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Title: Effects of Delayed Emission on Gamma Noise Methods

Author(s): Kostelac, Cole Michael
Hutchinson, Jesson D.
Cutler, Theresa Elizabeth
Alajo, Ayodeji B

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Effects of Delayed Emission on Gamma Noise Methods

Cole Kostelac[1,2], Jesson Hutchinson[1], Theresa Cutler[1], Ayodeji Alajo[2]

[1] Los Alamos National Laboratory
[2] Missouri University of Science and Technology

July 7th 2026

LA-UR-26-

33nd International Meeting On Reactor Noise

6th-8th July 2026 Grenoble, France

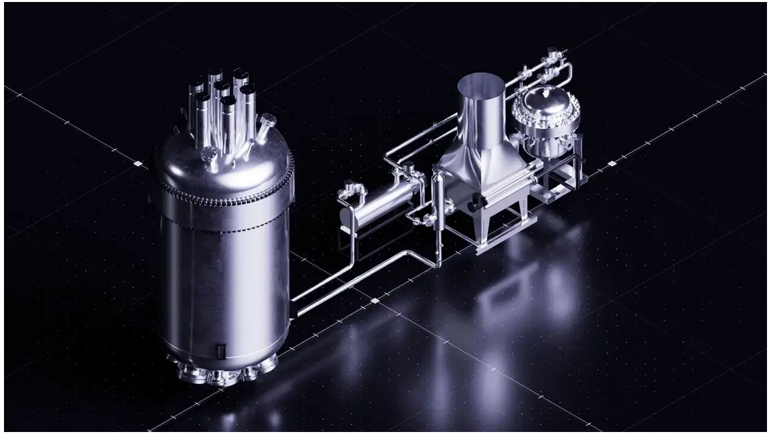
Reforming Nuclear Reactor Testing at the Department of Energy

Executive Order 14301

- On May 23rd, 2025, EO 14301 was signed and directed the Department of Energy to establish a new test reactor program.
  - *“The Secretary shall approve <u>at least three reactors</u> pursuant to this pilot program with the goal of <u>achieving criticality</u> in each of the three reactors by <u>July 4, 2026</u>.”*

Valar Atomics

- Valar Atomics is private company pursuing a small prismatic block graphite moderated, TRISO fueled, helium cooled high temperature gas reactor (HTGR) design.
- In August 2025 Valar Atomics was selected by the DOE to partake in the new test reactor program.

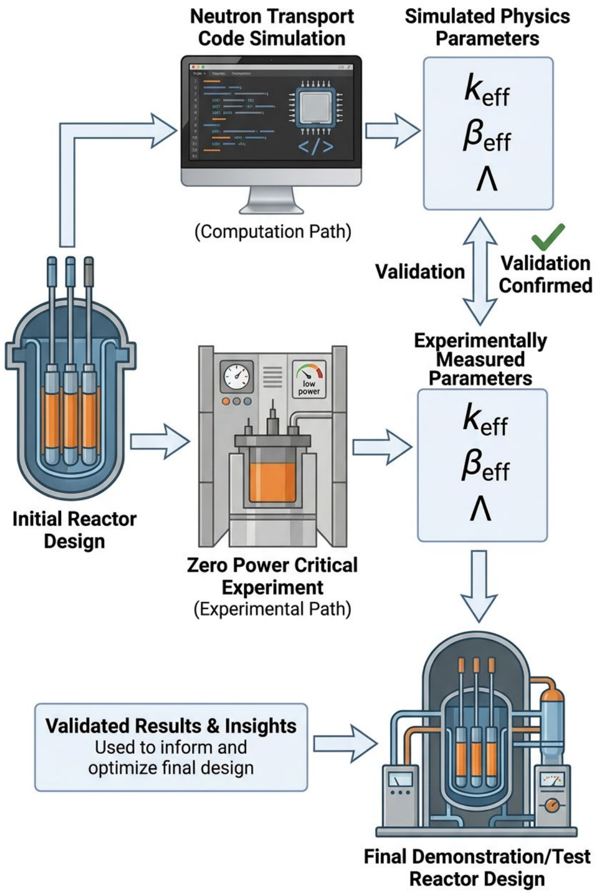


VALAR ATOMICS

Project NOVA

Los Alamos Collaboration with Valar Atomics

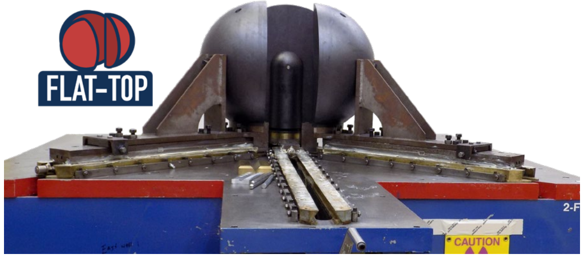
- Prior to building their test reactor, it was important to initially validate Valar's modeling techniques.
- A representative zero power critical experiment reflecting their core design was conducted at the National Criticality Experiments Research Center (NCERC) by Los Alamos National Laboratory, utilizing their graphite, fuel, control components, and burnable absorbers.



National Criticality Experiments Research Center

- NCERC is the sole general purpose criticality experiments facility in the United States.
- Operated by LANL, it is in the Device Assembly Facility at the Nevada National Security Site.

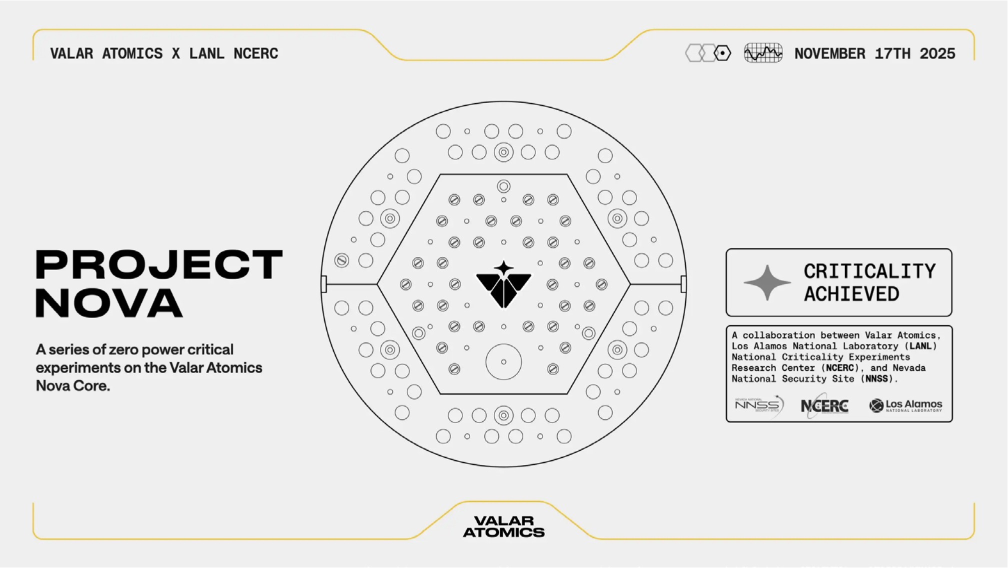
- Criticality Experiments
- Reactor Physics
- Dosimetry
- Detector R&D
- Criticality Safety



Project NOVA

Los Alamos Collaboration with Valar Atomics

- On November 17th, 2025 the NOVA core was first taken critical at NCERC.
- Three additional weeks of critical and subcritical critical configurations were made.
  - Neutron and gamma noise measurements were made of the system to understand its kinetic behavior.



