Neutron Pulsed Die-Away Experiments at LLNL

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Why PNDA for TSL Validation?

- Does not require fissile material
  - Non-nuclear facilities, reduced costs, fewer regulations, safer
- Very simple target shapes and compositions
  - Reduced uncertainties in benchmarks
  - Reduced material costs
  - Easy to change temperature
- Only sensitive to absorption and scattering of target medium
  - Reduces uncertainties from other nuclear data and compensating effects
  - Tune target size to vary effect of absorption vs. scattering
- Well conducted experiments have uncertainties of 0.1% - 0.5%

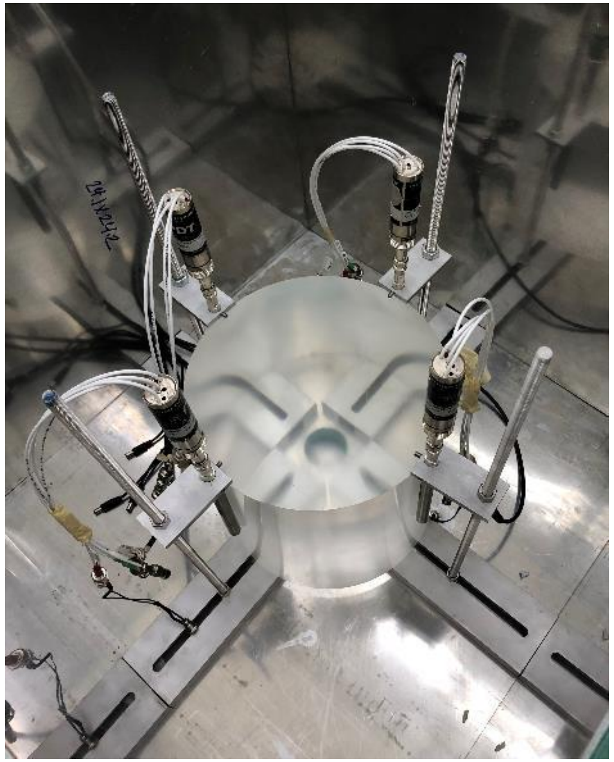
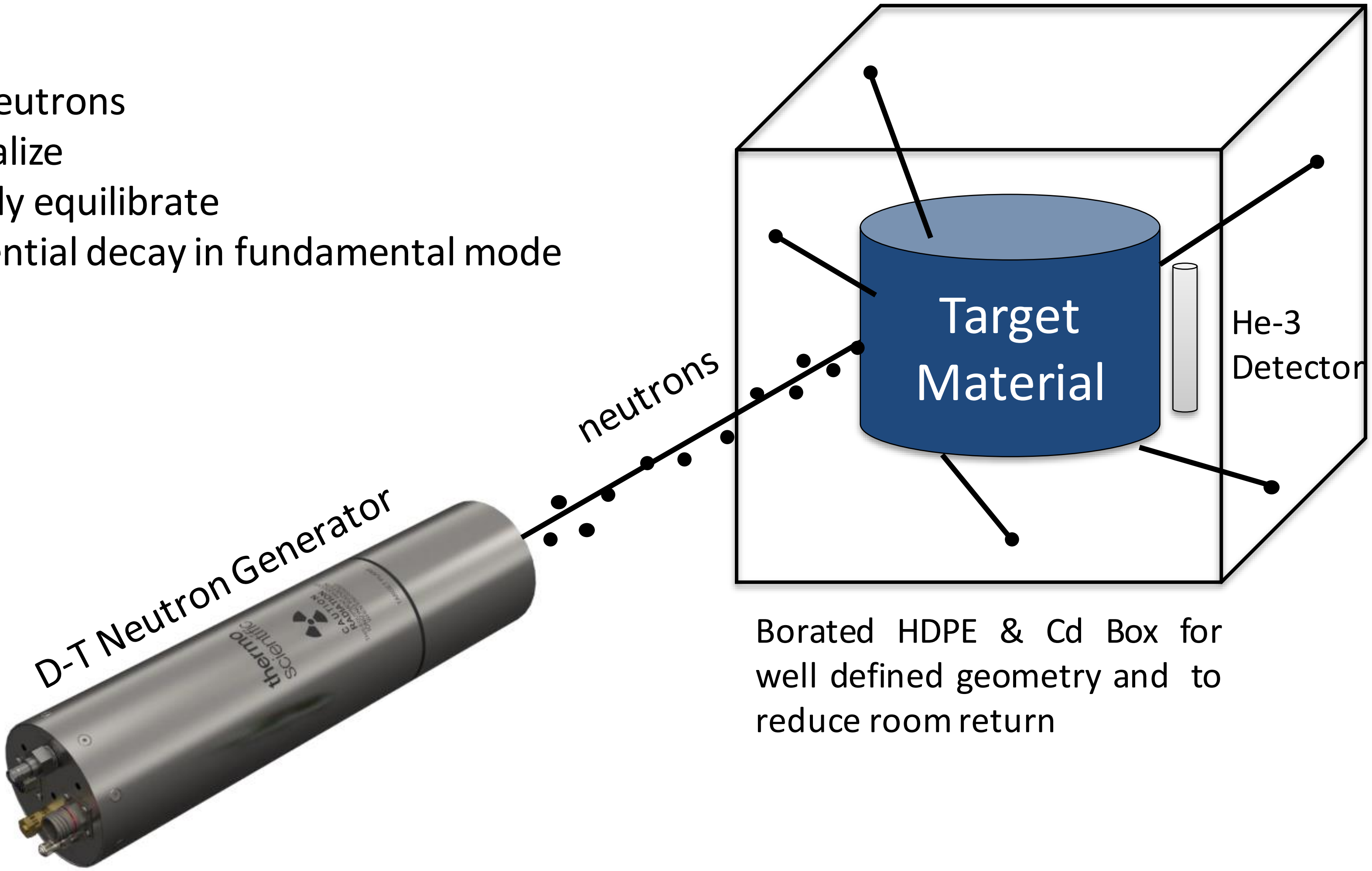


Figure: Measurement of Lucite target

Pulsed Neutron Die Away Experiments

1. Inject Pulse of Neutrons
2. Neutrons thermalize
3. Neutrons spatially equilibrate
4. Measure exponential decay in fundamental mode



