Measured and Simulated Energy, Multiplicity, and Angular Correlations in Fission

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Eoin Sansevero
Department of Nuclear Engineering and Radiological Sciences, University of Michigan
Undergraduate Rising Senior
Professor Sara A. Pozzi

Stefano Marin, Stephan Okar, Isabel Hernandez, Phillip Bauwens, Dr. Shaun Clarke

Motivation and Mission Relevance

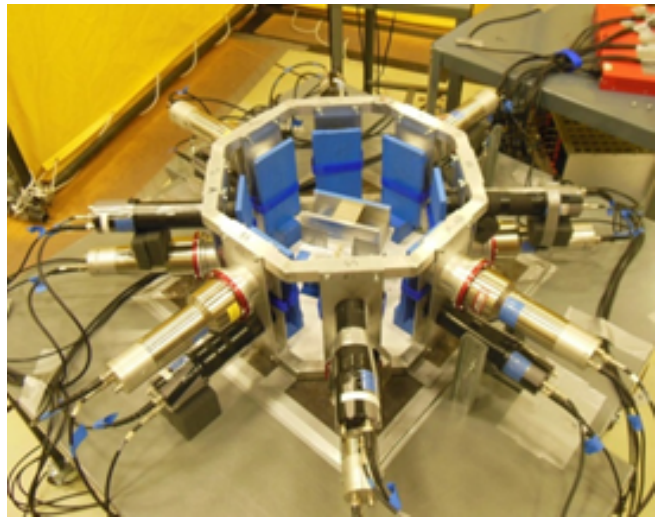
Radiation emitted from fission interactions contain unique identifying signatures that can be used for source identification and characterization.

Current detection systems used to characterize nuclear materials assume no cross correlations in energy, multiplicity, and angle.

These correlations are expected from the physics of fragment de-excitation.

Applications to Nonproliferation:

- More accurate characterization of Special Nuclear Material (SNM).
- Inform physics-based fission event generators for more accurate simulation of fission and fragment de-excitation.



Tony H. Shin, Michael Y. Hua, Angela Di Fulvio, David L. Chichester, Shaun D. Clarke, Sara A. Pozzi

Technical Approach

Fission data measurements were taken using the Chi Nu array in 2015.

Source: ^{252}Cf(sf), fabricated at Oak Ridge National Laboratory
Geometry: 1 meter radius hemisphere
Detectors: 42 EJ-309

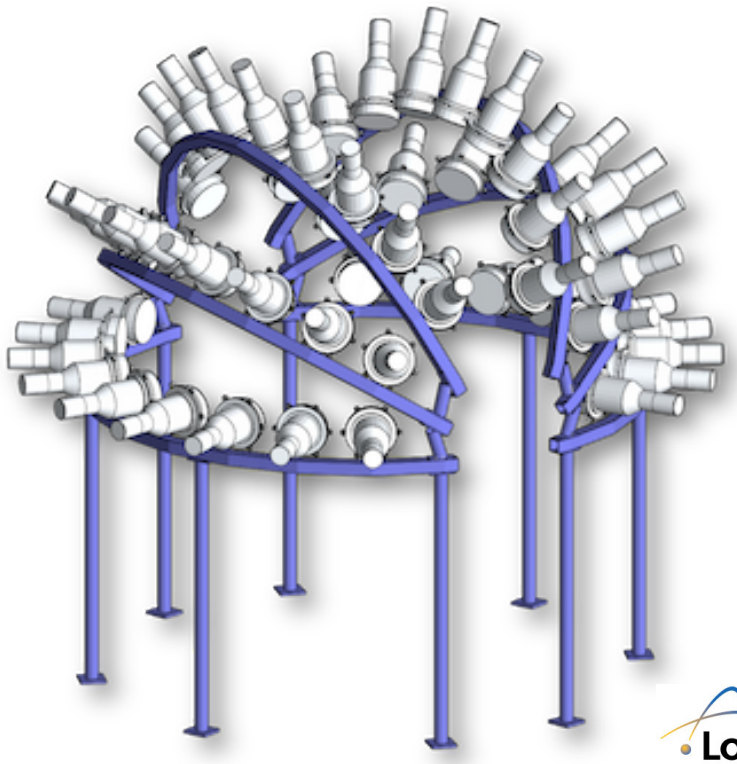
Using these measurements, a negative multiplicity correlation was shown for emitted neutrons and photons on an event-by-event basis.