Project NOVA

Los Alamos Collaboration with Valar Atomics

Nuclear Engineering International

Valar’s NOVA Core hits first criticality

NOVA Core, built by Valar Atomics, achieved zero-power criticality at LANL's National Criticality Experiments Research Center.

Dec 11, 2025

World Nuclear News

Valar Atomics project achieves early criticality milestone

The company said its NOVA Core achieved zero-power criticality at LANL's National Criticality Experiments Research Center on 17 November.

Nov 21, 2025

WIRED

Valar Atomics Says It’s the First Nuclear Startup to Achieve Criticality

A Trump administration pilot program aims for three nuclear startups to reach a key milestone by July 4, 2026. Valar Atomics says it's the...

Nov 17, 2025

Interesting Engineering

US startup hits key nuclear milestone with help from Los Alamos lab

Valar Atomics achieves criticality, marking the first fission reaction by a U.S. nuclear startup with DOE lab support.

Nov 18, 2025

Ward 250 Test Reactor

- Data obtained from Project NOVA was used to inform the final modeling and construction of Valar's Ward 250 test reactor in Utah.

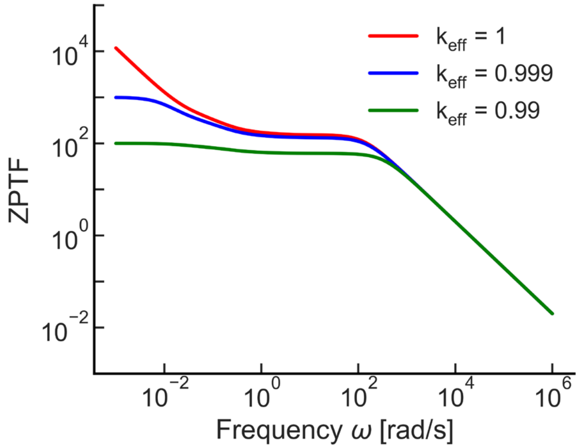
Ward 250 Test Reactor

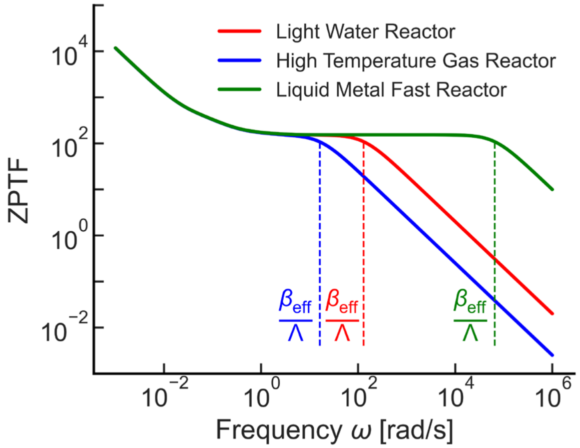
- On June 18th, 2026, Ward 250 achieved initial zero-power criticality.
- On June 24st, 2026, full power (100 kW_{th}) was achieved.

Project NOVA

Neutron and Gamma Noise for Zero Power Physics Testing

- Frequency domain microscopic noise methods (Cohn-α) allow for the experimental measurement of the Zero Power Reactor Transfer Function (ZPTF)
- Useful for determining subcriticality and reactor kinetics parameters.





Gamma Noise

- Typically, gamma noise data is fit to the neutron noise equations.
- Literature shows good agreement between gamma noise and neutron noise in measuring the prompt neutron decay constant, α.
  - For measuring α only “high” frequencies are used ($\omega >> \lambda_i$)

- What about for “low” frequencies? ($\omega << \lambda_i$)
  - Contamination from delayed gamma emissions?
  - Can this be theoretically understood and accounted for?

Delayed Emission and Gamma Noise

- Delayed gammas from short-lived fission product decay are correlated to fission chains, but over different timescales.

- Like delayed neutron precursors, these delayed gamma emissions come from numerous isotopes with different yields and decay constants.

- Unlike delayed neutrons, these delayed gamma emissions due not propagate the fission chain itself.

Gamma Noise Derivation

Including Delayed Emission

Unifying Neutron and Gamma Noise

Stochastic Point Kinetics Equations With Gammas (Langevin Technique)

Standard Neutron PKEs

$$\frac{dn(t)}{dt} = \frac{\rho - \beta}{\Lambda} n(t) + \sum_{i=1}^{I} \lambda_{n,i} C_{n,i}(t) + \eta(t),$$

Neutron Population

$$\frac{dC_{n,i}(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_{n,i} C_{n,i}(t), \quad i = 1, \ldots, I,$$

Delayed Neutron Precursors

$$\gamma(t) = \frac{Y_p}{\nu\Lambda} n(t) + \sum_{k=1}^{K} \lambda_{\gamma,k} C_{\gamma,k}(t)$$

Gamma Population

$$\frac{dC_{\gamma,k}(t)}{dt} = \frac{y_k}{\nu\Lambda} n(t) - \lambda_{\gamma,k} C_{\gamma,k}(t), \quad k = 1, \ldots K.$$

Delayed Gamma Precursors

Gamma PKEs

Unifying Neutron and Gamma Noise

Stochastic Point Kinetics Equations With Gammas (Langevin Technique)

$$\frac{dn(t)}{dt} = \frac{\rho - \beta}{\Lambda} n(t) + \sum_{i=1}^{I} \lambda_{n,i} C_{n,i}(t) + \eta(t),$$

$$\frac{dC_{n,i}(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_{n,i} C_{n,i}(t), \quad i = 1, \ldots, I,$$

$$\gamma(t) = \frac{Y_p}{\nu\Lambda} n(t) + \sum_{k=1}^{K} \lambda_{\gamma,k} C_{\gamma,k}(t)$$

$$\frac{dC_{\gamma,k}(t)}{dt} = \frac{y_k}{\nu\Lambda} n(t) - \lambda_{\gamma,k} C_{\gamma,k}(t), \quad k = 1, \ldots K.$$

Parameter	Description
$\gamma(t)$	Gamma Population
Y_p	Prompt gammas per fission
$\lambda_{\gamma,k}$	Delayed gamma precursor of the k^{th} group decay constant
$C_{\gamma,k}$	Delayed gamma precursor of the k^{th} group population
y_k	Delayed gammas per fission event the k^{th} group
ν	Total neutrons per fission
$\eta(t)$	Noise equivalent source for neutron production