Borated HDPE & Cd Box for well defined geometry and to reduce room return

Integral Parameter: α eigenvalue

$$\phi(t) = \phi_0 \exp(-\alpha t) + R$$

$$\alpha = \overline{v\Sigma_a} + \overline{vD_0}\, B_0^2 - CB_0^4 + \cdots$$

- α: flux decay-time eigenvalue [s^{-1}]
- D_0 [cm^2s^{-1}] is the asymptotic diffusion coefficient
- C: “cooling coefficient” [cm^4s^{-1}]
- B_0^2: geometric Buckling [cm^{-2}]
- *v* thermal neutron velocity (2.2 x 10^5 cm/s)
- Σ_a macroscopic absorption cross section [cm^{-1}]

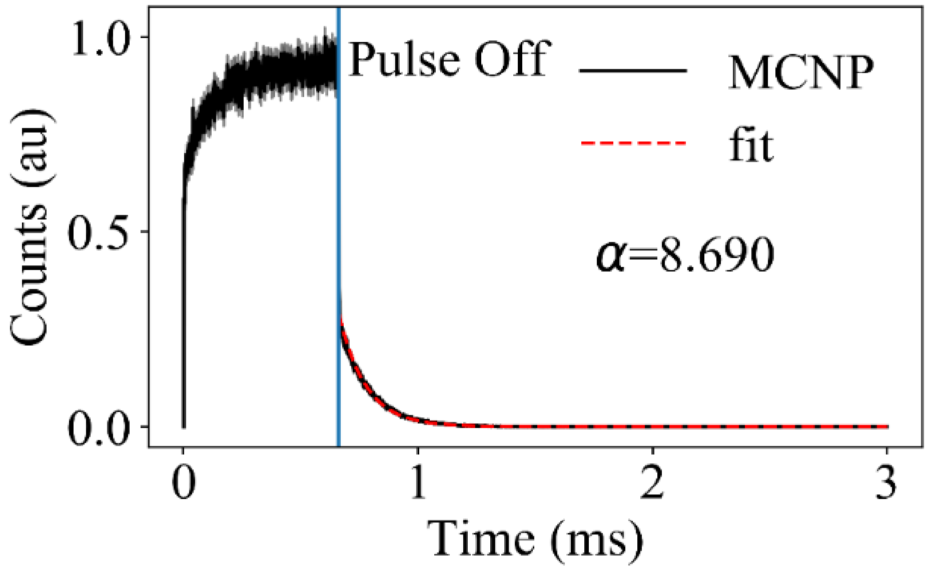


Figure: Example of pulsed-die-away curve modeled in MCNP

Sensitivity to TSLs

- Example: Historical water experiment in cylindrical geometry
  - A. Bracci & C. Coceva, "The diffusion parameters of thermal neutrons in water." *Il Nuovo Cimento*, **4** (1956)

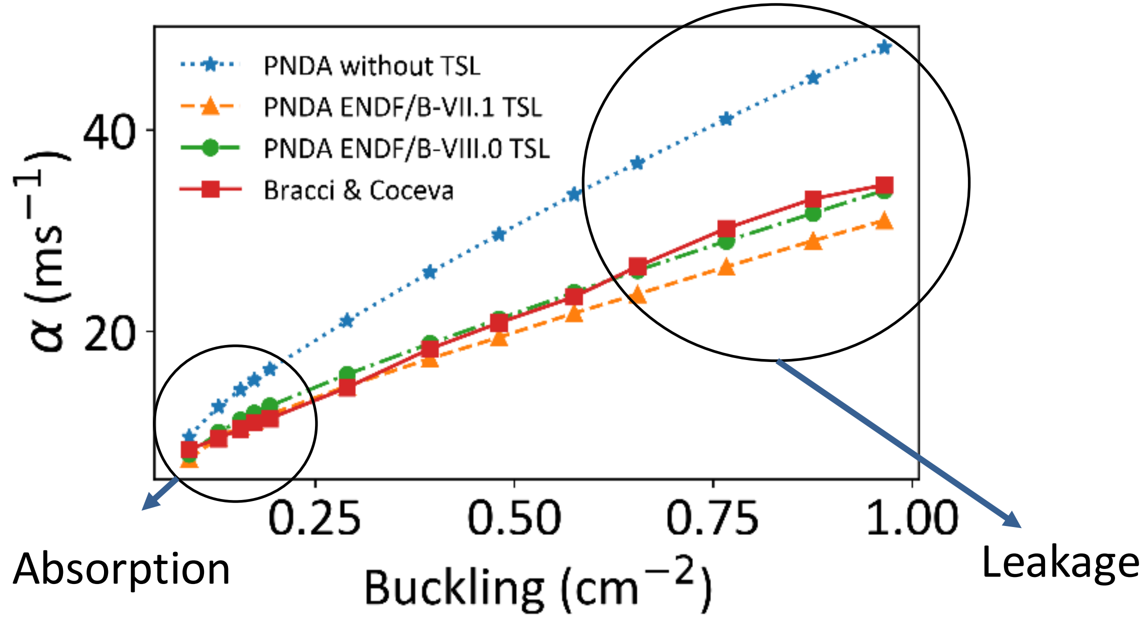


Figure: α vs. Buckling curve for experimental and simulated data

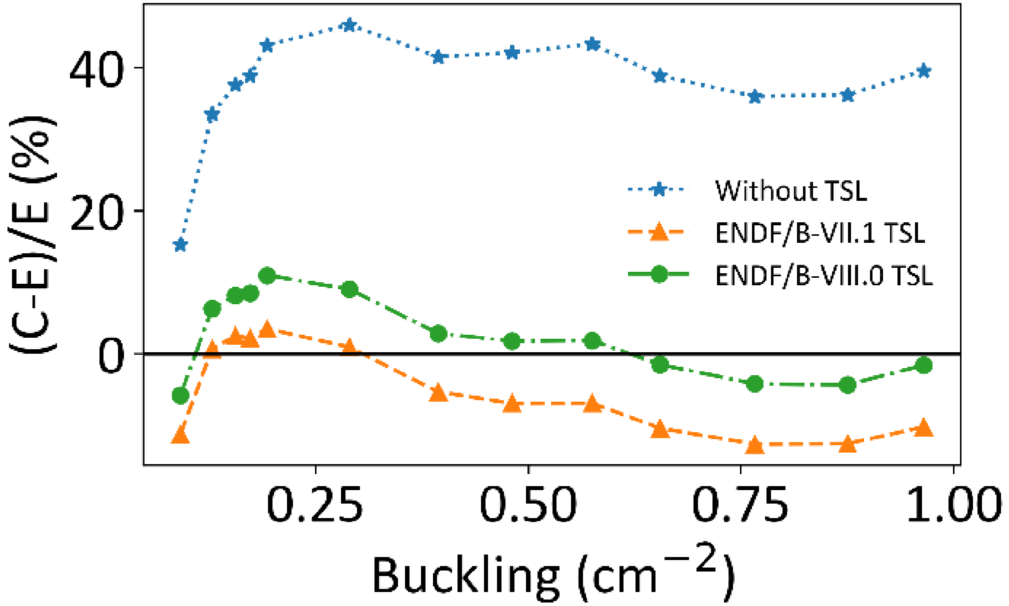


Figure: Bias of simulations without TSLs, with ENDF/B-VII.1, and with ENDF/B-VIII.0 TSLs

