Subcritical Prompt Neutron Decay Constant Estimates in CROCUS

2024 MTV Workshop

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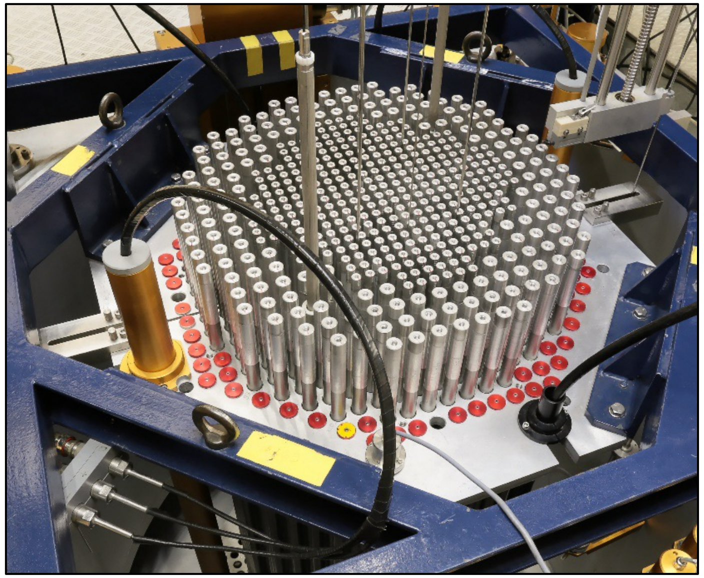
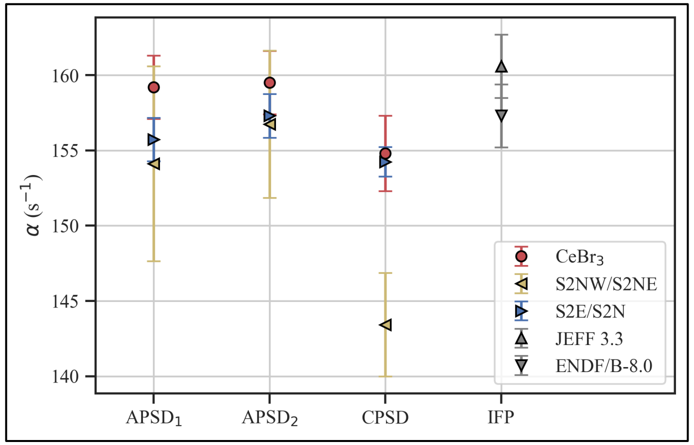
Introduction and Motivation

- Monitor a zero-power research reactor operation from online radiation signals
  - Completed work for 3 mW critical
  - Found that correlated (γ, γ) data was most reliable
- Now distinguish startup/shutdown subcritical states from critical operation
  - Leverage the time-correlated fission chain signal
- Calculate the prompt neutron decay constant for several states



CROCUS, EPFL



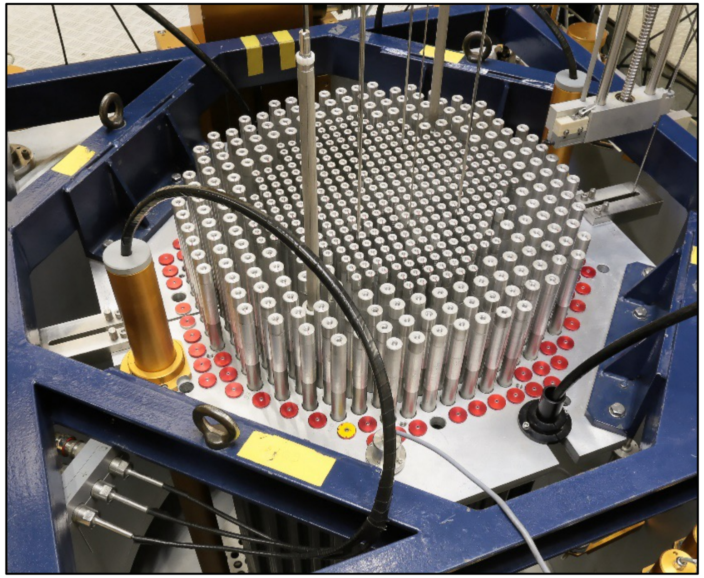
https://doi.org/10.1109/TNS.2023.3337657

Mission Relevance

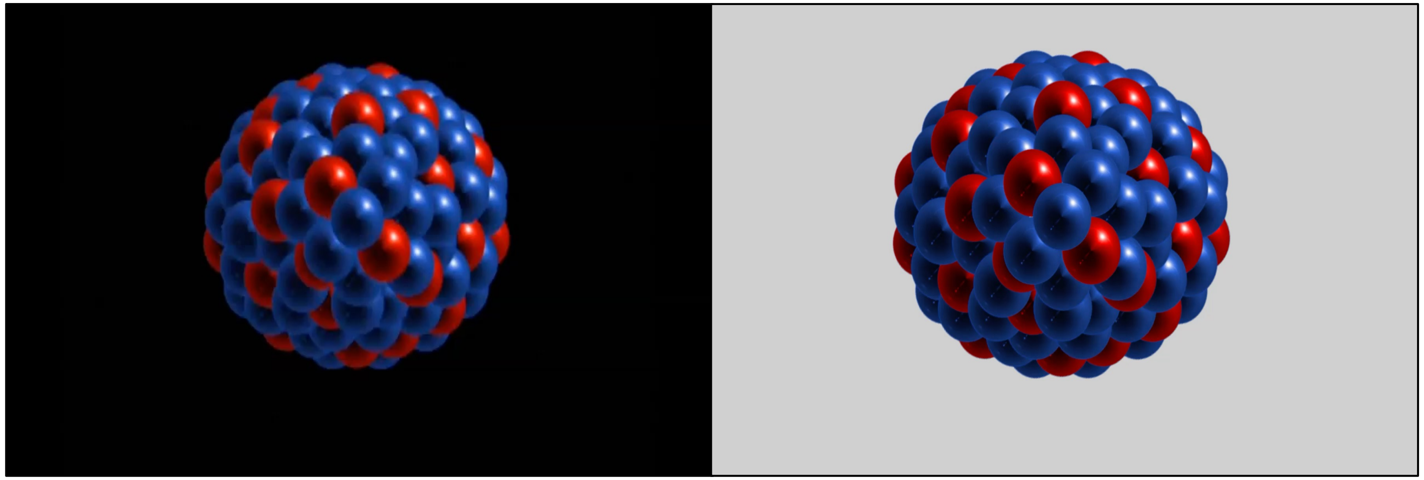
- Characterizing sub-critical state adds to reactor monitoring toolkit
- Verifying sub-critical states can corroborate startup and shutdown activities
  - Refueling or reconfiguration occurs during shutdown
- Perturbation in state can indicate material changes and defects

Technical Approach

- Measure CROCUS zero-power reactor
- Hosted by EPFL in Lausanne, Switzerland
- Focus on correlated gamma emissions based on previously published critical analysis