Unifying Neutron and Gamma Noise
Neutron and Gamma Populations in Terms of Transfer Functions

$$n(\omega) = H_n(\omega)\,\eta(\omega)$$

$$\gamma(\omega) = \frac{1}{\Lambda} H_\gamma(\omega)\,n(\omega)$$

$$H_n(\omega) = \frac{1}{i\omega - \frac{\rho-\beta}{\Lambda} - \sum_i \frac{\lambda_{n,i}\beta_i/\Lambda}{i\omega+\lambda_{n,i}}}$$

Neutron transfer function

$$H_\gamma(\omega) = \left[\frac{Y_p}{\nu} + \sum_k \frac{\lambda_{\gamma,k} y_k/\nu}{i\omega + \lambda_{\gamma,k}}\right]$$

Gamma transfer function

Unifying Neutron and Gamma Noise

Detector Signal Expressions

- We now have the frequency domain expressions of the neutron and gamma population.
- Experimentally, we don't observe the whole populations, rather only a small portion as measured by a detector $z_n(t)$ and $z_\gamma(t)$.
- These detector responses in the frequency domain can be written as:

$$z_n(\omega) = \varepsilon_n \frac{n(\omega)}{\Lambda}$$

Neutron detector

$$z_\gamma(\omega) = \varepsilon_\gamma \gamma(\omega)$$

Gamma detector

Unifying Neutron and Gamma Noise

Detector Cross Power Spectral Densities

$$|CPSD_{nn}(\omega)| = 2D\frac{\bar{z}_{n1}\bar{z}_{n2}}{F\Lambda^2}|H_n(\omega)|^2$$

This is the standard equation for neutron noise measurements in the frequency domain (Cohn-α)

$$|CPSD_{\gamma\gamma}(\omega)| = 2D\frac{\bar{z}_{\gamma 1}\bar{z}_{\gamma 2}\nu^2}{F\Lambda^2\left(Y_p+\sum_k y_k\right)^2}|H_\gamma(\omega)|^2|H_n(\omega)|^2$$

This is the **new** equation for gamma noise (including delayed gammas)

Unifying Neutron and Gamma Noise
Detector Cross Power Spectral Densities

$$|CPSD_{nn}(\omega)| = 2D\frac{\bar{z}_{n1}\bar{z}_{n2}}{F\Lambda^2}\frac{1}{\left|i\omega - \frac{\rho-\beta}{\Lambda} - \sum_i \frac{\lambda_{n,i}\beta_i/\Lambda}{i\omega+\lambda_{n,i}}\right|^2}$$

Neutron detector CPSD

$$|CPSD_{\gamma\gamma}(\omega)| = 2D\frac{\bar{z}_{\gamma1}\bar{z}_{\gamma2}\nu^2}{F\Lambda^2(Y_p+\sum_k y_k)^2}\left|\frac{Y_p}{\nu}+\sum_k \frac{\lambda_{\gamma,k}y_k/\nu}{i\omega+\lambda_{\gamma,k}}\right|^2\frac{1}{\left|i\omega - \frac{\rho-\beta}{\Lambda} - \sum_i \frac{\lambda_{n,i}\beta_i/\Lambda}{i\omega+\lambda_{n,i}}\right|^2}$$

Gamma detector CPSD

Unifying Neutron and Gamma Noise
Ratio of Detector CPSDs

- The count rate normalized ratio of neutron to gamma noise isolates interesting information about the gamma noise of the system.

$$\frac{|CPSD_{nn}(\omega)|}{|CPSD_{\gamma\gamma}(\omega)|}\frac{\bar{z}_{\gamma 1}\bar{z}_{\gamma 2}}{\bar{z}_{n1}\bar{z}_{n2}} = \frac{\left(Y_p + \sum_k y_k\right)^2}{\left|Y_p + \sum_k \frac{\lambda_{\gamma,k} y_k}{i\omega + \lambda_{\gamma,k}}\right|^2}$$

- And at frequencies above that of the shortest-lived delayed gamma precursors ($\omega >> \lambda_{\gamma,k}$) the follow relation can be established.

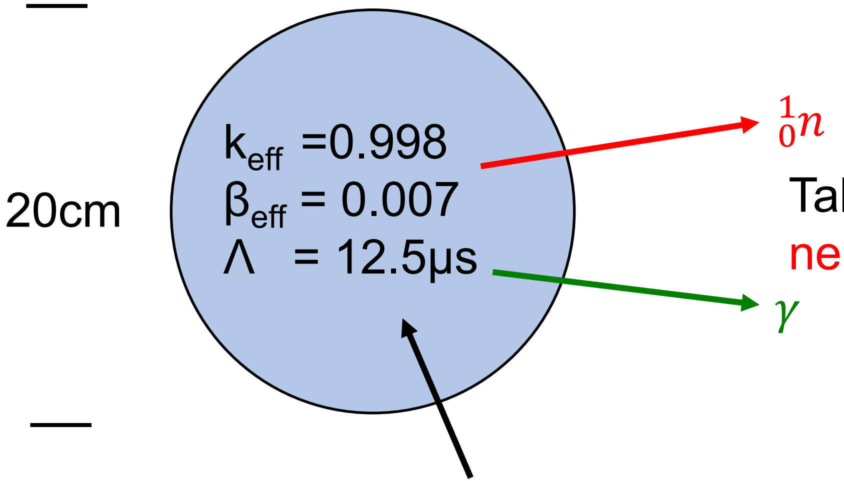
$$\sqrt{\frac{|CPSD_{nn}(\omega)|}{|CPSD_{\gamma\gamma}(\omega)|}\frac{\bar{z}_{\gamma 1}\bar{z}_{\gamma 2}}{\bar{z}_{n1}\bar{z}_{n2}}} - 1 \approx \frac{\sum_k y_k}{Y_p}$$

Ratio of measured delayed to prompt gammas

MCNP Toy Problem

MCNP Toy Problem Using PTRAC

To explore the effects of delayed gamma emission on gamma noise, a simple MCNP simulation was performed.