Experimental Parameters

- P383 D-T neutron generator
  - Maximum yield of 5 x 10^8 neutrons/s
  - Minimum frequency of 150 Hz
  - Minimum pulse width of 10 µs
- Four He-3 tubes
  - Operated at 1100 V
  - 50 ns pulse width
- Time-tagging electronics
  - Provides time stamps of detected neutrons, generator pulse
  - ALMM (100 ns resolution)
- Box to limit room return
  - Borated high-density polyethylene
  - Cadmium lining

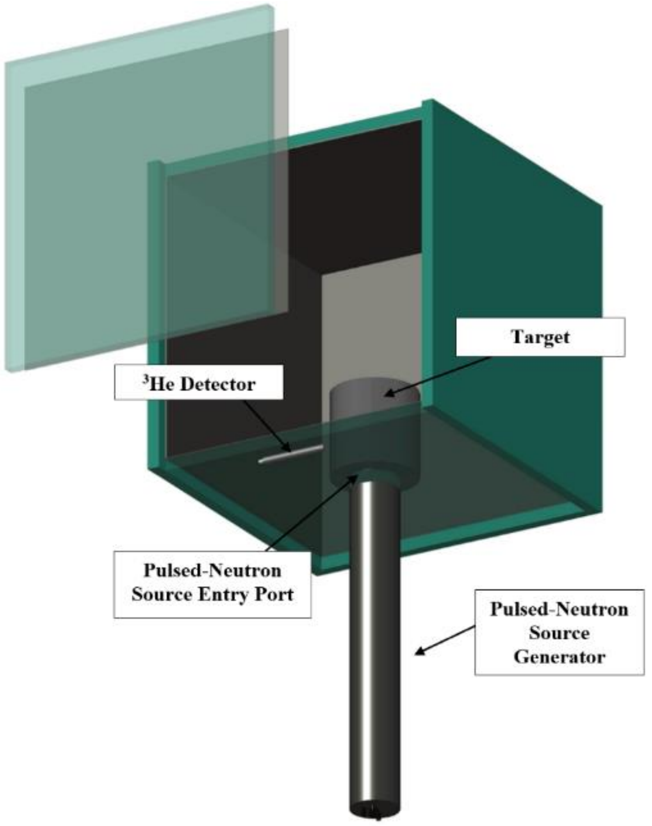
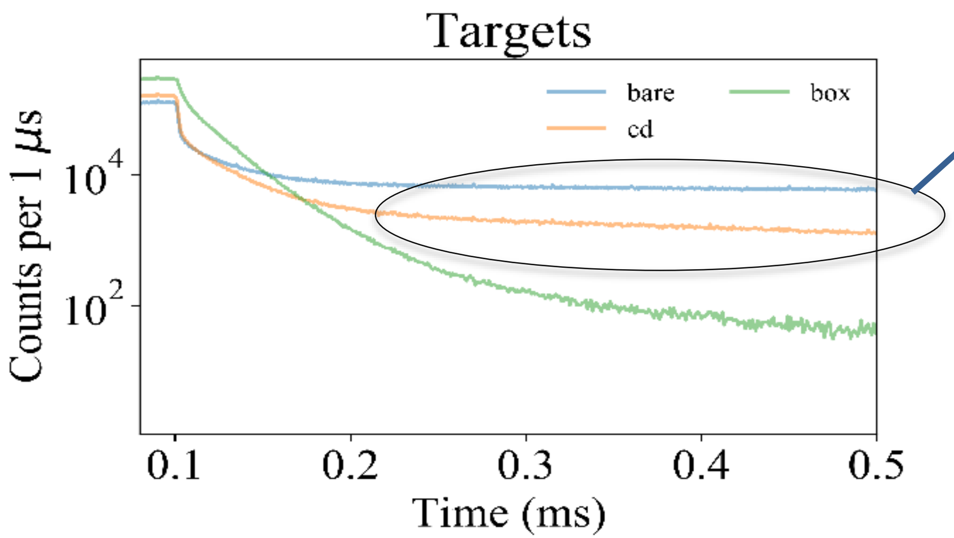


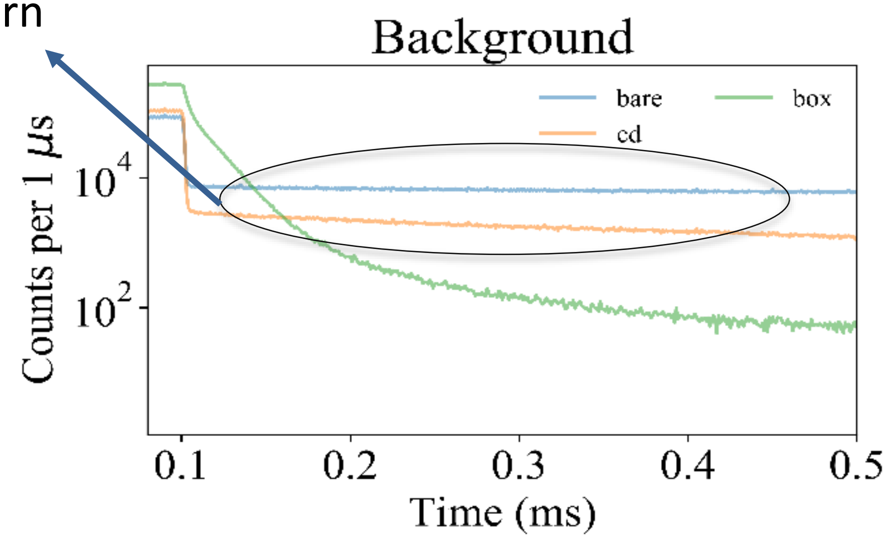
Figure: AutoCAD rendering of PNDA

Effect of Shielding Box

Measurements in Low-Scatter Facility



Room Return



Sensitivity Depends on Target Size

- Small targets (large Bucklings) are more sensitive to scattering
- Large targets (small Bucklings) are more sensitive to absorption

$$B_0^2 = \left(\frac{\pi}{H + 2\delta}\right)^2 + \left(\frac{2.405}{R + \delta}\right)^2$$

$$\alpha = \underbrace{\overline{v\Sigma_a}}_{\text{Absorption}} + \underbrace{\overline{vD_0}\, B_0^2 - CB_0^4}_{\text{Scattering}}$$