CROCUS, EPFL



Single Fission, MTV

Fission chain, MTV

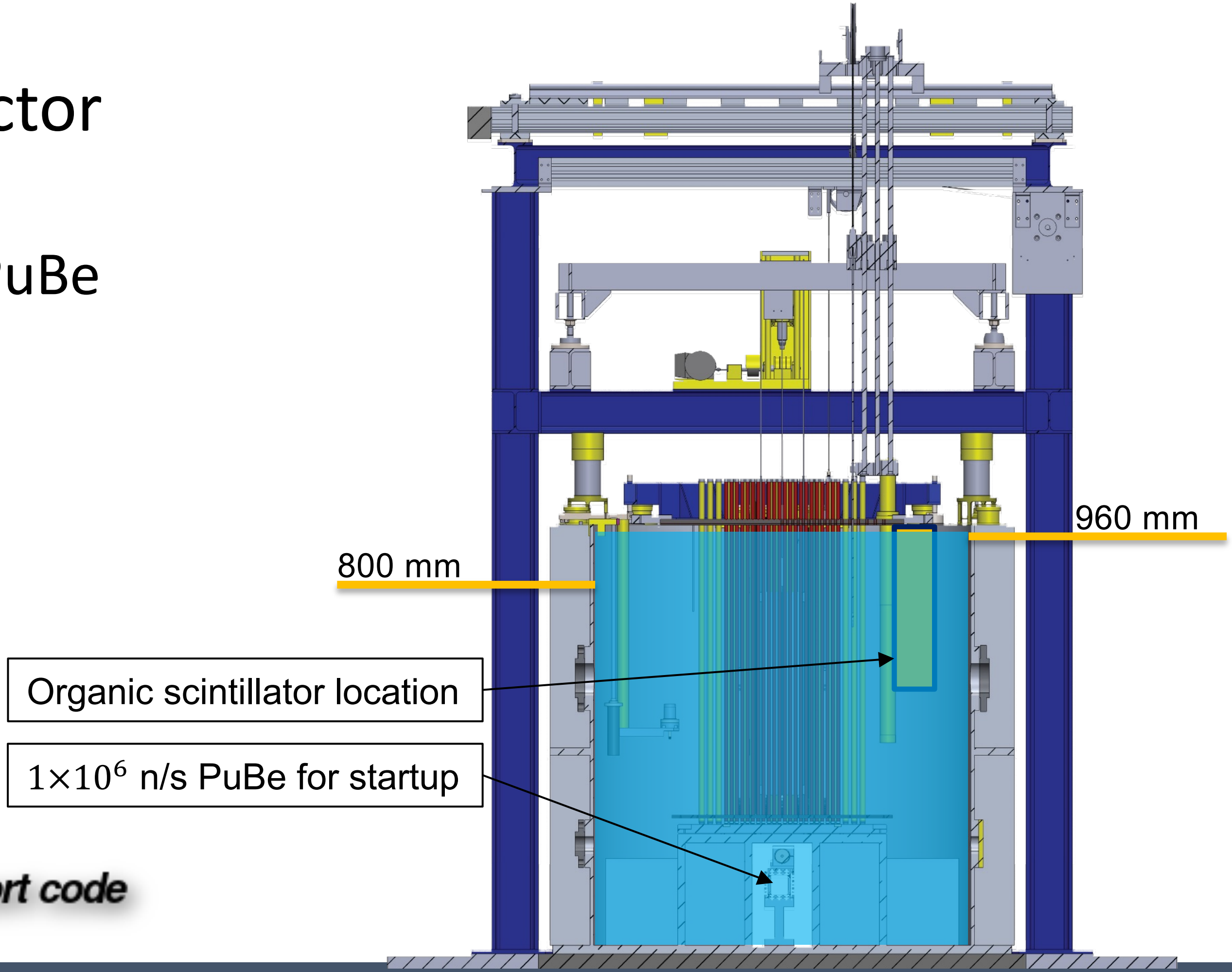
Technical Approach: CROCUS Configurations

- Measure CROCUS zero-power reactor
  - 3 mW critical
  - Several subcritical states driven by PuBe

Water level (mm)	$\rho(\$)$
800	-1.4
850	-0.9
900	-0.5
925	-0.3
950	-0.1

Serpent

a Continuous-energy Monte Carlo neutron and photon transport code



https://doi.org/10.5075/epfl-thesis-8336

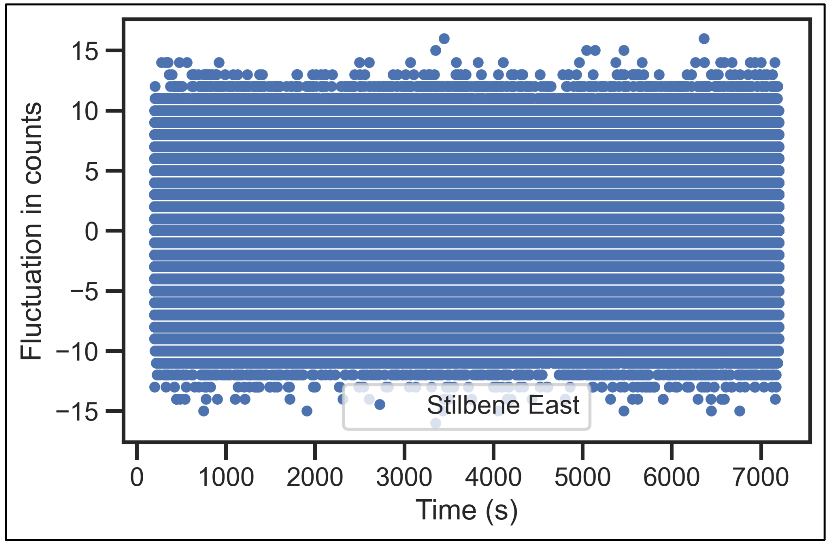
Technical Approach

- Assume point kinetics approximation
- Calculate the prompt neutron decay constant, α, with power spectral density (a.k.a. Cohn-α) analysis

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

$$\alpha = \frac{\beta_{\mathrm{eff}} - \rho}{\Lambda}$$

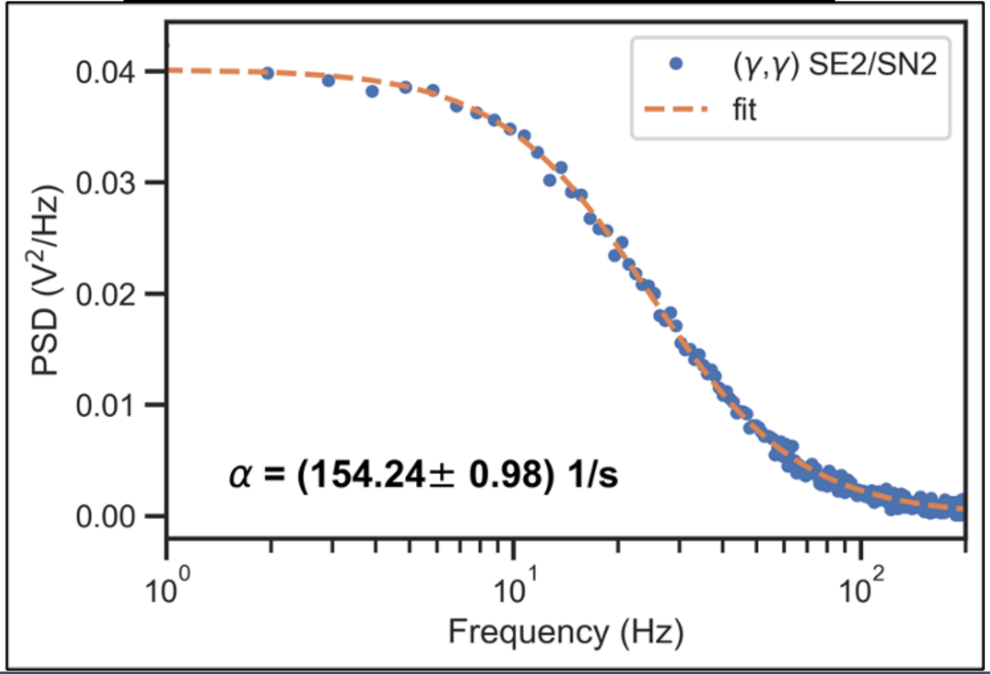
$$P_{xy}(\omega) = \frac{\epsilon_i \epsilon_j F D_\nu}{(\rho - \beta_{\mathrm{eff}})^2} \frac{1}{1 + \left(\frac{\omega}{\alpha}\right)^2}$$