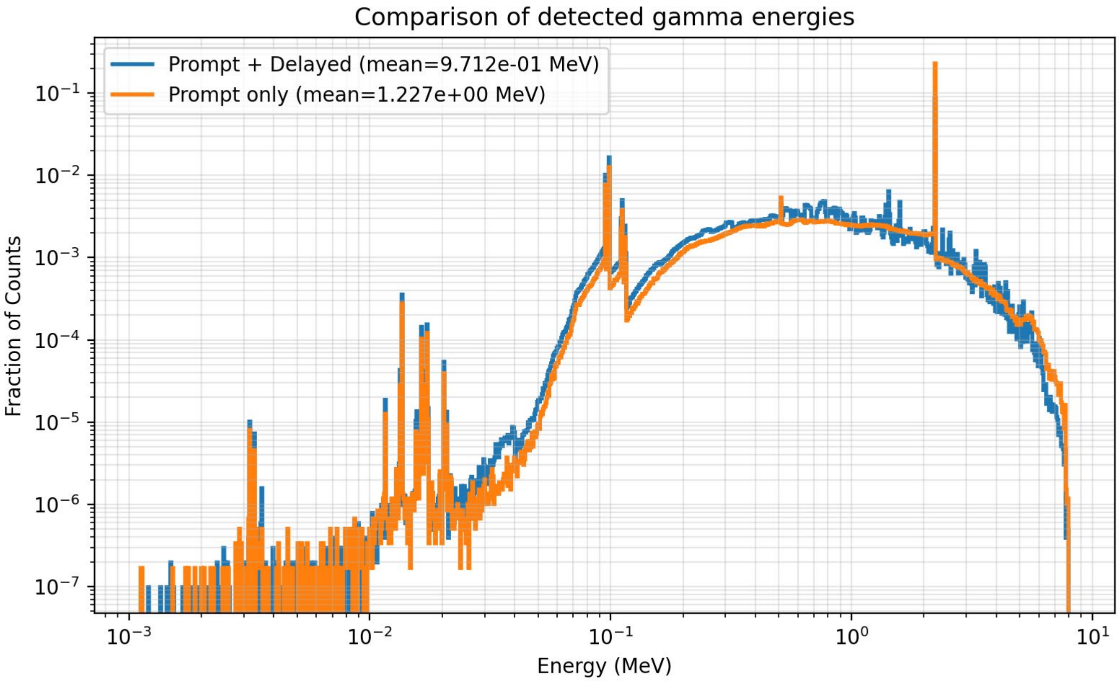
Tallying all leakage neutrons and gammas

Unreflected $^{1}H/^{235}U$ Solution

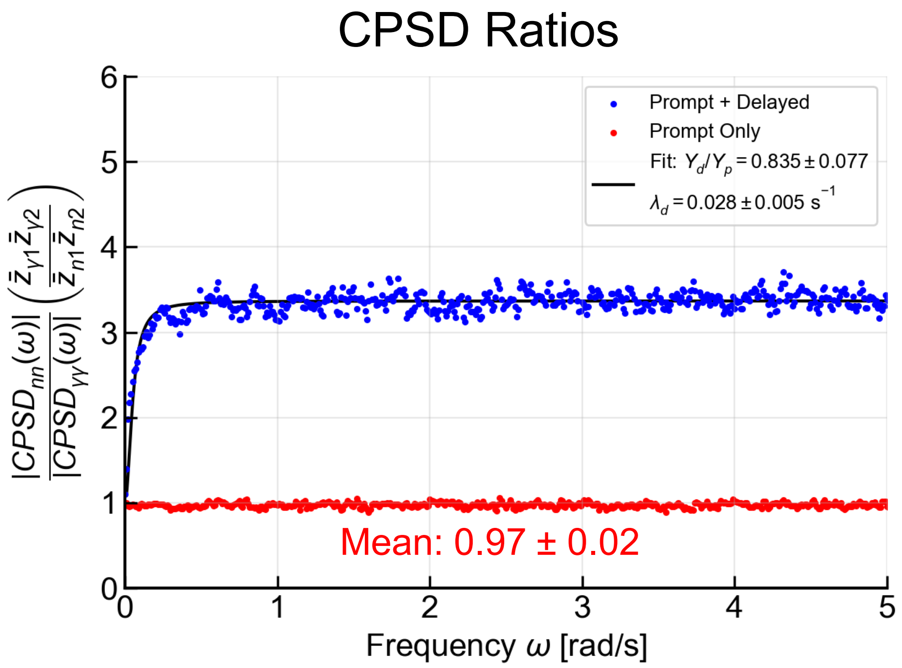
Delayed gamma emission from fission product decay can be included using the ACT card in MCNP6.3

MCNP Toy Problem Using PTRAC

- Decrease in mean detected gamma energy when delayed gammas included (as expected)



MCNP Toy Problem Using PTRAC



With delayed gammas

$$\frac{|CPSD_{nn}(\omega)|}{|CPSD_{\gamma\gamma}(\omega)|}\frac{\bar{z}_{\gamma 1}\bar{z}_{\gamma 2}}{\bar{z}_{n1}\bar{z}_{n2}} = \frac{(Y_p + \sum_k y_k)^2}{\left|Y_p + \sum_k \frac{\lambda_{\gamma,k} y_k}{i\omega + \lambda_{\gamma,k}}\right|^2}$$

Fit assumes one "effective" delayed gamma group, y_d λ_d

For no delayed gammas (Σy_k=0)

$$\frac{|CPSD_{nn}(\omega)|}{|CPSD_{\gamma\gamma}(\omega)|}\frac{\bar{z}_{\gamma 1}\bar{z}_{\gamma 2}}{\bar{z}_{n1}\bar{z}_{n2}} = \frac{(Y_p + 0)^2}{|Y_p + 0|^2} = 1$$