Thanks to its long flight path, the energy of the neutrons can be determined by time of flight.

$$\chi \quad \nu$$

Spectra Neutrons

Chi-Nu detector array located at Los Alamos Neutron Science Center.

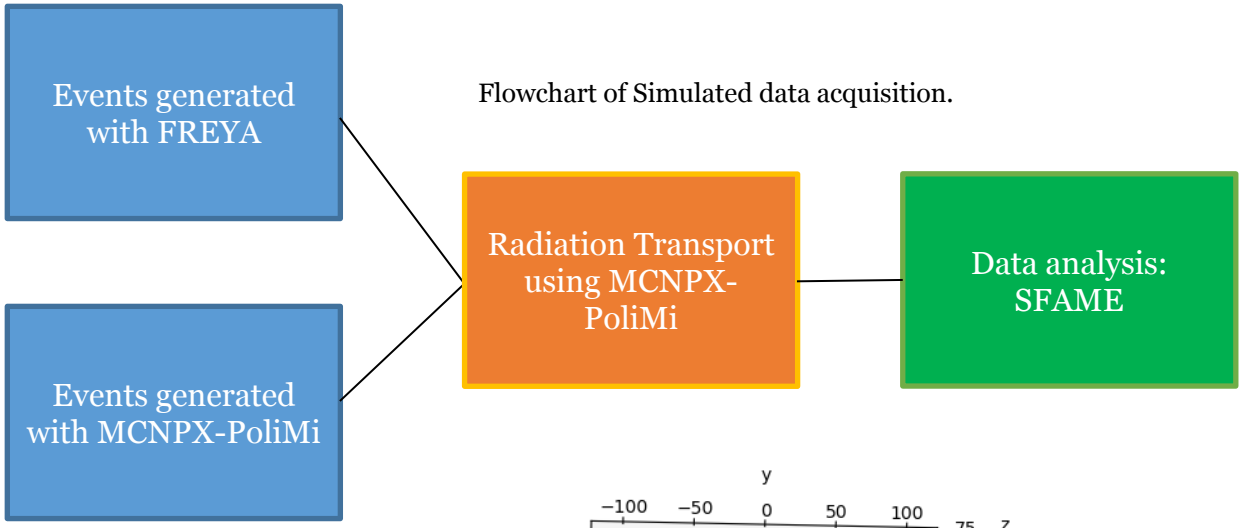


Technical Approach (cont.)

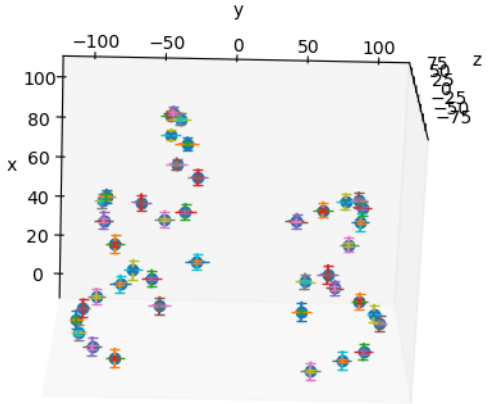
We select two sources of events to be used as inputs in radiation transport:

FREYA
Uses models of nuclear physics to generate fission events and their accompanying neutron and photon emission.

MCNPX-PoliMi (IPOL1 = 10)
Randomly samples (MonteCarlo) evaluated nuclear data for the emission of neutrons and photons accompanying fission.



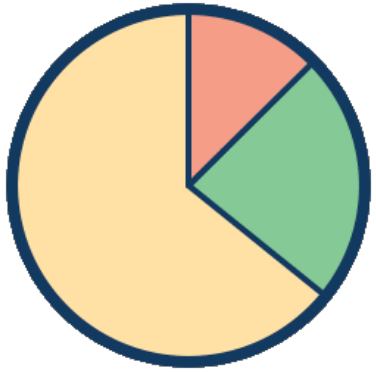
Flowchart of Simulated data acquisition.



Positions of the active detectors modeled from the particle interactions in POLIMI.

