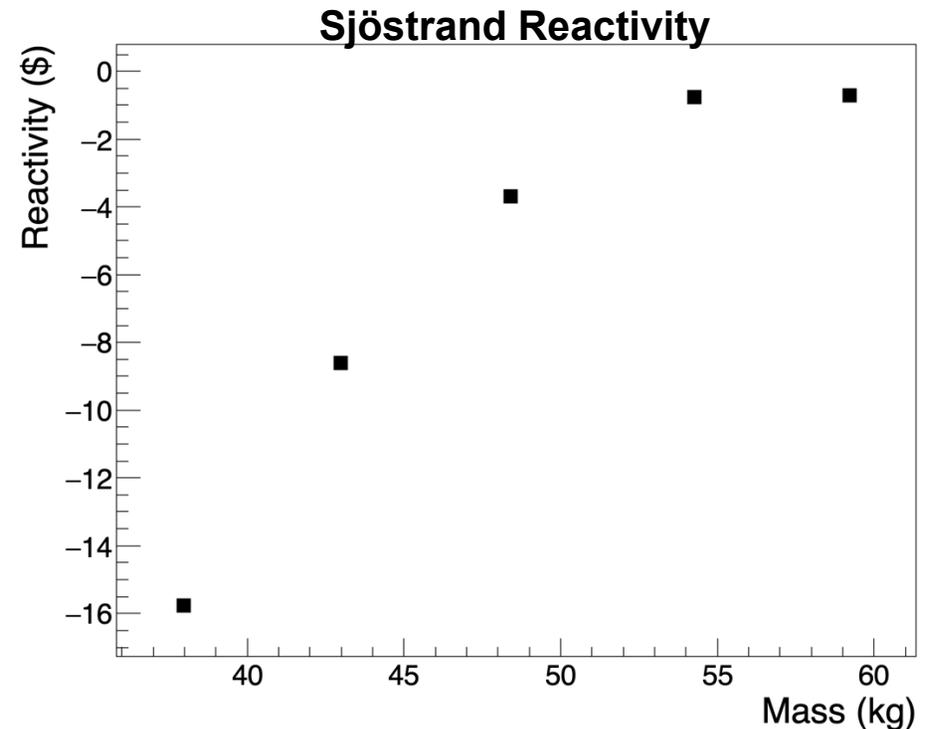
Separate Effort:
# Organic scintillators for time correlated measurements

- We are also interested in fast timing applications

- ^{3}He systems like NoMAD have inherent time resolution limits

- R&D of organic scintillator applications led by Rob Weldon

Organic scintillators for time correlated measurements

- Organic liquid scintillators
- Direct detection of fast neutrons (recoil based)
- No moderation, fast response → ideal for bare systems
- Time resolution (~900 ps)
- Excellent for neutron noise measurements of fast systems
- Measurements: Rossi-α, Feynman-α
- Pulse shape discrimination – eliminate gamma signal
- Reactivity range: all configurations
- Neutron energy spectroscopy possible