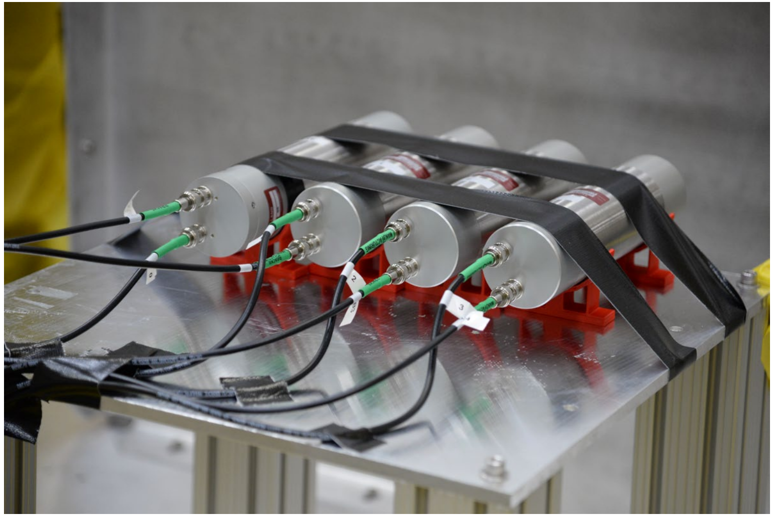
Experiment Setup

Experiment Setup

Neutron Noise

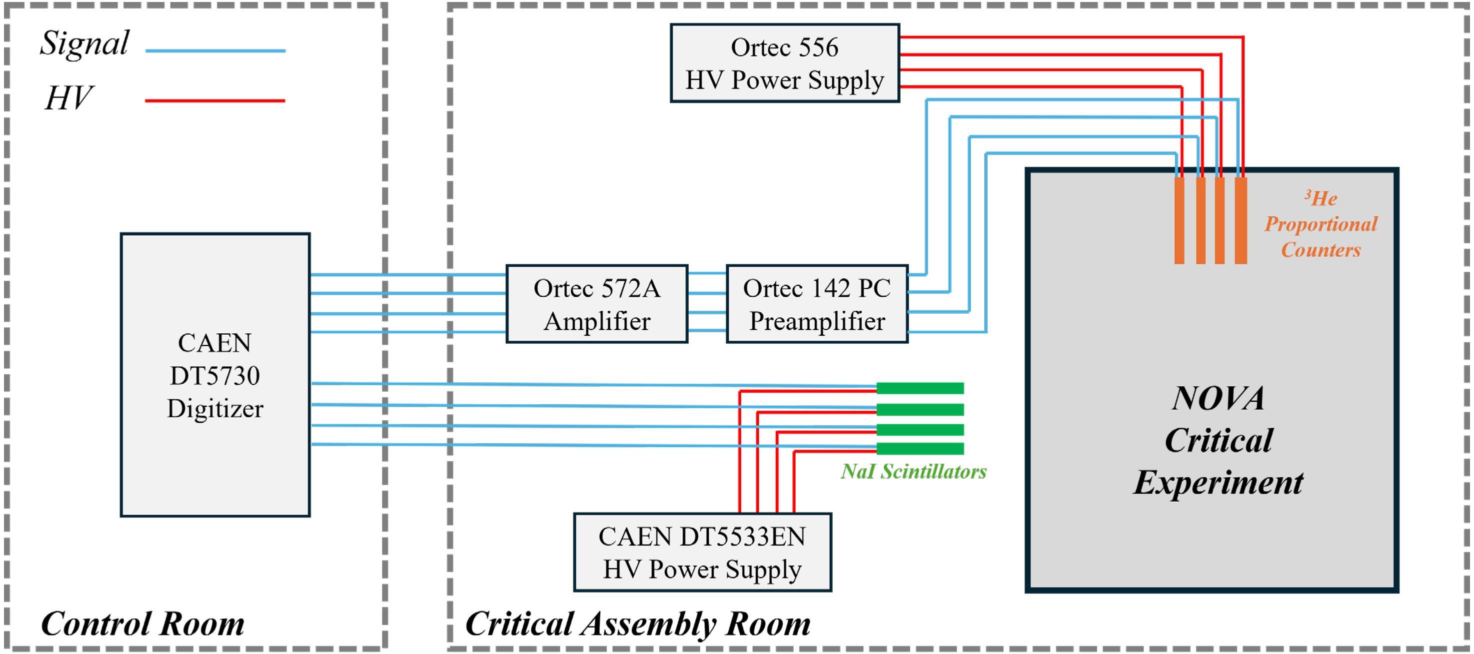
Four in-reflector ^3He proportional counters

Gamma Noise



Four ex-core NaI gamma scintillators

Detector Setup



Measurement and Fitting Procedure

- A four-hour measurement of NOVA was performed at delayed critical.
- CPSDs were estimated using the sum of detectors 1 and 2 crossed with detectors 3 and 4.
- Assumed one "effective" delayed gamma group.
  - y_d delayed gammas per fission
  - λ_d effective decay constant

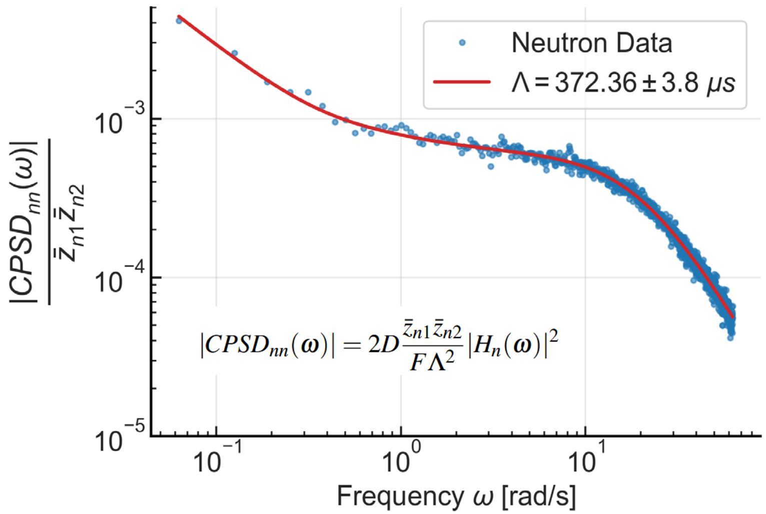
Group	a_i[33]	β_i	λ_i (s^{-1})[33]
1	0.0331	0.000242	0.0124
2	0.2190	0.001599	0.0305
3	0.1959	0.001430	0.111
4	0.3950	0.002884	0.301
5	0.1150	0.000840	1.14
6	0.0420	0.000307	3.01
Sum	**1.000**	**0.00730**	

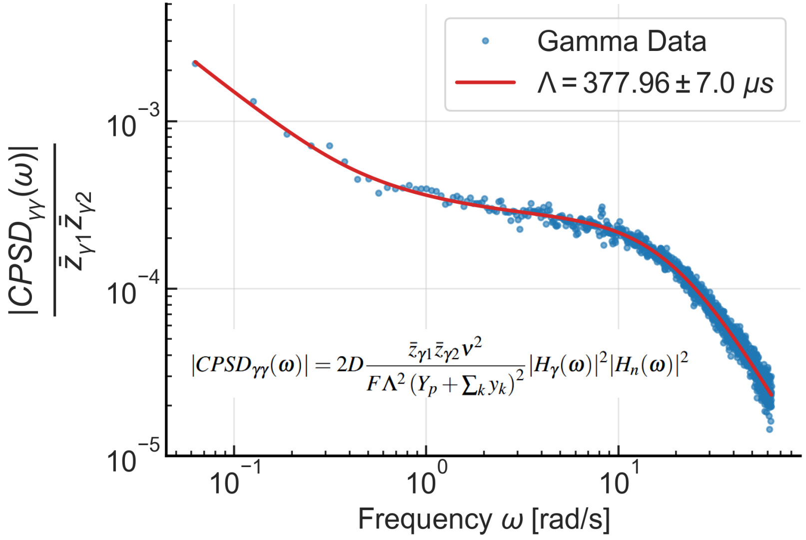
- Assumed β_{eff} of 0.00730 using Keepin 6-group thermal ^{235}U fission.