$$P_{xx}(\omega) = \int_{-\infty}^{\infty} dt \cdot e^{-i\omega t} \cdot C(t)$$

Fourier Transform

"Welch" Approximation



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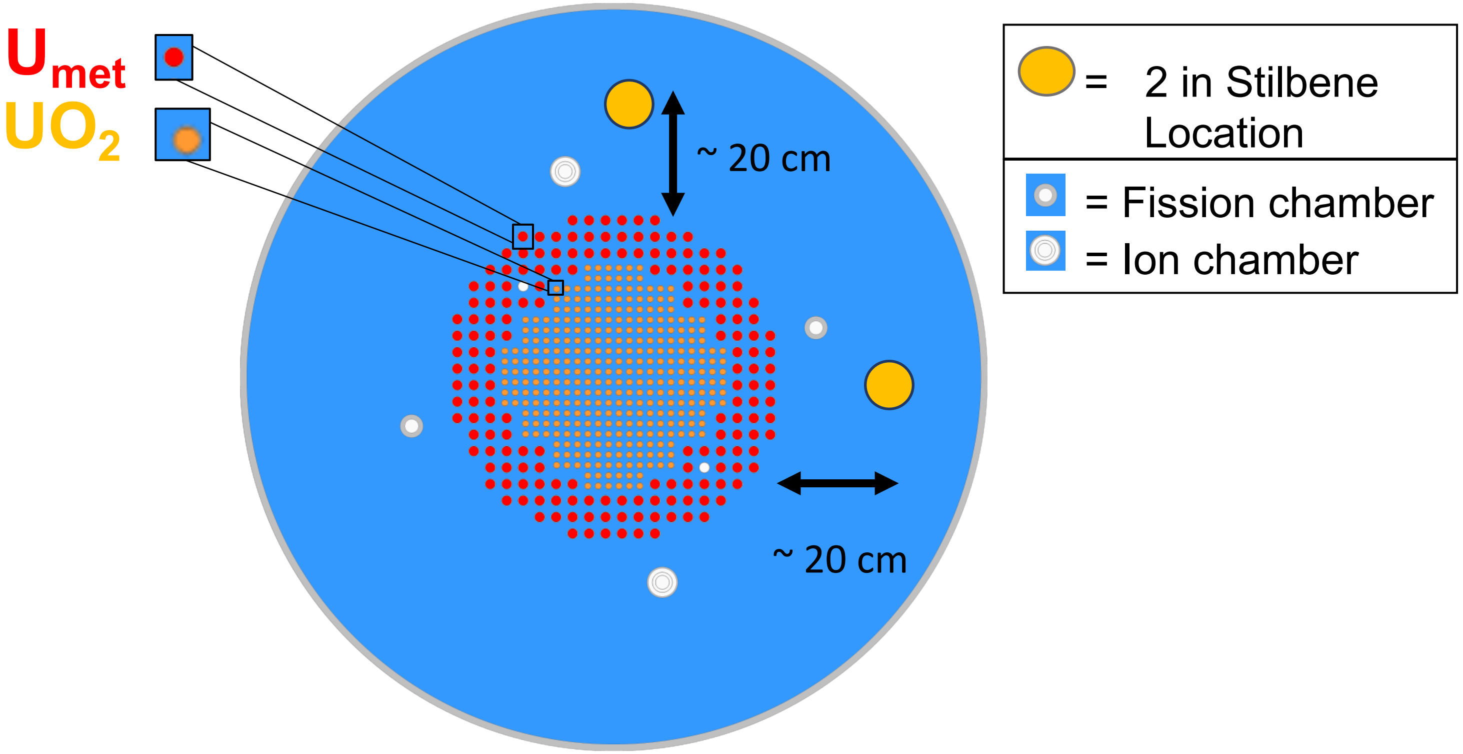
Technical Approach: Measurement Positions