Calculation of fission observables through event-by-event simulation, Jørgen Randrup and Ramona Vogt

Energy-Multiplicity Correlations



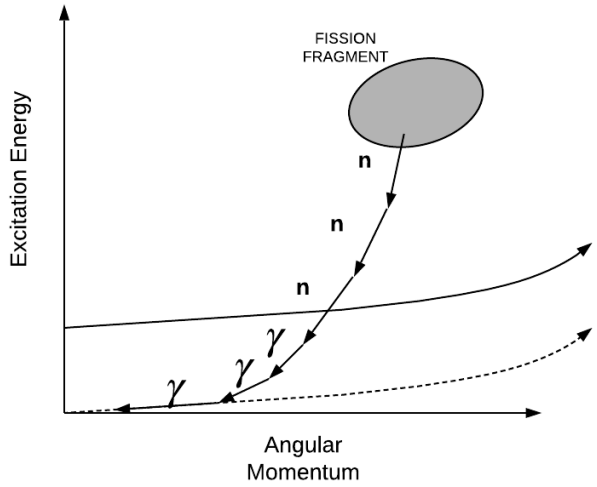
The area of pie chart represents fragment initial excitation energy. The area of pieces represents energies of emitted neutrons.

Neutron-Neutron Energy Competition

- Fission fragments have finite excitation energy, leading to energy competition between emitted particles.
- We expect a negative correlation between the average neutron energy and the multiplicity.
- i.e., the energy relation between particles emitted from a single fragment.

Total Fragment Energy and Momentum

- The fragment initial excitation energy and angular momentum conditions correlate to the energy and multiplicity of the emitted particles.
- i.e., the relation of the Q value to the energy and multiplicity of the emitted particles from both fragments.



Fragment de-excitation via emission of neutrons first, followed by photons.

Energy-Multiplicity Results

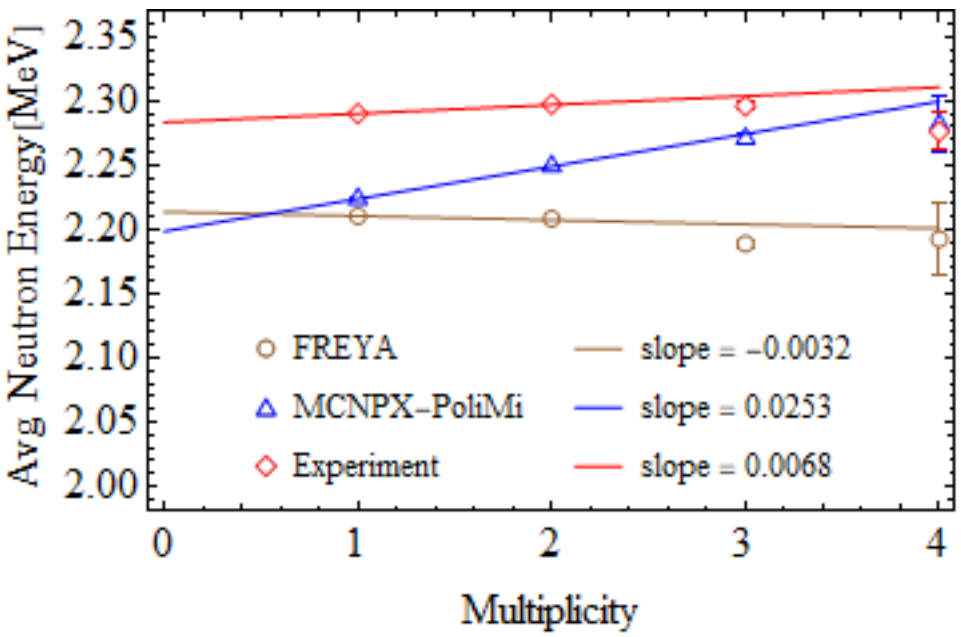
How does the Watt Spectrum depend on multiplicity?

