IAEA nBHEAM 2025

A new GEANT4 fission physics model for simulation of high-energy neutron detection and measurements

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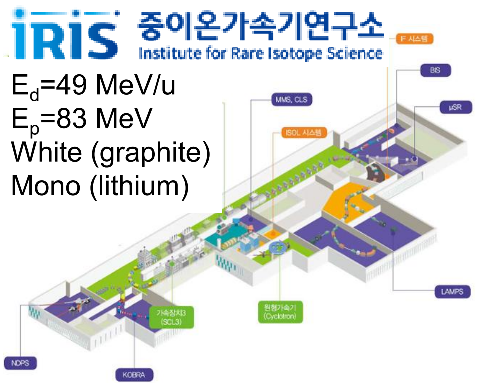
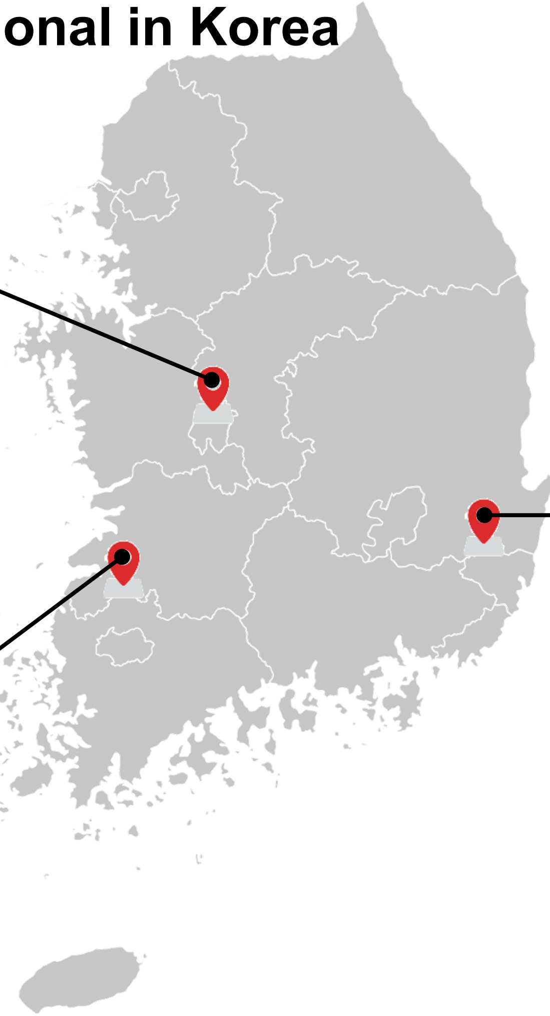
01 Neutron Facilities in Korea

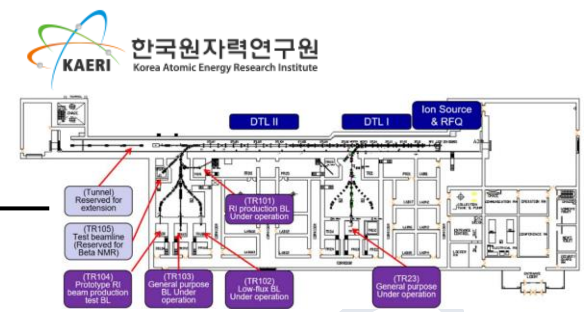
Accelerator-driven High-energy Neutron Sources

- **High-energy neutron sources based on accelerators are currently operational in Korea**

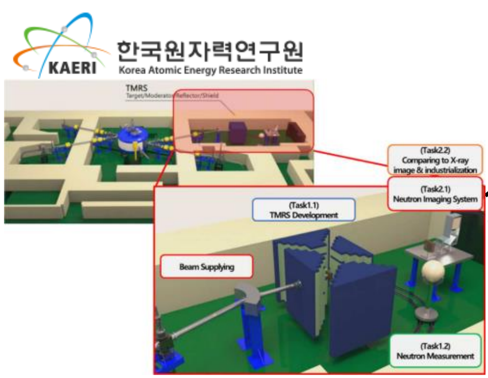


E_d=49 MeV/u
E_p=83 MeV
White (graphite)
Mono (lithium)