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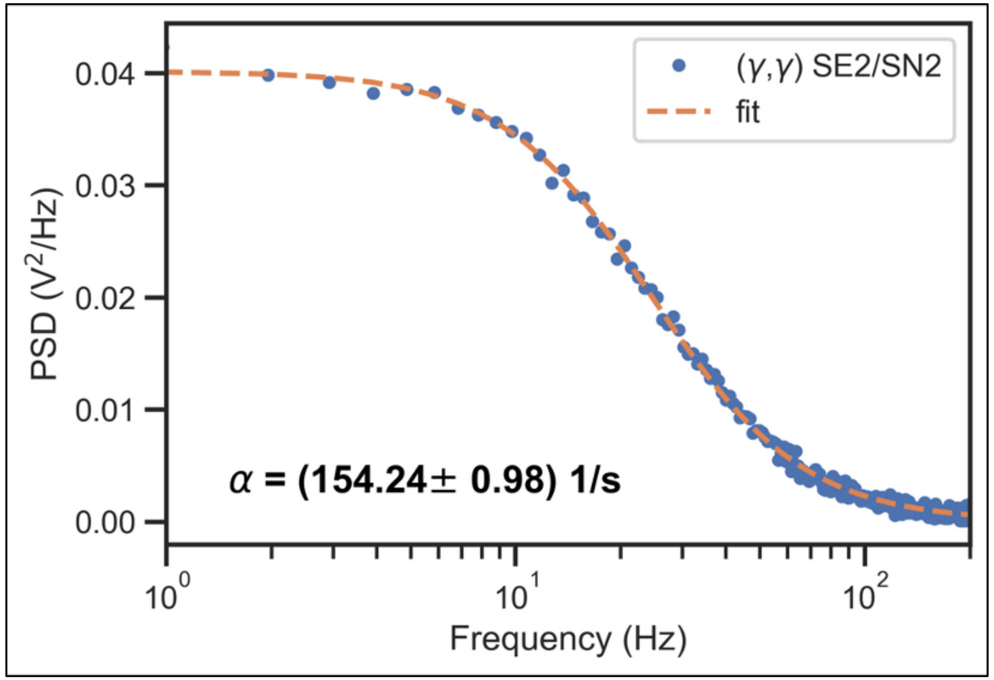
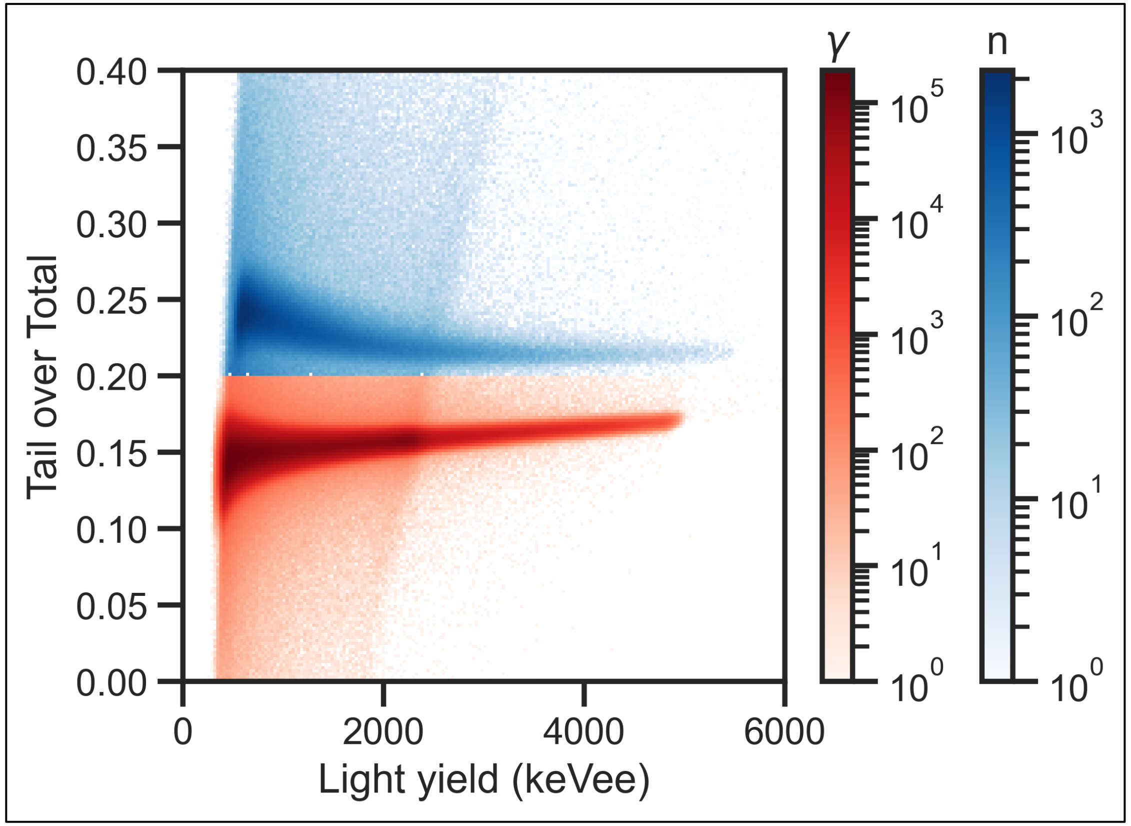
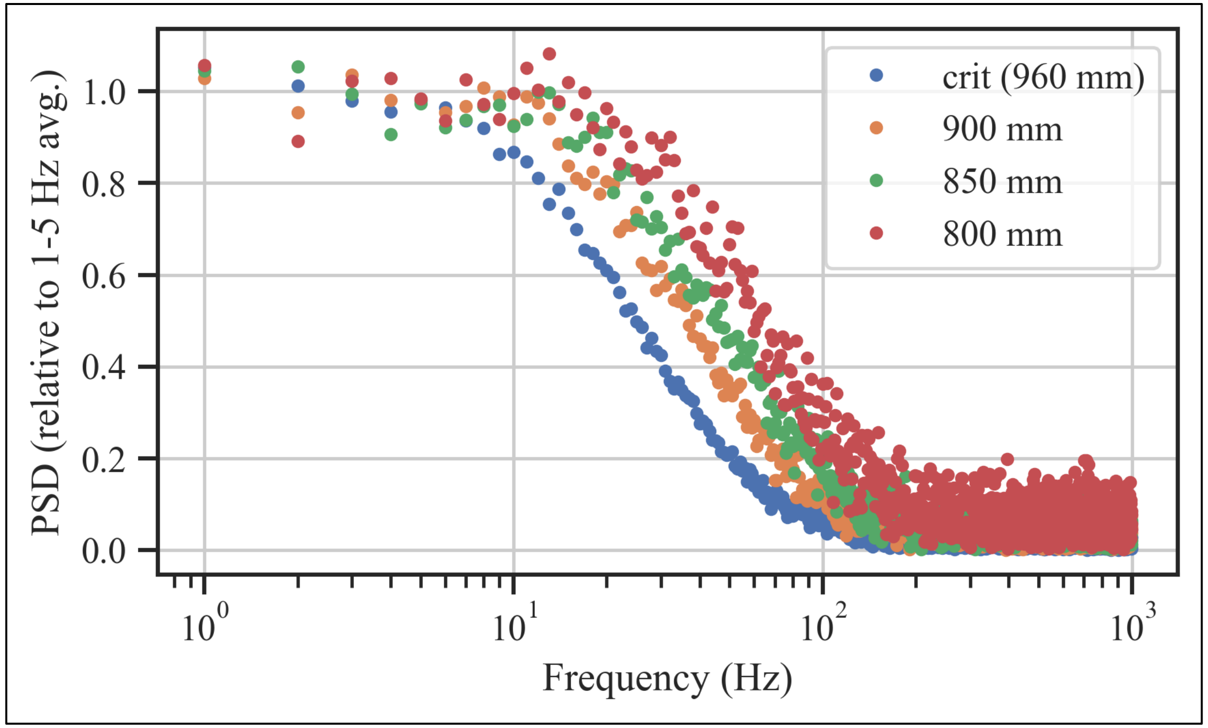