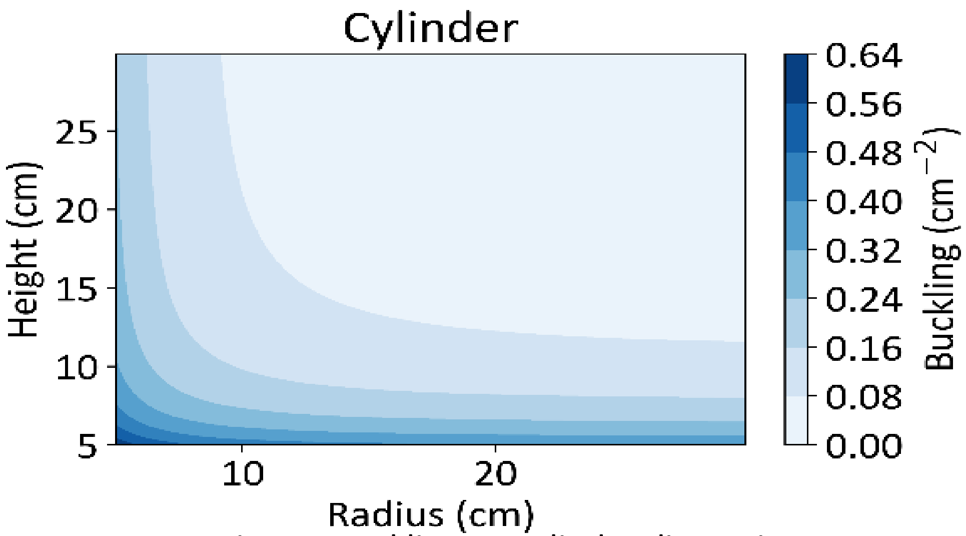


Figure: Buckling vs. cylinder dimensions

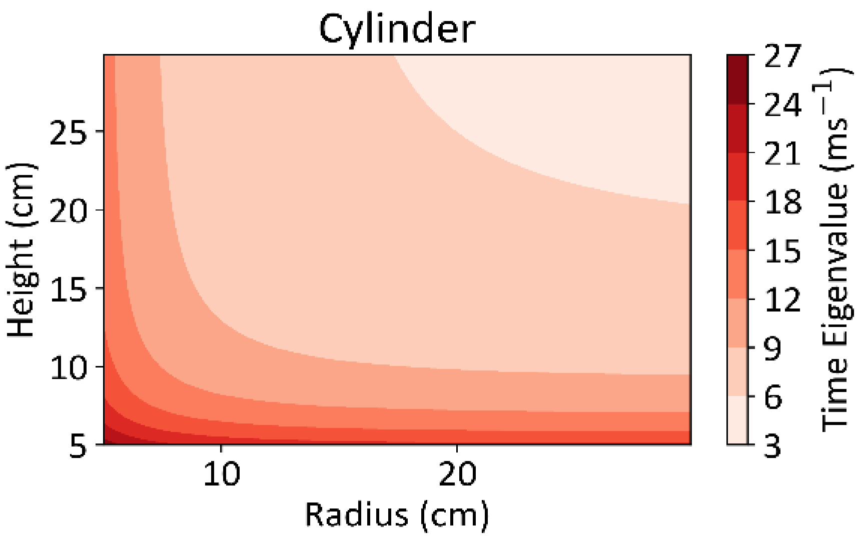
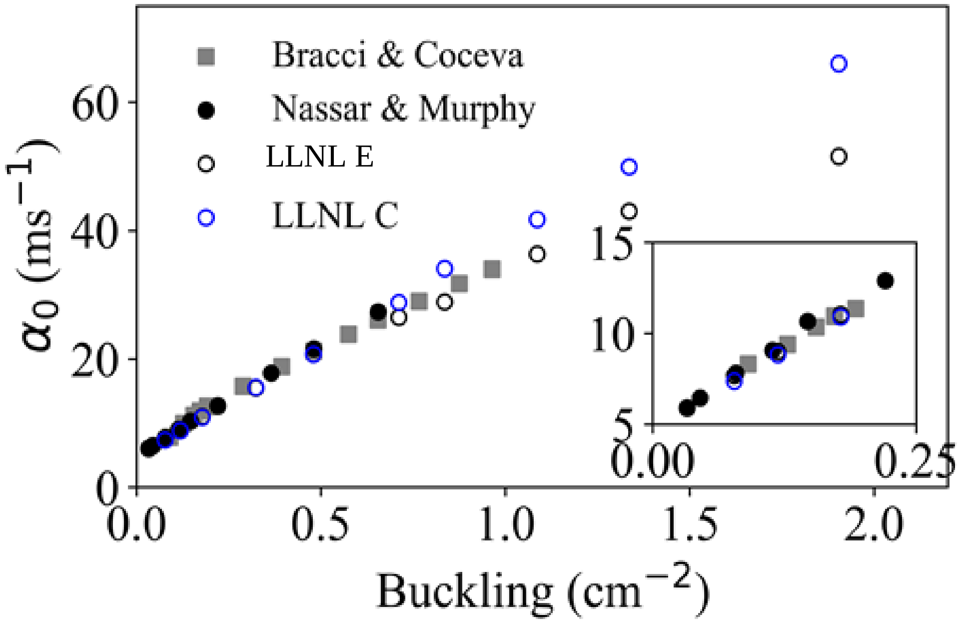
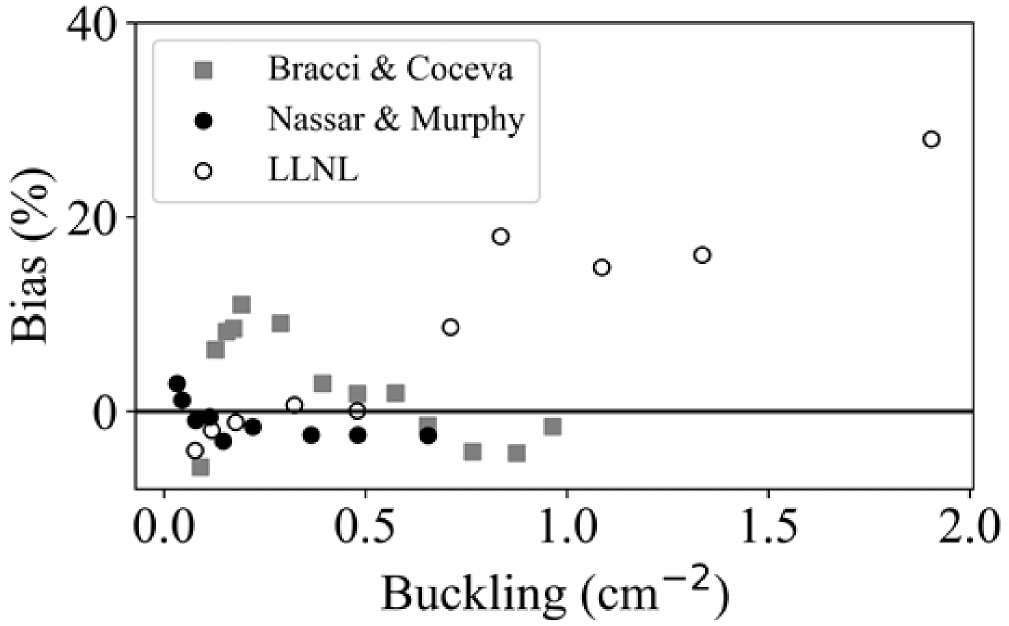