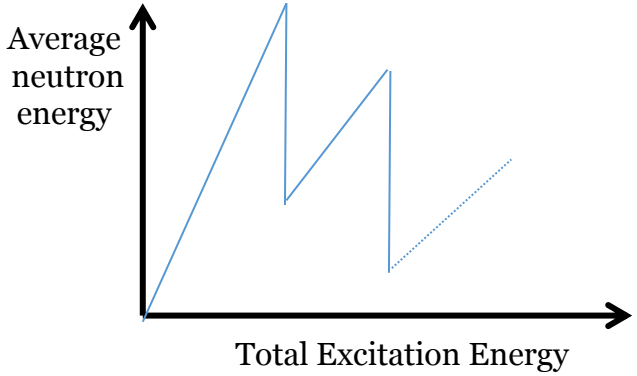
We characterize the neutron spectrum using the neutron mean energy, $\langle E \rangle$, defined as:

$$\langle E \rangle = \frac{1}{N} \sum_{i=1}^{N} E_i \mathbb{P}(E_i)$$

This is approximately independent of the neutron-neutron competition. However, it is highly dependent on the initial fragment conditions.

Systematic bias indicated from POLIMI suggests the experimental result has an overall negative correlation more closely resembling the results of FREYA.





Energy-Multiplicity Results (cont.)

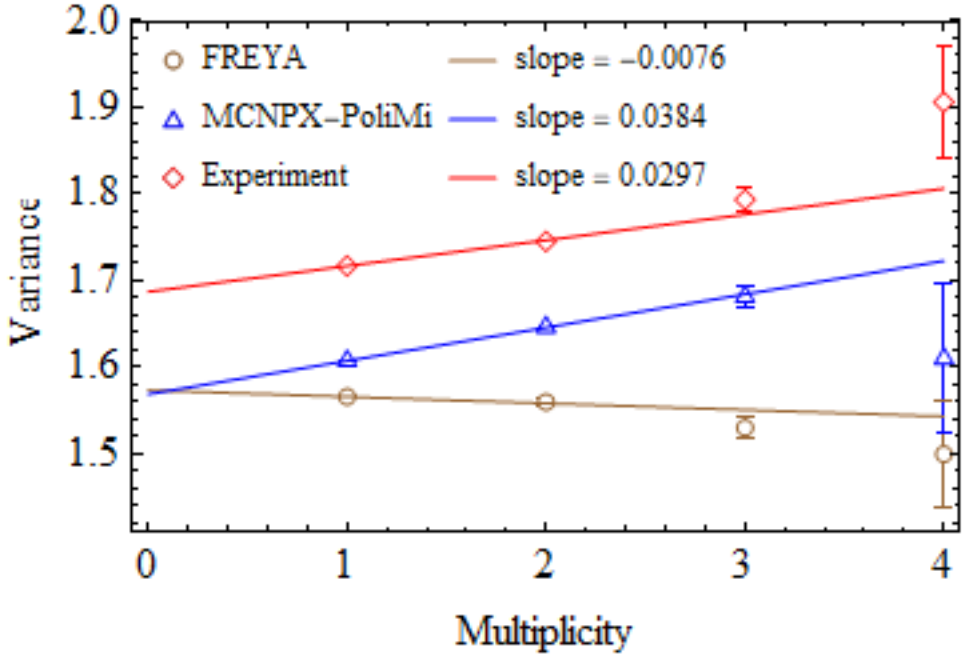
To isolate the competition between neutron energies within a single event, we find the variance of the total neutron energy:

$$\sigma^2(E_1 + E_2 + \cdots + E_N) = \sigma^2(E_{TOTAL}) = \sum_{i=1}^{N} \sigma^2(E_i) + 2 \cdot \left(\sum_{i<j}^{N} \mathrm{cov}(E_i, E_j) \right)$$

To illustrate the usefulness of this quantity, let us assume that $\mathrm{cov}(E_i, E_j)$ is a constant, then:

$$\frac{\sigma^2(E_{TOTAL})}{N} = \sigma^2(E) + C_{ij}(N-1)$$

We observe positive correlation in PoliMi and Experiment, while FREYA shows a slight negative correlation.