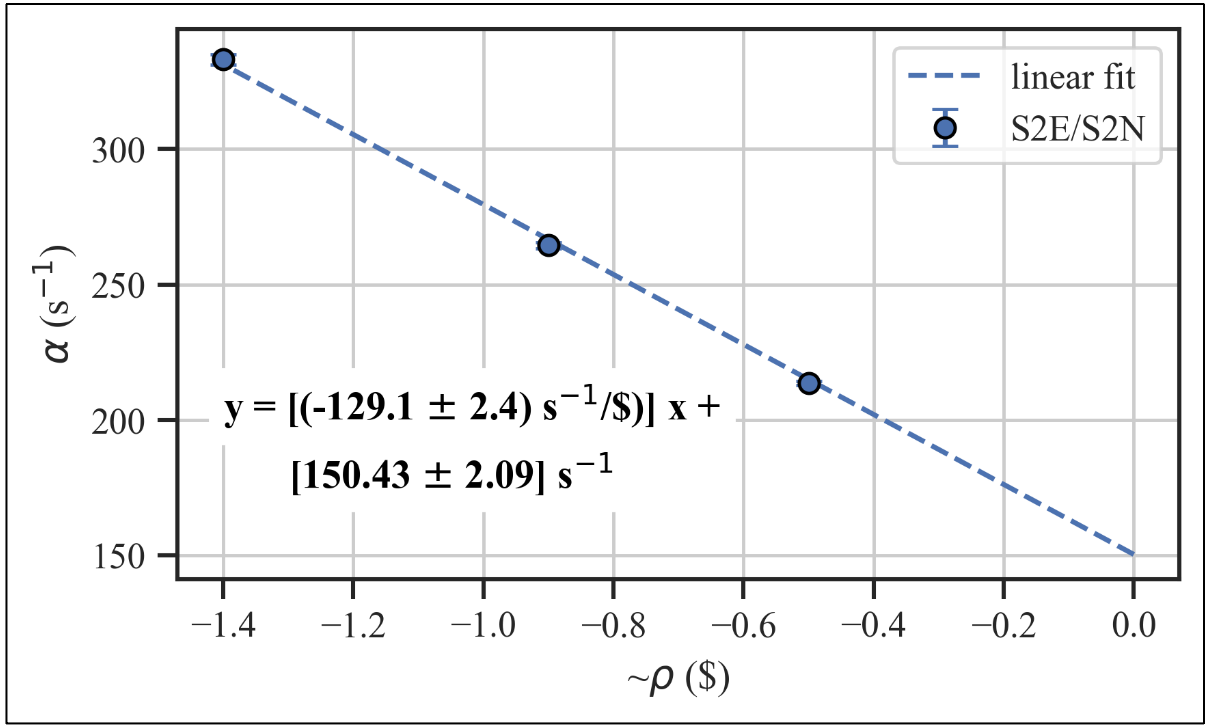
Technical Approach – Pulse-shape Discrimination

- One stilbene detector
- 20 cm from the edge of the core (in water moderator)
- Measuring for **120 minutes at 3 mW critical**
- Higher Tail over Total Ratio for neutron detections
- Neutrons are classified as upper blue band
- Gamma-rays are classified as lower red band
- Two distinct and separate bands
- Neutron band is approximately three orders of magnitude less than gamma band



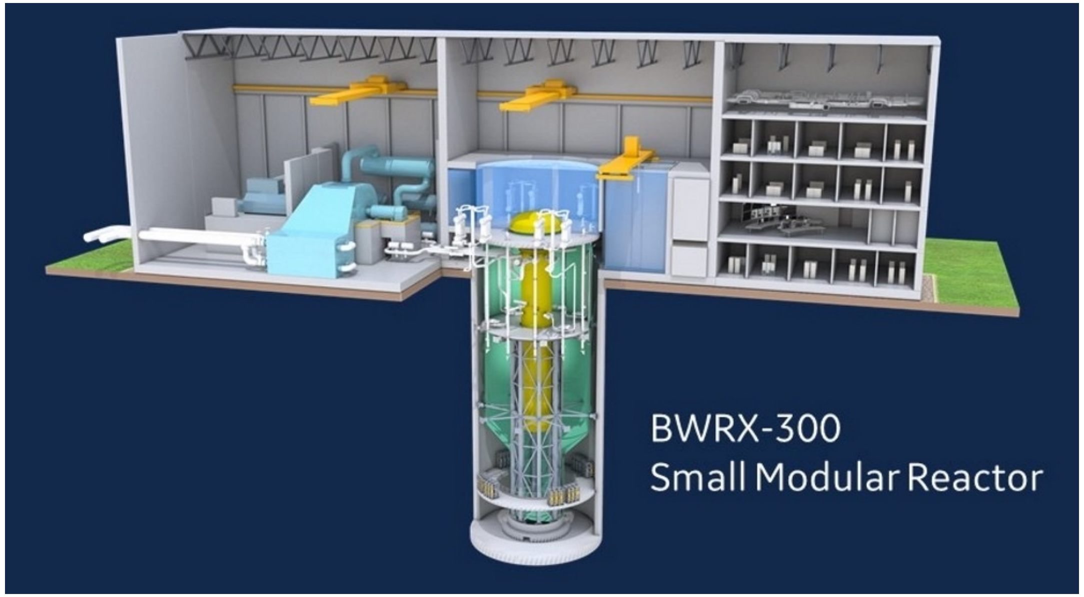
Results – Cohn-α





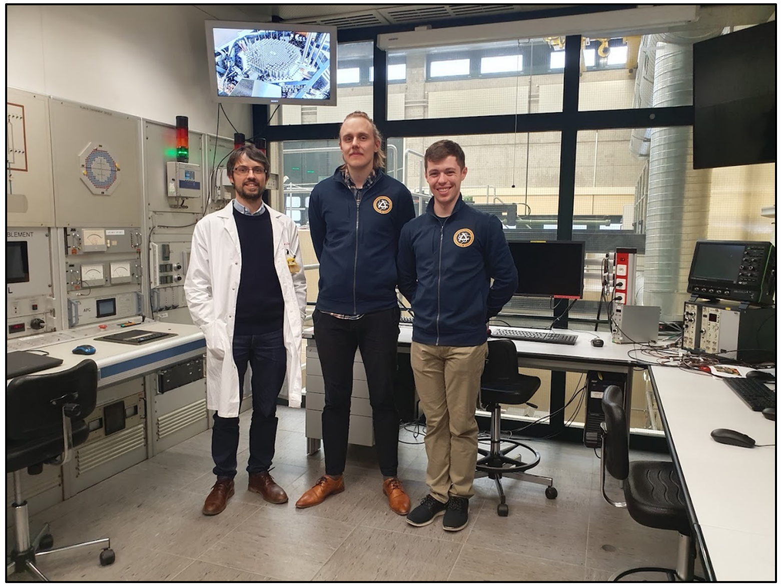
Expected Impact

- Distinguishable subcritical and critical fission chain kinetics provides additional modality for zero-power reactor monitoring
- Could be extended to low-power reactor regimes
  - Potentially small modular and microreactor designs
- Accurate estimates of α could also sense material defects and changes