Figure: α vs. cylinder dimensions

H_2O Validation & Comparison to Literature



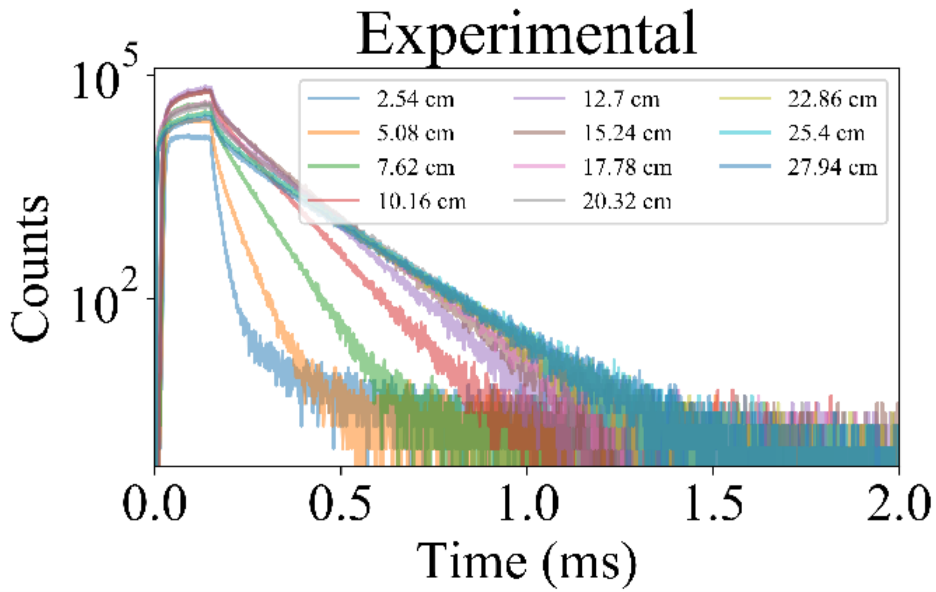
$$\alpha = \overline{v\Sigma_a} + B_0^2 D_0 - C B_0^4$$

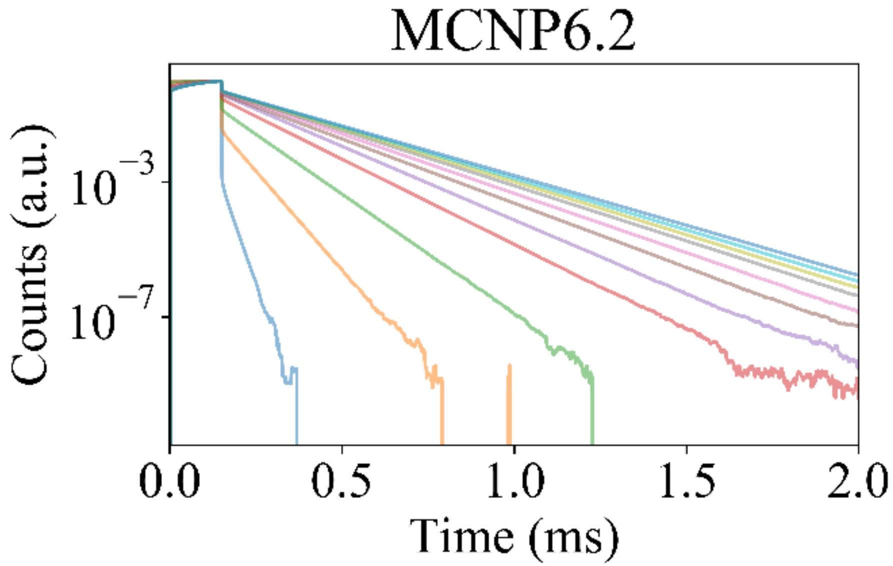


	(cm^2-s^{-1})	D_0 (cm^2-s^{-1})	C (cm^4-s^{-1})
LLNL Experiment	4.99 ± 0.49	34.24 ± 1.36	5.03 ± 0.71
LLNL Calculation	4.25 ± 0.34	36.84 ± 0.94	2.25 ± 0.49
Bracci & Coceva	4.87 ± 0.33	35.50 ± 1.49	4.23 ± 1.64
Nassar & Murphy	4.68 ± 0.15	39.10 ± 1.31	5.43 ± 1.94