Experimental Results

CPSD Fits

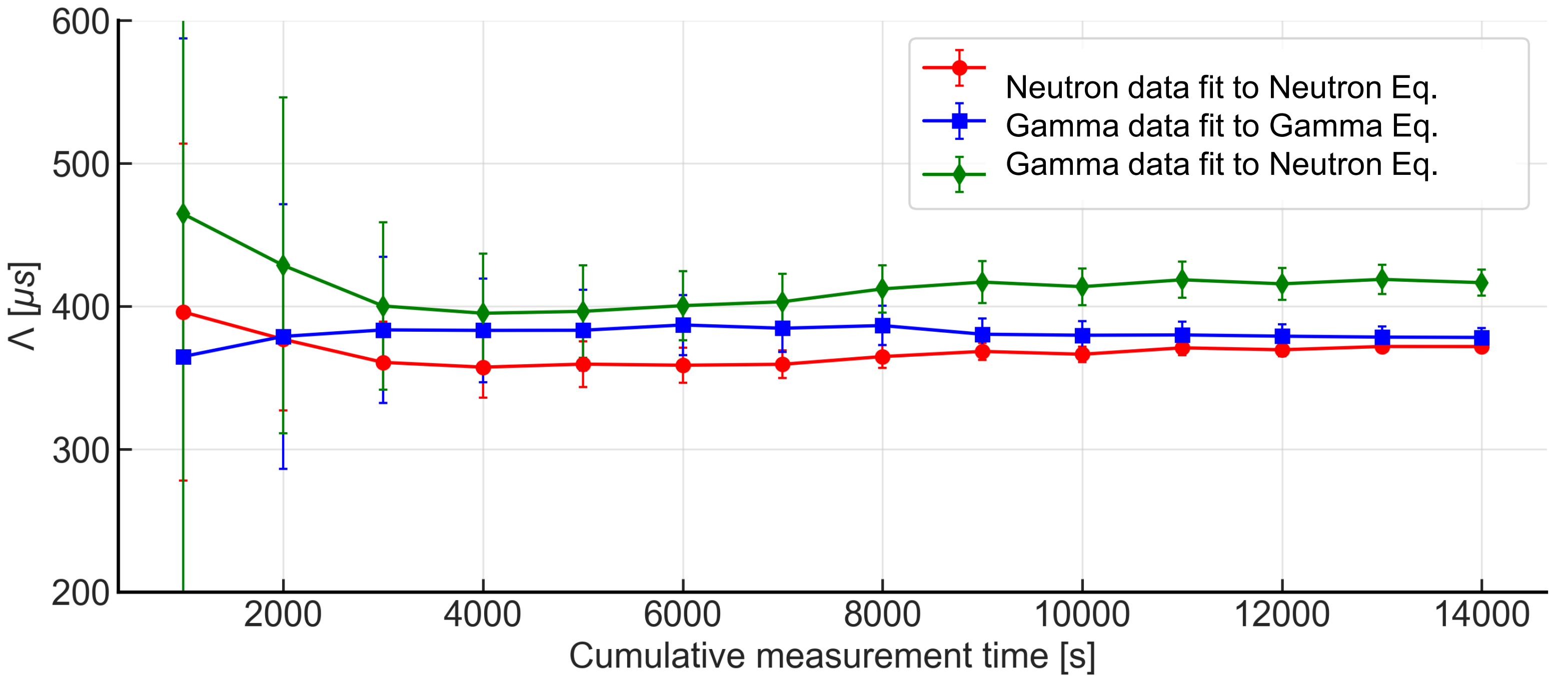
- Estimations of Λ using neutron and gamma noise
- Long measurement time allowed for observation of low frequency (ω > $1 sec^{-1}$) delayed neutron effects.





Λ as a Function of Measurement Time

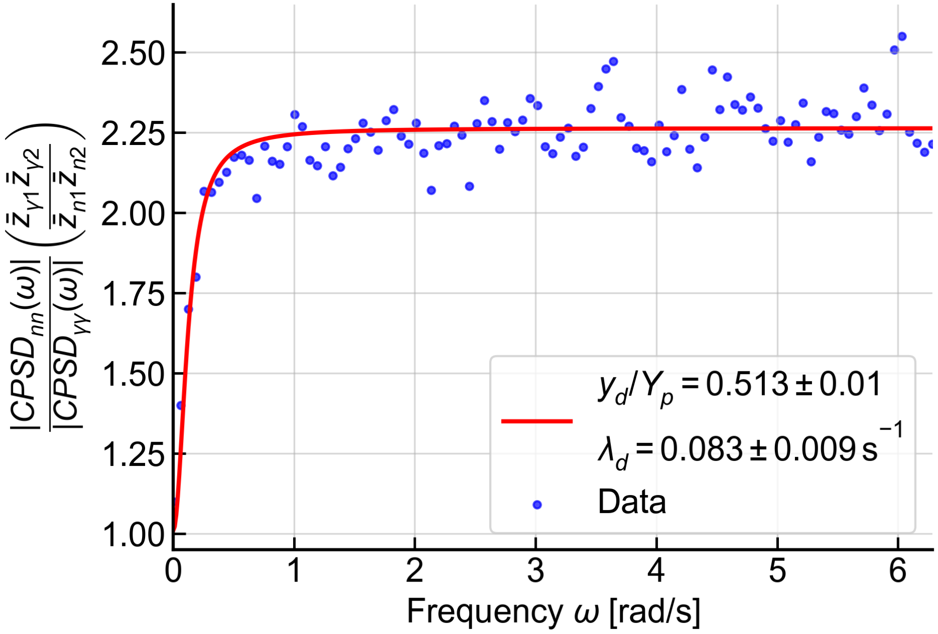
- Disregarding effects of delayed gamma emission (green) shows clear bias in estimations of Λ



Ratio of Neutron to Gamma CPSDs

$$\frac{|CPSD_{nn}(\omega)|}{|CPSD_{\gamma\gamma}(\omega)|}\frac{\bar{z}_{\gamma 1}\bar{z}_{\gamma 2}}{\bar{z}_{n1}\bar{z}_{n2}} = \frac{\left(Y_p + \sum_k y_k\right)^2}{\left|Y_p + \sum_k \frac{\lambda_{\gamma,k} y_k}{i\omega + \lambda_{\gamma,k}}\right|^2}$$

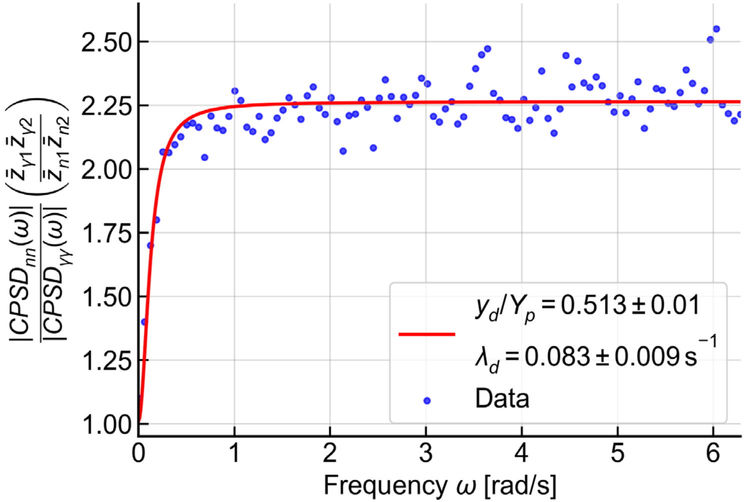
- The normalized CPSD ratios reveal the effects of delayed emission on gamma noise.
- At $\omega < 1$ sec^{-1} the CPSDs have different <u>shapes</u> due to the decay of gamma emitting fission products.
- At $\omega > 1$ sec^{-1} the ratio become constant, indicating identical <u>shapes</u>, but different <u>amplitudes</u>.