Rossi-α Measurement

NATIONAL LABORATORY
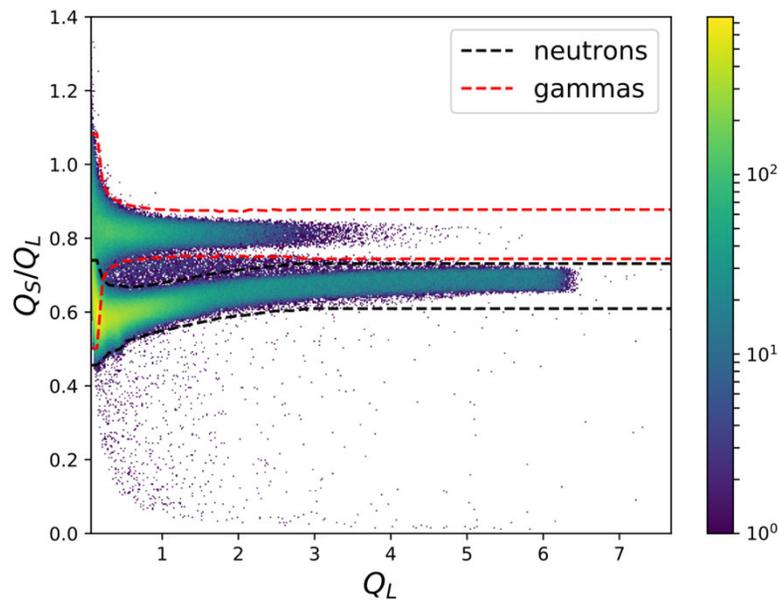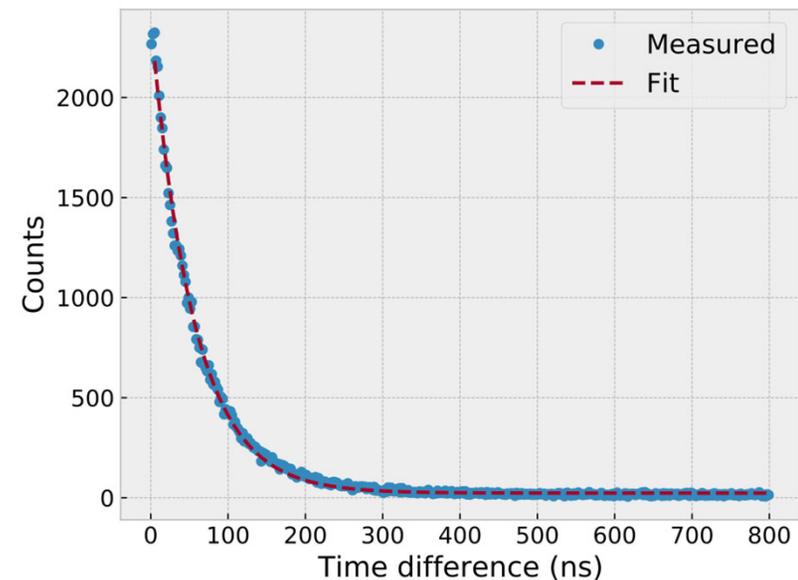
Conclusion & Future Work

Accomplishments

- Analysis of pulsed active interrogation data has begun

- Development of reactivity analysis based on pulsed neutron methods

- Preliminary results show expected trends

- Fast-timing analysis using organic scintillators

Next Steps

- Refinement of pulsed neutron method algorithms

- Analysis of sources of systemic bias

- Comparison with other reactivity estimation methods

Questions?

Calculating Reactivity of a Subcritical System
Using the Pulsed Neutron Method

Basic method: a burst of neutrons is injected into a subcritical multiplying system and the decay of the neutron population is observed over time

The fundamental-mode decay constant for prompt neutrons, α_0, is given by

$$\alpha_0 \equiv \frac{1}{n}\frac{dn}{dt} = \frac{k\left(1-\beta_{\text{eff}}\right)-1}{l}$$

where l is the prompt neutron lifetime and β_{eff} is the effective delayed neutron factor.

Using the definition of reactivity $\$ \equiv \dfrac{\rho}{\beta_{\text{eff}}} = \dfrac{k-1}{k\beta_{\text{eff}}}$, α_0 is related to reactivity by $\alpha_0 = \dfrac{k\beta_{\text{eff}}}{l}\left(\$-1\right)$

G. Keepin, *Physics of Nuclear Kinetics (Addison-Wesley, 1965)*, 273-277

Los Alamos
NATIONAL LABORATORY

Calculating Reactivity of a Subcritical System Using the Pulsed Neutron Method

At delayed critical ($\$ = 0$), the decay constant α becomes

$$\alpha_{DC} = -\frac{k\beta_{\text{eff}}}{l}$$

and α_0 can be expressed as

$$\alpha_0 = \alpha_{DC}\left(\$ - 1\right)$$

Thus, the reactivity is directly proportional to the fundamental-mode decay constant α_0, and the proportionality constant can be obtained by measurement of the decay constant at delayed critical.