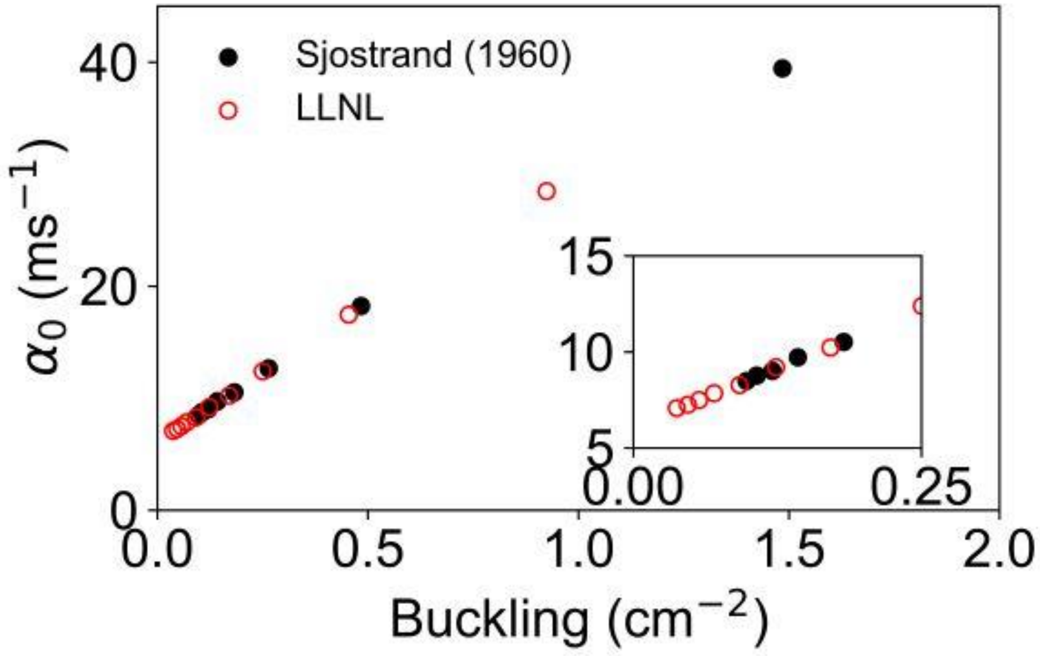
HDPE Die-Away Curves

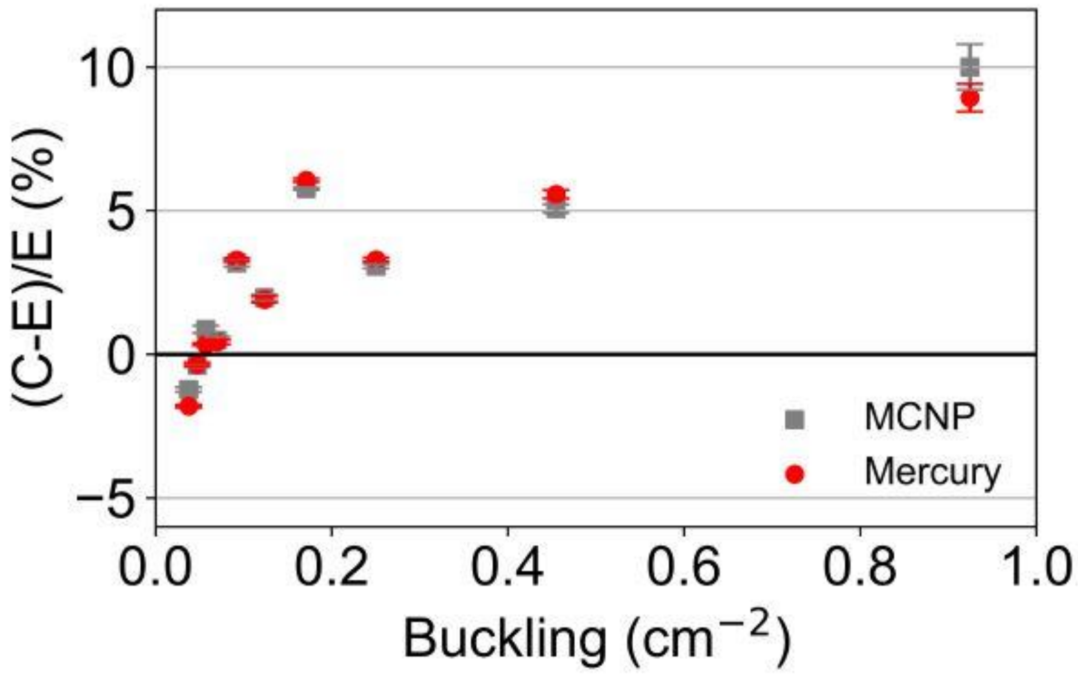
Figure: HDPE cylinders used in PNDA experiment