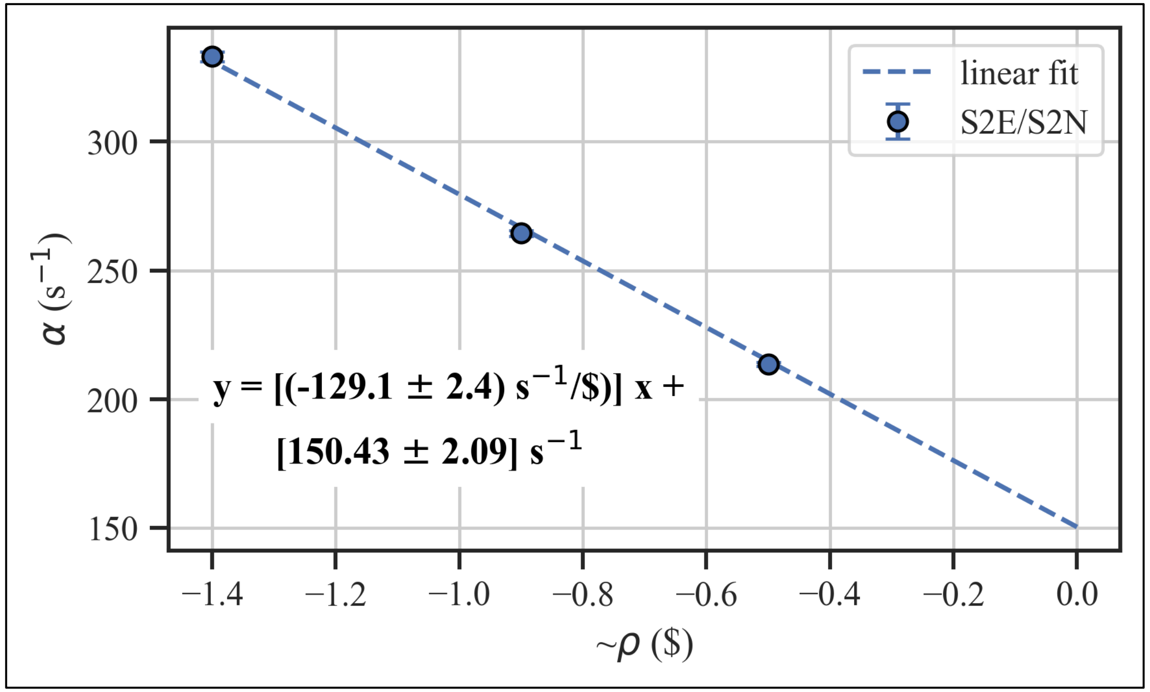
MTV Impact

- Work with Dr. Oskari Pakari, postdoc in our group, to connect with EPFL and CROCUS facility
- LANL NEN-2
  - Measurement of MUSIC Benchmark for fission chain kinetic analyses
  - Mentors: Jesson Hutchinson, Dr. Geordie McKenzie, Dr. Robert Weldon
  - Continuing collaboration on MUSIC as Graduate Research Assistant (Intern)
- Development of α calculation code-base with EPFL and NEN-2



Conclusion

- Precise subcritical estimates of the prompt neutron decay constant, α
- Allow for confirmation of reactor subcritical state
  - Without temporal analysis, could be mistaken for reactor at low power
- Sensitivity to α in subcritical and critical zero- and low-power regimes provides ability to
  - Monitor facility activity
  - Detect material defects in steady state operation



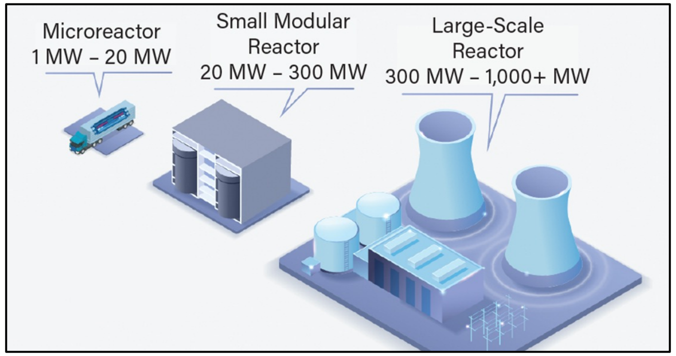
Next Steps

- Present continued CROCUS analysis at 2024 ANS PHYSOR (April 21-24)
- Replicated measured Cohn-α response in simulation (MCNP/SERPENT)
- Apply Cohn-α to MUSIC benchmark measurements
- Explore low-power regime and limits of measurements of α

ANS PHYSOR 2024
International Conference on Physics of Reactors

MCNP
MONTE CARLO N-PARTICLE

Serpent
a Continuous-energy Monte Carlo neutron and photon transport code



Acknowledgements

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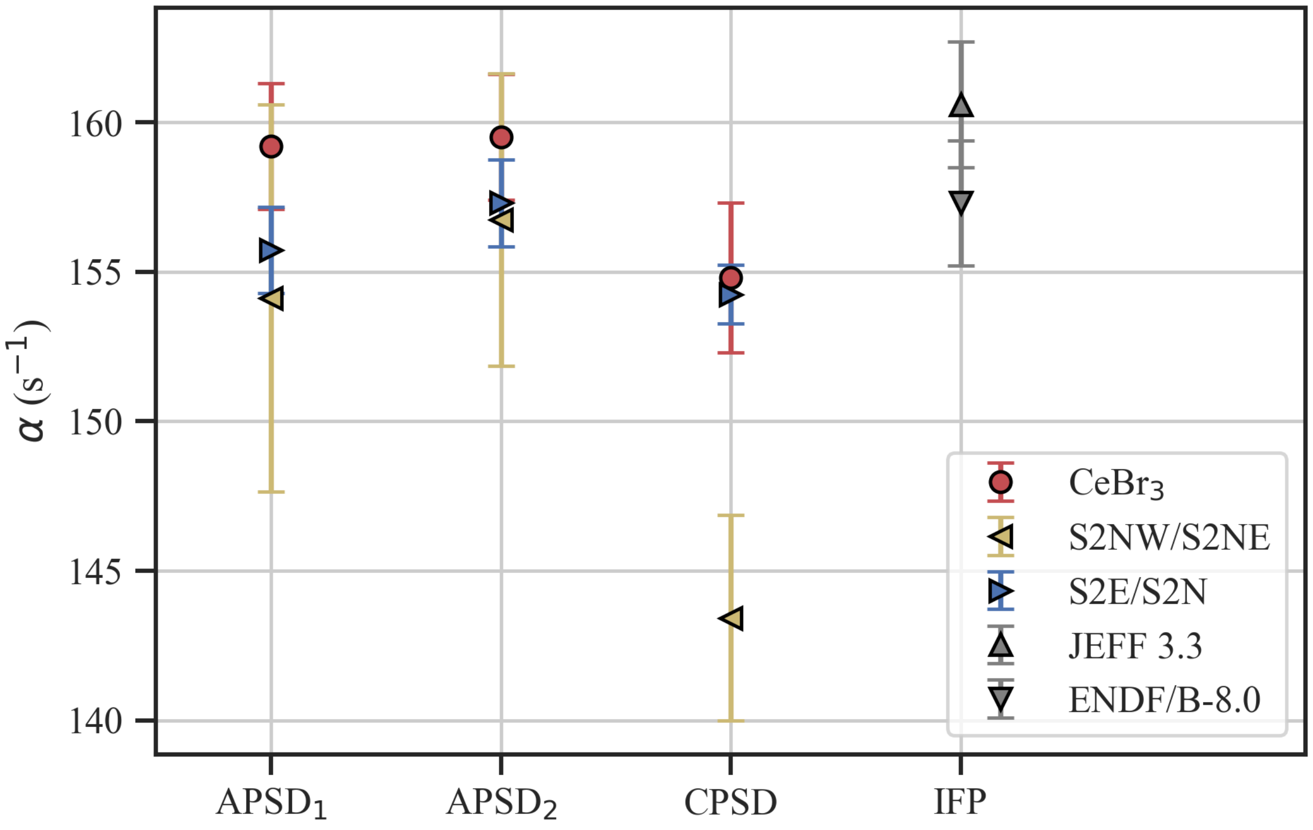
Additional Slides