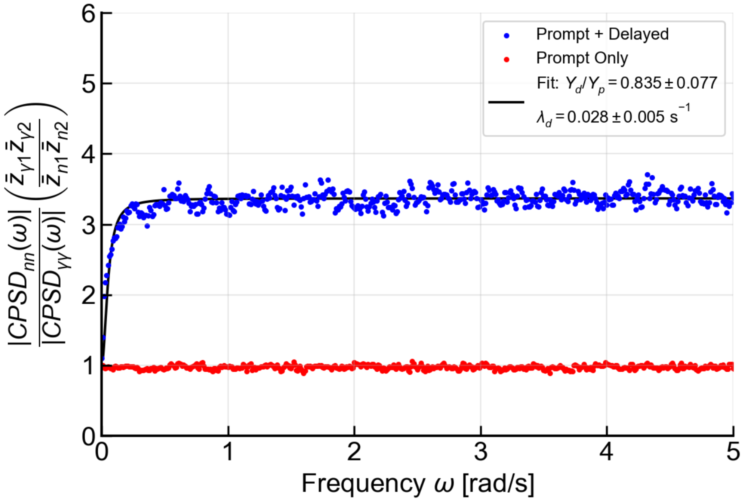
Ratio of Neutron to Gamma CPSDs

Comparison to MCNP Toy Problem

Experimental (NOVA)



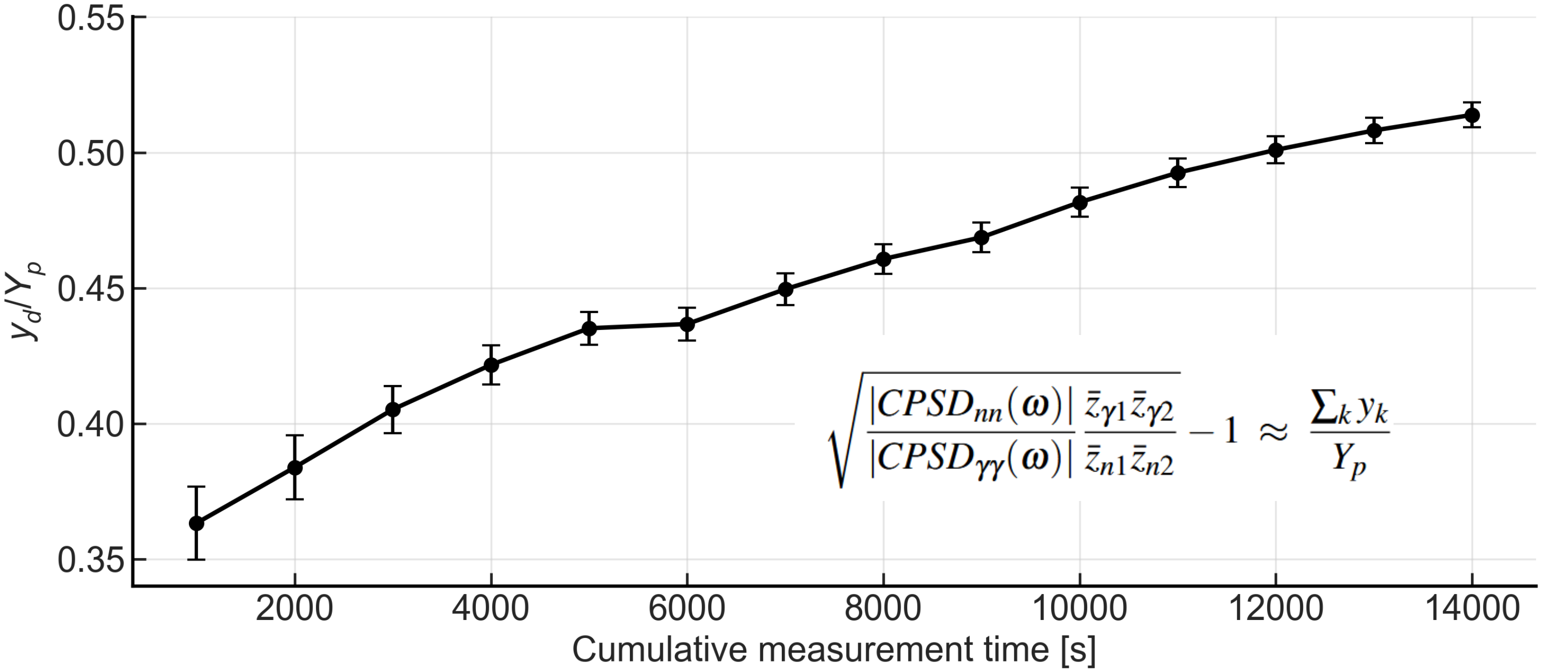
Simulation (Toy Problem)



Less delayed gammas observed in experiment likely due to shielding effects

Delayed to Prompt Gamma Ratio

- Ratio of delayed to prompt gammas increases as measurement time increases as expected due to fission product build up.



Discussion of Results

- Using a theoretical model that includes delayed gamma emission gives greater agreement in estimations of Λ compared against traditional neutron noise.

- An effective one group of delayed gammas gave a decay constant of 0.083 ± 0.009 sec^{-1}.
  - This suggests that at “high” frequencies, the <u>shapes</u> of the neutron and gamma CPSDs are identical.

- The ratio of neutron to gamma noise CPSDs allows for the estimation of measured delayed to prompt gammas.
  - Expected increase as a function of measurement time.

Concluding Remarks

- We provide a theoretical description and simulated and experimental results to demonstrate that gamma noise at low frequencies is contaminated by delayed gamma emissions.

- This work considers the effects of delayed gamma emission from fission product decay, but could be generalized to other delayed, but fission chain correlated, gamma emissions.
  - Capture gammas, activation gammas, inelastic scattering gammas, etc.

- No noise equivalent source (NES) was used for prompt gamma production. This treatment would be required for estimating the effective delayed neutron fraction using gamma noise.
  - Like the neutron NES, this source is frequency independent, so it influences the gamma CPSD amplitude, but not its shape.

Questions?