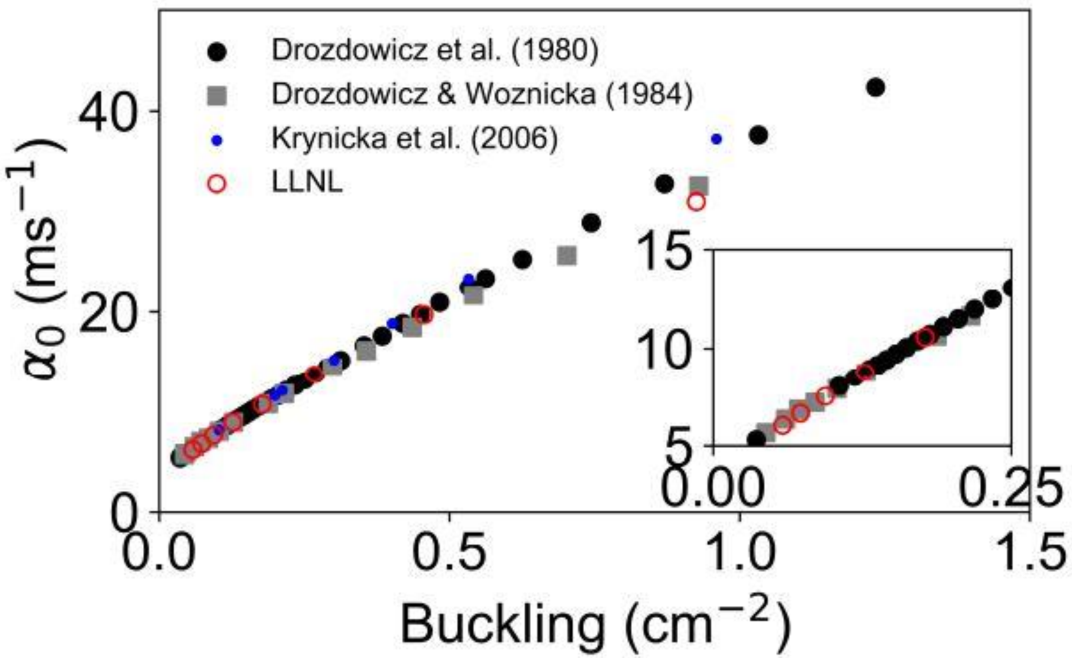
First HDPE Validation

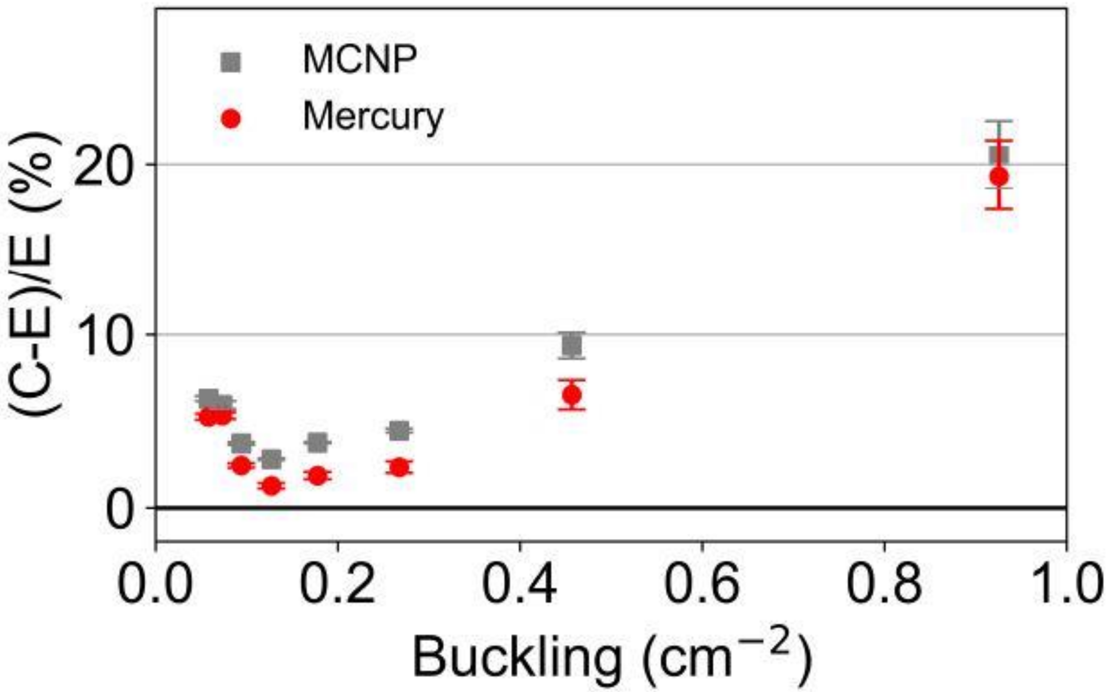




- General trend of increasing bias with smaller sampler size (larger buckling)

Lucite Results
Polymethyl Methacrylate





Drozdowicz, Krzysztof, et al. "Thermal neutron diffusion parameters for plexiglass." *Nuclear Instruments and Methods* 178.2-3 (1980): 513-516.

Krynicka, Ewa, et al. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 251.1 (2006): 19-26.

PNDA's Advantages/Role in Nuclear Data Validations

- Offers a cost-effective experiment for an integral benchmark.
- Ability to focus on specific cross section data validation including thermal neutron absorption and thermal scattering laws.
- Low experimental uncertainty making it an excellent benchmark candidate.
- Easily tunable. Temperature dependent cross section validation by cooling or heating up targets.

Questions, Comments, Discussion

- **References:**

  - G. von Dardel and N. G. Sjostrand, "Diffusion Parameters of Thermal Neutrons in Water," Physical Review, vol. 96, no. 5, pp. 1245-1249, 1954.
  - J. Holmes, M. Zerkle and D. Heinrichs, "Benchmarking a first-principles thermal neutron scattering law for water ice with a diffusion experiment," *EPJ Web of Conferences,* vol. 146, p. 13004, 2017.
  - J. Holmes, M. Zerkle and A. Hawari, "Validation of Thermal Scattering Laws for Light Water at Elevated Temperatures with Diffusion Experiments," in *PHYSOR 2020: Transition to a Scalable Nuclear Future*, Cambridge, United Kingdom, 2020.
  - D. Siefman, E. Heckmaier, W. Zwyiec, D. Heinrichs, "IER-501 CED-1: Preliminary Design of a New Pulsed-Neutron Die-Away Experimental Testbed for Thermal Scattering Law Benchmarks (PNDA)," *Lawrence Livermore National Laboratory*, LLNL-TR-820718, 2021

Interpretation of Results

- Need to select data to include in the fit
- Too early data:
  - Flux is not fully thermalized or in fundamental spatial mode
- Too late data:
  - Noisy (room return) and larger uncertainty in α

$$\phi_{fit}(t) = \phi_0 \exp(-\alpha t) + R$$

$$\chi^2 = \sum_i \frac{\left(\phi_{data}^{(i)} - \phi_{fit}^{(i)}\right)^2}{\sigma_{data}^2}$$

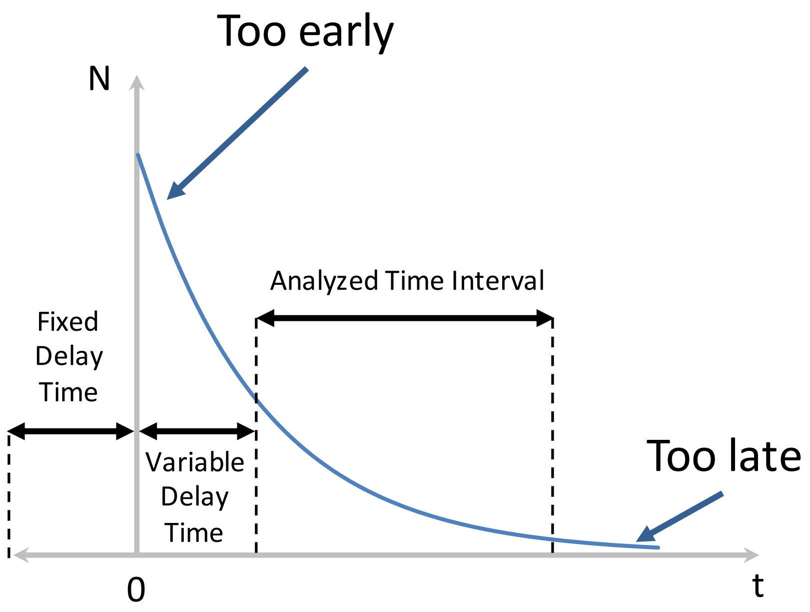
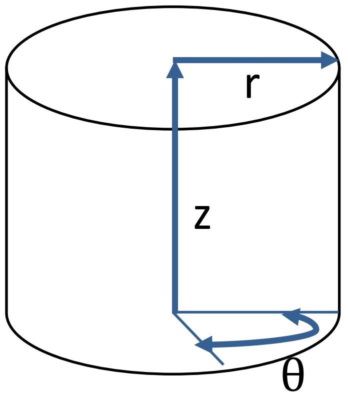