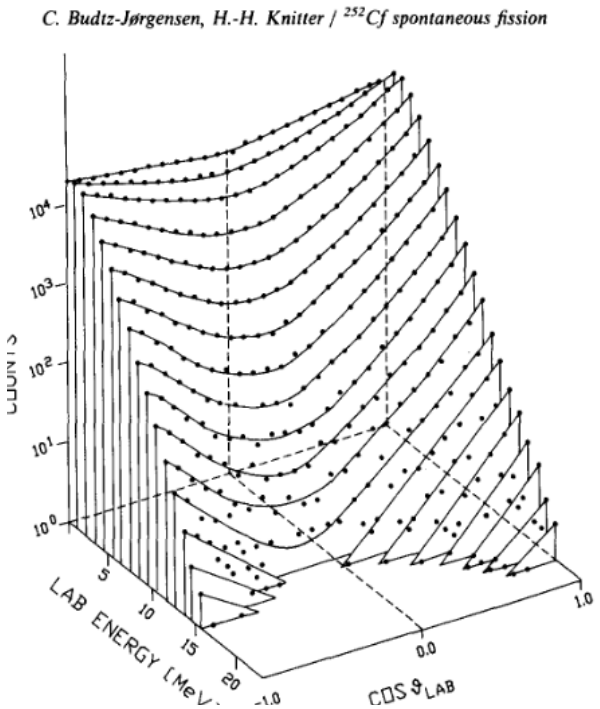


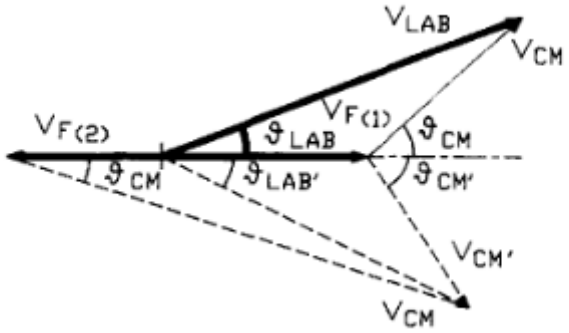
Angular Correlations

What is the role of emission angles in energy correlations?

Angle distributions provide information on how energy is shared between fragments.

1. Neutrons emitted from the same fragment are expected to have a (-) energy correlation due to competition.
2. Neutrons emitted from different fragments are expected to have a (+) energy correlation.





Boosting effect increases neutron energies in the direction of fragment motion.

This is particularly apparent when $KE_{neutron} \ll KE_{fragment}$.

Distribution of the angle between the light fragment and the emitted neutron. [C. Budtz –Jorgensen and H. H. Knitter, *Simultaneous Investigations of Fission Fragments and Neutrons in* ^{252}Cf]

Angular Results

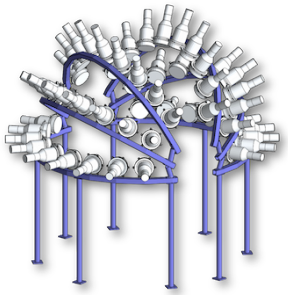
Each detector is characterized by a specific angle based on the simulated interaction coordinates.

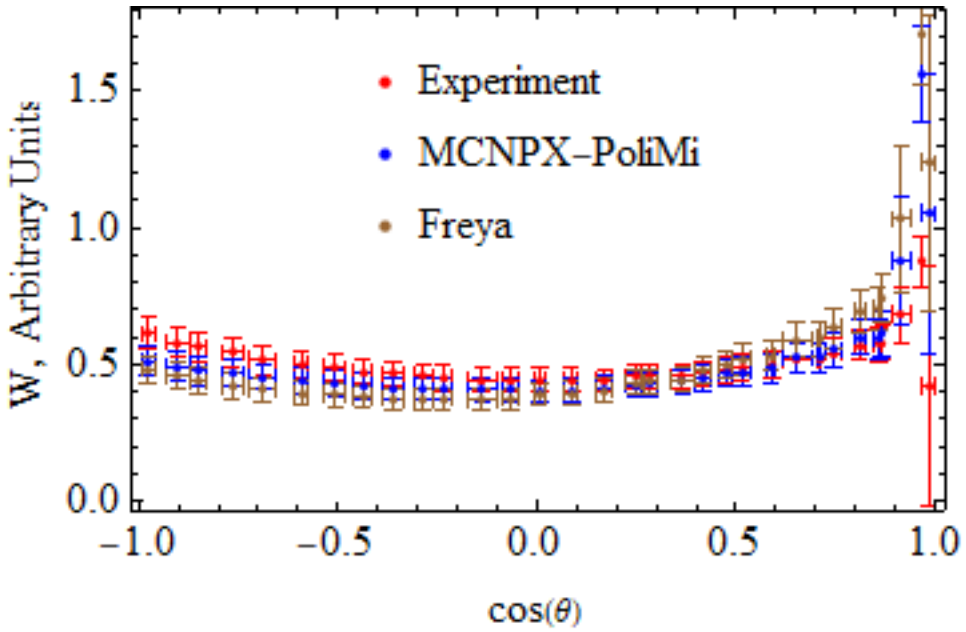
We record the bi-correlation counts, W_{ij}, using the doubles rate D_{ij} for each detector pair and weight this by the product of the singles rates:

$$W_{ij} = \frac{D_{ij}}{S_i S_j}$$

Cross talk effects can be seen at low angles.