Critical prompt neutron decay constant, α, estimates



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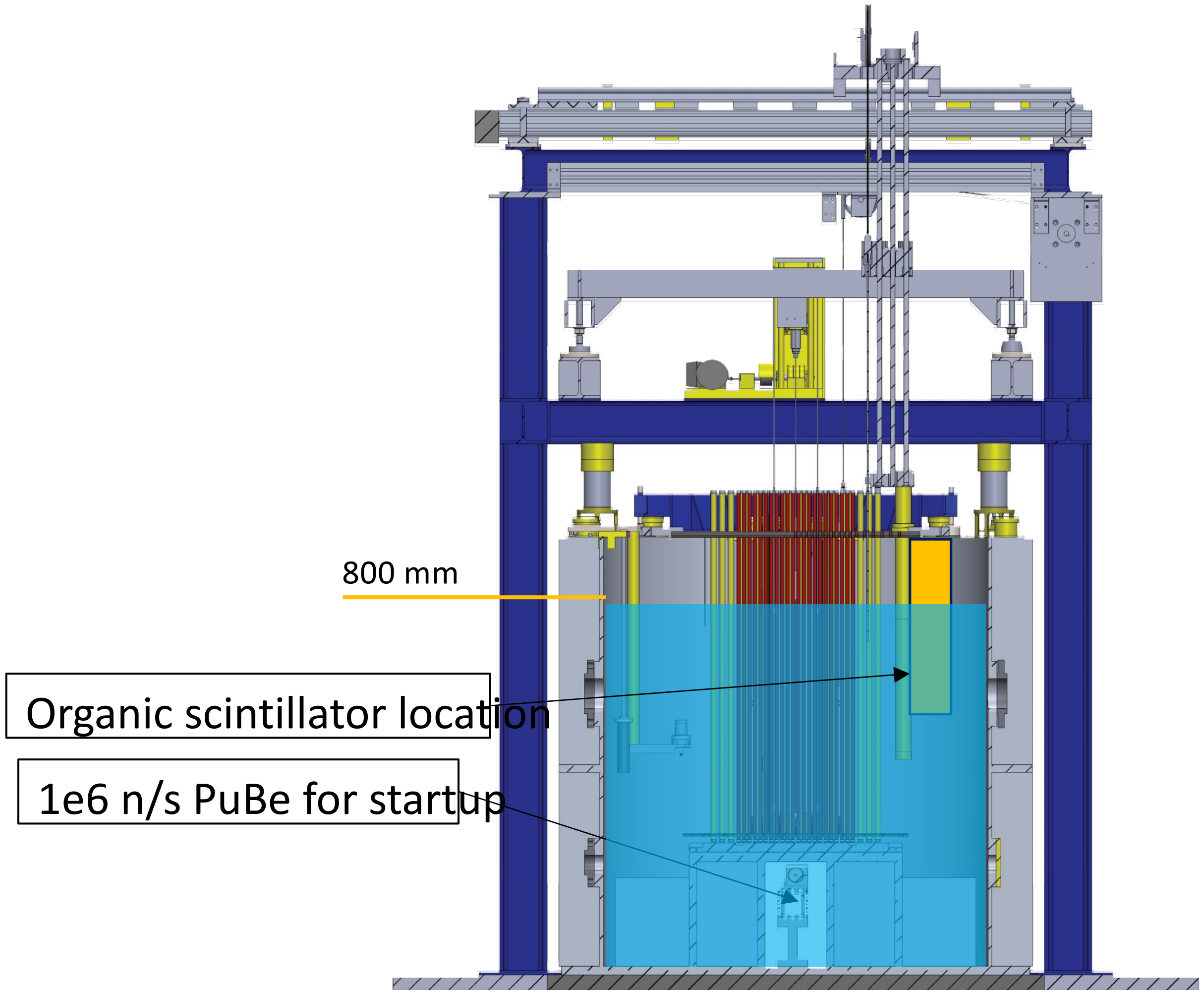
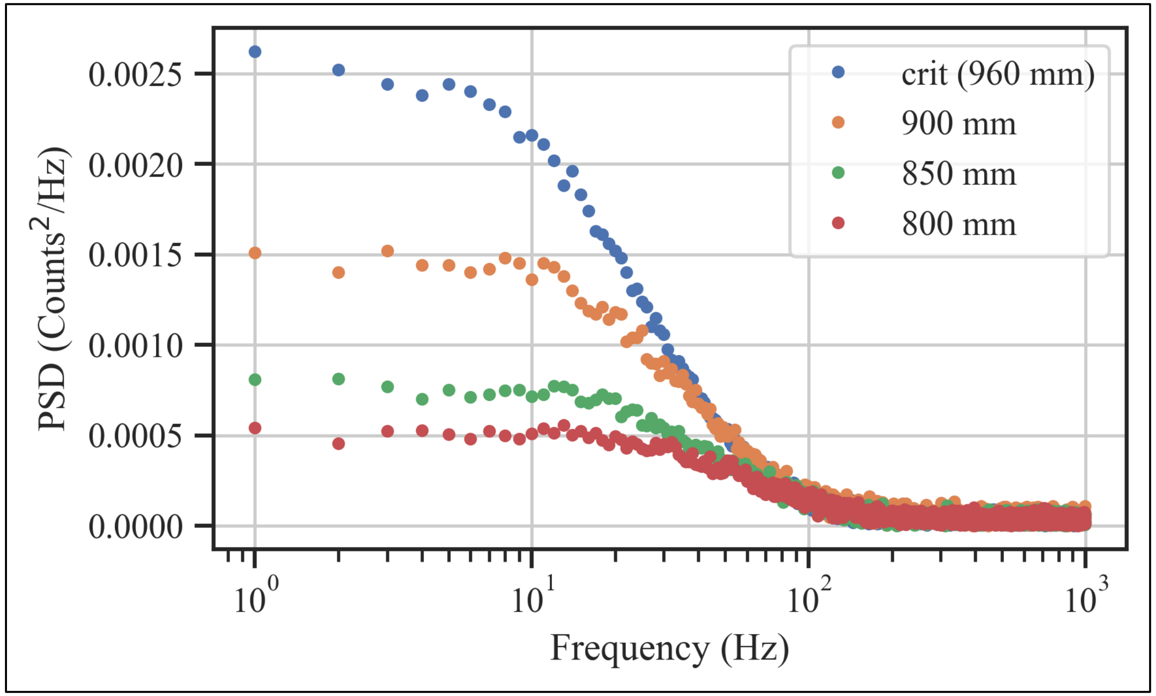
$$\alpha = \frac{\beta_{\mathrm{eff}} - \rho}{\Lambda}$$

Results: Cross power spectral density (CPSD), SE2/SN2



$$P_{xy}(\omega) = \frac{\epsilon_i \epsilon_j F D_\nu}{(\rho - \beta_{\text{eff}})^2} \frac{1}{1+\left(\frac{\omega}{\alpha}\right)^2} + \text{C}$$