Figure: Position of the analyzed time interval

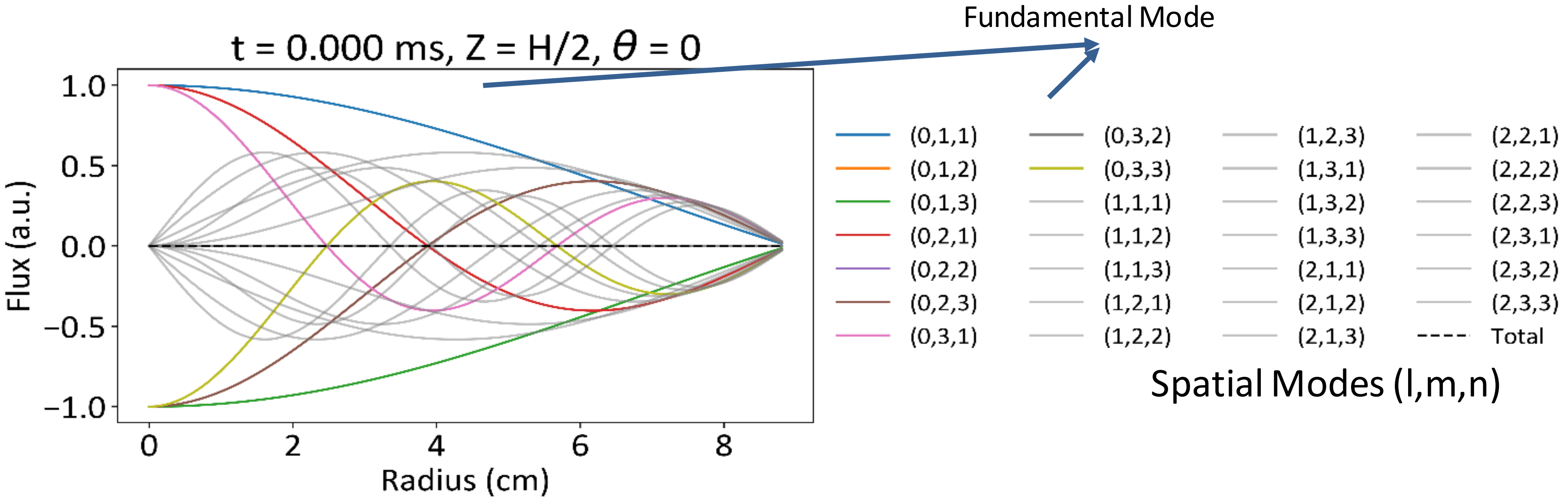
Decay to Fundamental Mode

Large Cylindrical Sample

$$\phi(r,\theta,z,t) = \sum_{l,m,n} C_{l,m,n} \sin\left(\frac{n\pi}{H} z\right) J_l(a_{l,n} r) \cos l\theta \exp\left[-\underbrace{\left(\overline{v\Sigma_a} + \overline{vD_0}\, B^2_{n,m,l}\right)}_{\alpha_{l,m,n}} t\right]$$



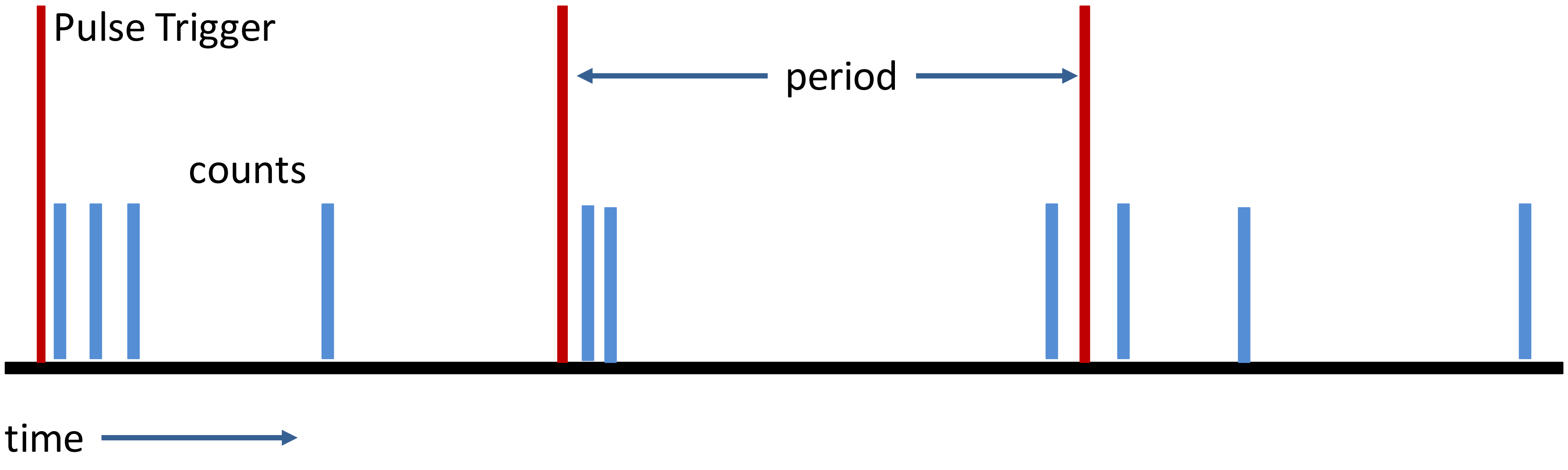
Focusing only on modes of Bessel function:



Spatial Modes (l,m,n)

Algorithm

- Neutron counts and generator trigger recorded as list mode data
- Few counts per pulse, but many pulses allows to reconstruct die away curve
- Trigger is initiating event, $t_{trigger}$
- Sum counts in bins on die away curve as $t_{tag} - t_{trigger}$ in histogram



Algorithm: Sum pulse counts to construct curve