We can impose angle cuts to determine if emitted neutrons come from the same or different fragments.





Average bicorrelation counts, $\overline{W_{ij}}$, averaged over the detector pairs (i, j) in each angle bin.

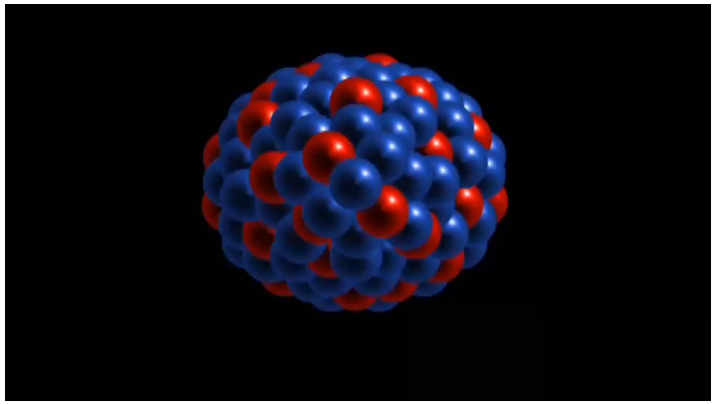
Expected Impact

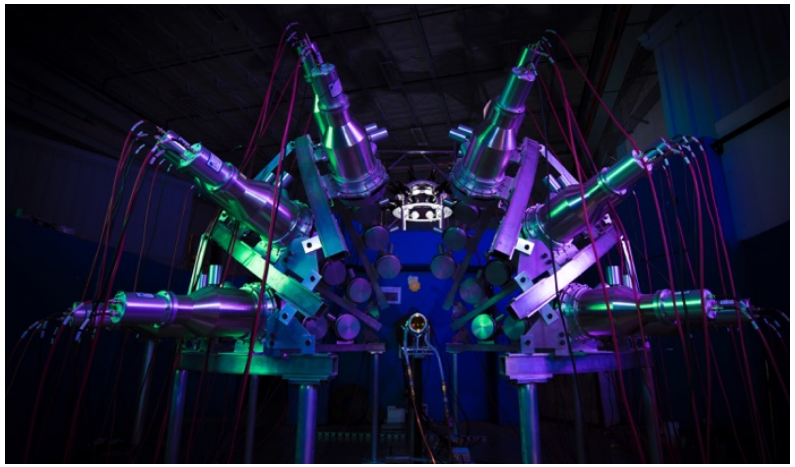
By combining these two correlations, we can quantify the relationship between emitted neutrons within the same fission event over various emission angles.

The measurement of such a correlation would improve our current models of nuclear fission, which can better inform fission event generators that are used for various fields within nuclear engineering.

- How do these correlations compare for neutrons emitted from different fragments versus the same fragment?

Provide an additional way to identify SNM, an essential aspect of nonproliferation and safeguards.





MTV Impact

This work is a product of many collaborations between the University of Michigan DNNG Group and other MTV contributors, such as LANL and LLNL.

FREYA is an open source fission event generator, allowing many opportunities for collaboration and progress.

- These codes have applications to many areas of nuclear engineering and physics beyond nonproliferation.

The study of fission correlations adds to the analysis that can be done with many different kinds of detector technologies, and the MTV allows for this exposure.

Conclusion and Ongoing Work

Fission reactions undergone by special nuclear material produce correlations in energy, multiplicity, and angle in the emitted radiation.

Quantifying these combined cross correlations can help identification and characterization of Special Nuclear Material.

In further investigations, we hope to:

- ID and remove systematic biases and cross talk.
- Expand this analysis to fission events beyond multiplicity of 2.
- Apply this analysis to neutron-photon and photon-photon correlations.

eoins@umich.edu

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