G. Keepin, *Physics of Nuclear Kinetics (Addison-Wesley, 1965), 273-277*

Calculating Reactivity of a Subcritical System Using the Pulsed Neutron Method

- **Gozani method[1]**

  - $$\left(\frac{\rho}{\beta}\right)_{GO} \equiv \frac{\text{Extrapolated Prompt Fundamental Mode Area}}{\text{Delayed Neutron Area}}$$
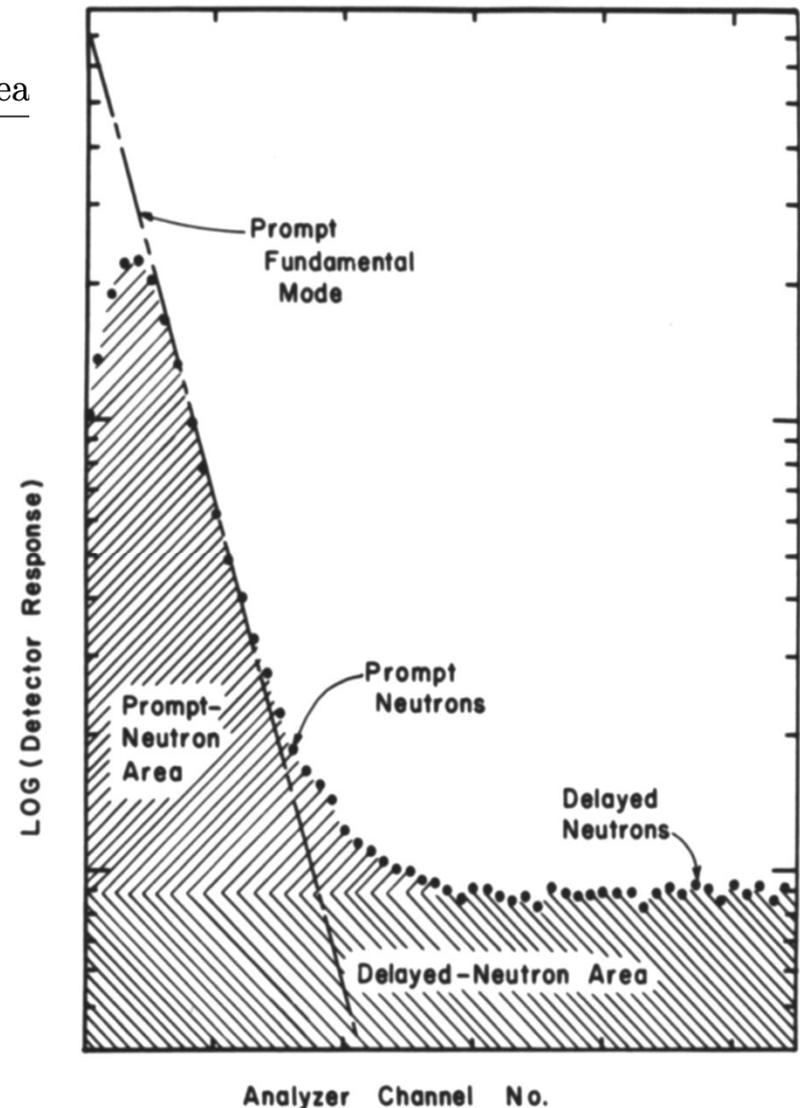
  - Eliminates non-fundamental harmonics by extrapolating the fundamental mode back to the time of the pulse

- **Garelis-Russell method[2]**

  - $\left(\frac{\rho}{\beta}\right)_{GR} \equiv \frac{\alpha_0}{\left(\frac{k\beta}{l}\right)} - 1$, where $\frac{k\beta}{l}$ is obtained from

  $$\int_0^\infty N_p \, e^{\frac{k\beta}{l}t} \, dt - \int_0^\infty N_p \, dt = \frac{N_d}{R}$$

  - Prompt neutron response is weighted by an exponential factor. More difficult to calculate and implement.

C. F. Masters and K. B. Cady, *Nuclear Science & Engineering*, 29:2, 272-282, 1967

[1]T. Gozani, *Nukleonik,* 4, 348, 1962

[2]E. Garelis and J. Russell, *Nuclear Science & Engineering,* 16:3, 263-270, 1963

MUSiC: Pulsed Neutron Method Preliminary Results