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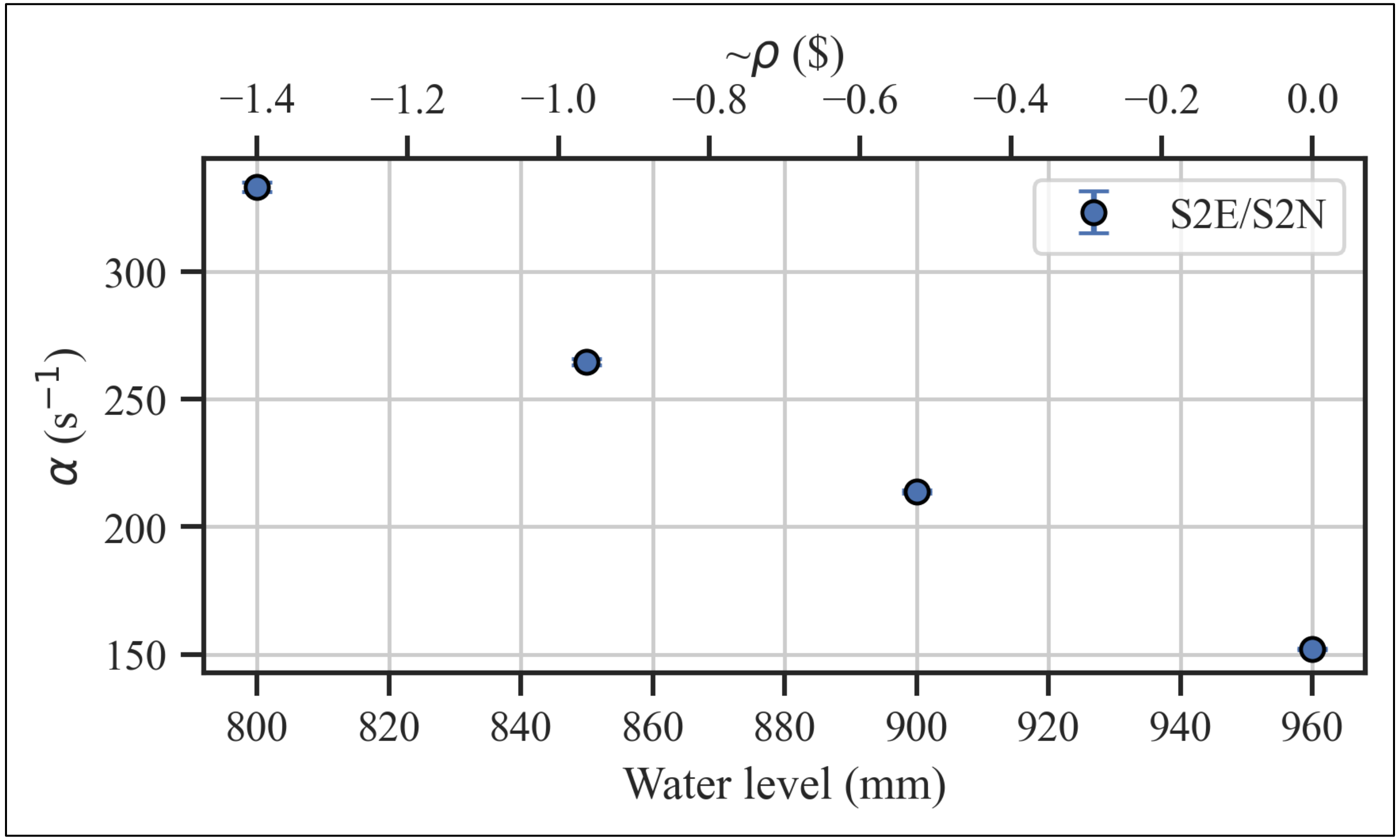


Water level (mm)	rho ($)^	alpha (s^(-1))	alpha_unc (s^(-1))
800	-1.4	333.01	1.98
850	-0.9	264.52	1.13
900	-0.5	213.63	0.67
960*	0	152.05	0.28

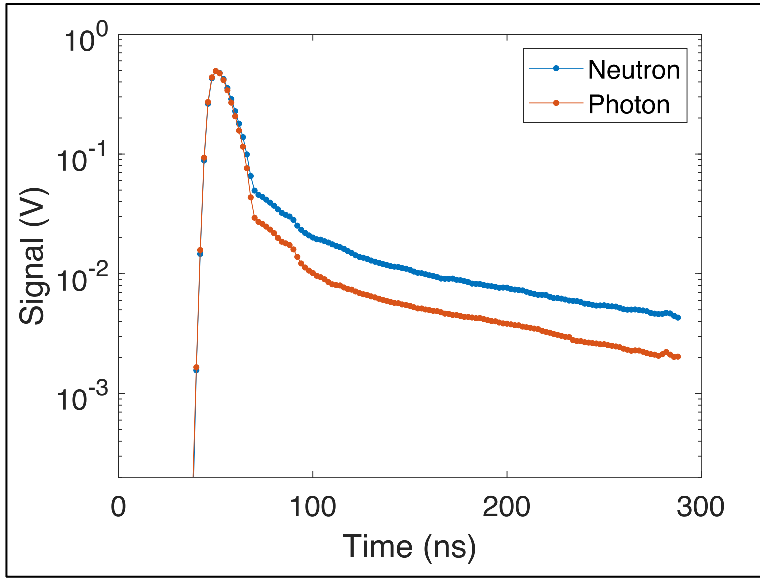
* = critical water level

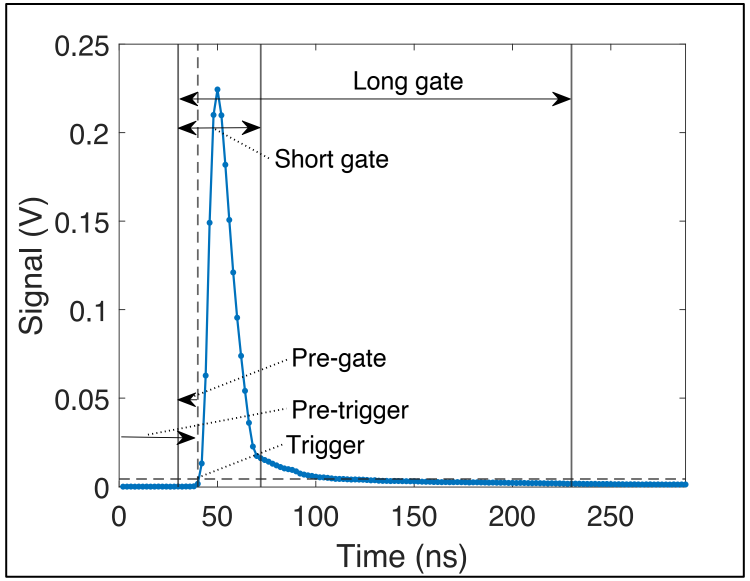
^ = Serpent 2 values

Data Analysis: Organic Scintillators

- Fine time resolution (< 1 nanosecond)
- Organic scintillators are dual particle sensitive
- Can detect photons. and neutrons simultaneously from fission events
- Quantify the ratio of prompt and delayed light output
  - $R = \frac{\text{long}-\text{short}}{\text{long}} = \frac{\text{tail}}{\text{total}}$

Incident Particle	Scatter Interaction	Free particle	Track length	Excitation States	Light Output
Gamma-ray	Compton	e^- (electron)	Long	Mainly singlet	Prompt
Neutron	Elastic	p^+ (proton)	Short	More triplet	Quenched and Delayed





Alpha Estimates from Previous Fission Chamber and $CeBr_3$