Extra Slides

Unifying Neutron and Gamma Noise
A Quick Aside on Cohn-α

As the name suggests, Cohn-α is used to measure $\alpha = \frac{\rho-\beta}{\Lambda}$, so where is it hiding?

$$\langle |z_n(\omega)|^2 \rangle = 2D\frac{z_n^2}{F\Lambda^2}|H_n(\omega)|^2 = 2D\frac{z_n^2}{F\Lambda^2}\frac{1}{\left| i\omega - \frac{\rho-\beta}{\Lambda} - \cancelto{0}{\sum_i \frac{\lambda_{n,i}\beta_i/\Lambda}{i\omega+\lambda_{n,i}}} \right|^2}.$$

For frequencies above that of the decay constant of the shortest-lived delayed neutron precursor group ($\omega \gg \lambda_i$)

$$\langle |z_n(\omega)|^2 \rangle = 2D\frac{z_n^2}{F\Lambda^2}\frac{1}{(\omega^2+\alpha^2)}.$$

$$\langle |z_n(\omega)|^2 \rangle = \frac{2Dz_n^2}{F(\rho-\beta)^2}\frac{1}{(1+\frac{\omega^2}{\alpha^2})}.$$

Lorentzian distribution with break frequency at $\alpha = \frac{\rho-\beta}{\Lambda}$

Unifying Neutron and Gamma Noise
Neutron Noise to Measure β and Λ

- Measuring α is easy. Measuring β and Λ is hard.
- Consider the neutron APSD at delayed critical (ρ=0)

$$\frac{\langle |z_n(\omega)|^2 \rangle}{z_n^2} = \frac{2D}{F(-\beta)^2} \frac{1}{(1 + \frac{\omega^2}{(-\beta/\Lambda)^2})}.$$

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$$\frac{\langle |z_n(\omega)|^2 \rangle}{z_n^2} = \frac{2D}{F(-\beta)^2} \frac{1}{(1 + \frac{\omega^2}{(-\beta/\Lambda)^2})}.$$

Amplitude of Lorentzian is inversely proportional to β squared

Break frequency of Lorentzian is proportional to β/Λ squared

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Amplitude of Lorentzian is inversely proportional to β squared

Break frequency of Lorentzian is proportional to β/Λ squared

Thus β and Λ can be measured **<u>IF</u>** the following is known:

1. The Diven Factor (*D*) is known
2. The integral fission rate (*F*) is known (reactor power in fissions/sec)

Kinetic Parameter Measurements in the CROCUS Reactor Using Current Mode Instrumentation

Publisher: IEEE Cite This PDF

O. Pakari ; V. Lamirand ; G. Perret ; P. Frajtag ; A. Pautz All Authors

Kinetics Measurements of the KRUSTY Space Reactor Experiment

Cole Kostelac,[*,a,b] George McKenzie,[a] Jesson Hutchinson,[a] Rene Sanchez,[a] and Ayodeji Alajo[b]

[1] *Los Alamos National Laboratory, Los Alamos, New Mexico 87545*

[2] *Missouri University of Science and Technology, Rolla, Missouri 65409*

*Email: kostelac@lanl.gov

Unifying Neutron and Gamma Noise

Gamma Noise to Measure β and Λ?

- What about gamma noise? Can it be used to measure β and Λ?

- This has been an open question in the noise community

Unifying Neutron and Gamma Noise

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6.2 Outlook and recommendations

- Gamma noise has been shown to be potentially more accurate and cost-effective as compared to neutron noise. The information of β_{eff} is also coded in the gamma correlation amplitude, yet a method to extract the relevant parameters and associated uncertainty quantification does not yet exist. By studying the theoretical expressions, the here presented experimental data could be analyzed for an estimate of β_{eff} as well.

O. Pakari "Experimental and numerical study of stochastic branching noise in nuclear reactors". EPFL Ph.D. Dissertation (2020)

Unifying Neutron and Gamma Noise
Gamma Noise to Measure β and Λ?

- Consider the gamma detector APSD

$$\langle |z_\gamma(\omega)|^2 \rangle = 2D \frac{z_\gamma^2 \nu^2}{F\Lambda^2 (Y_p + \sum_k y_k)^2} \left| \frac{Y_p}{\nu} + \sum_k \frac{\lambda_{\gamma,k} y_k/\nu}{i\omega + \lambda_{\gamma,k}} \right|^2 \frac{1}{\left| i\omega - \frac{\rho-\beta}{\Lambda} - \sum_i \frac{\lambda_{n,i}\beta_i/\Lambda}{i\omega + \lambda_{n,i}} \right|^2}.$$

For frequencies above that of the decay constant of the shortest-lived delayed neutron and gamma precursor group ($\omega \gg \lambda_i$ and $\omega \gg \lambda_k$)

$$\langle |z_\gamma(\omega)|^2 \rangle = 2D \frac{z_\gamma^2 \nu^2}{F\Lambda^2 (Y_p + \sum_k y_k)^2} \frac{Y_p^2}{\nu^2} \frac{1}{(\omega^2 + \alpha^2)}.$$

Rearrange to Lorentzian form

$$\langle |z_\gamma(\omega)|^2 \rangle = 2D \frac{z_\gamma^2 \nu^2}{F(\rho-\beta)^2 (Y_p + \sum_k y_k)^2} \frac{Y_p^2}{\nu^2} \frac{1}{(1 + \frac{\omega^2}{\alpha^2})}.$$

Unifying Neutron and Gamma Noise

Gamma Noise to Measure β and Λ?

$$\langle |z_\gamma(\omega)|^2 \rangle = 2D \frac{z_\gamma^2 \nu^2}{F(\rho-\beta)^2 (Y_p + \sum_k y_k)^2} \frac{Y_p^2}{\nu^2} \frac{1}{(1+\frac{\omega^2}{\alpha^2})}.$$

Assuming no delayed gammas $\sum_k y_k = 0$

$$\langle |z_\gamma(\omega)|^2 \rangle = 2D \frac{z_\gamma^2 \cancel{\nu^2}}{F(\rho-\beta)^2 (\cancel{Y_p} + \underbrace{\sum_k y_k}_{0})^2} \frac{\cancel{Y_p^2}}{\cancel{\nu^2}} \frac{1}{(1+\frac{\omega^2}{\alpha^2})}.$$

At delayed critical $\rho = 0$

$$\frac{\langle |z_\gamma(\omega)|^2 \rangle}{z_\gamma^2} = \frac{2D}{F(-\beta)^2} \frac{1}{(1+\frac{\omega^2}{(-\beta/\Lambda)^2})}.$$

Look Familiar?

Unifying Neutron and Gamma Noise

Gamma Noise to Measure β and Λ?

At delayed critical (ρ=0)

Gamma APSD

$$\frac{\langle |z_\gamma(\omega)|^2 \rangle}{z_\gamma^2} = \frac{2D}{F(-\beta)^2} \frac{1}{(1 + \frac{\omega^2}{(-\beta/\Lambda)^2})}.$$

Look Familiar?

Neutron APSD

$$\frac{\langle |z_n(\omega)|^2 \rangle}{z_n^2} = \frac{2D}{F(-\beta)^2} \frac{1}{(1 + \frac{\omega^2}{(-\beta/\Lambda)^2})}.$$

If only prompt gammas are measured, gamma noise APSD behaves identically to neutron noise.

- Delayed gamma energies are no greater than 2 MeV, while prompt fission gammas extend to 7+ MeV
- Therefore, delayed gammas could be filtered with a lower-level discriminator