E_p=100 MeV
White (copper)

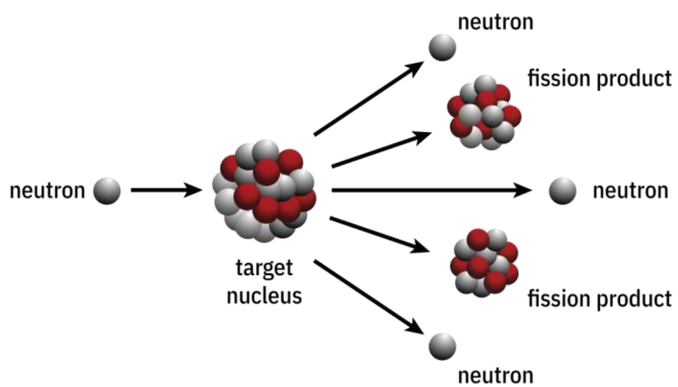


E_p=30 MeV
White (beryllium)

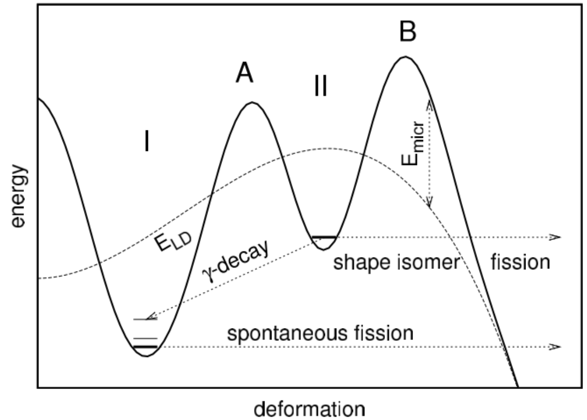
02 Fission for Neutron Detection

Nuclear Fission

- **Subatomic phenomenon in which a nucleus splits into two, emitting energetic neutrons and photons**



Nuclear fission (https://www.atomicarchive.com/science/fission)



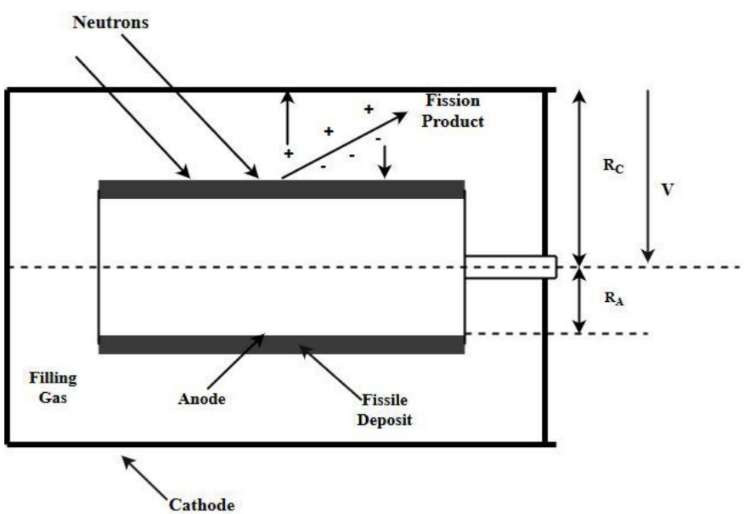
Schematic plot of the double-humped fission barrier as function of the elongation
J. Randrup, and R. Vogt, "Nuclear Fission", LLNL-BOOK-591732

- **Various research and applications**
  - Basic research
  - Energy production
  - Rare and medical radioactive isotopes production
  - Nuclear waste package assay
  - Nuclear safeguards and inspection

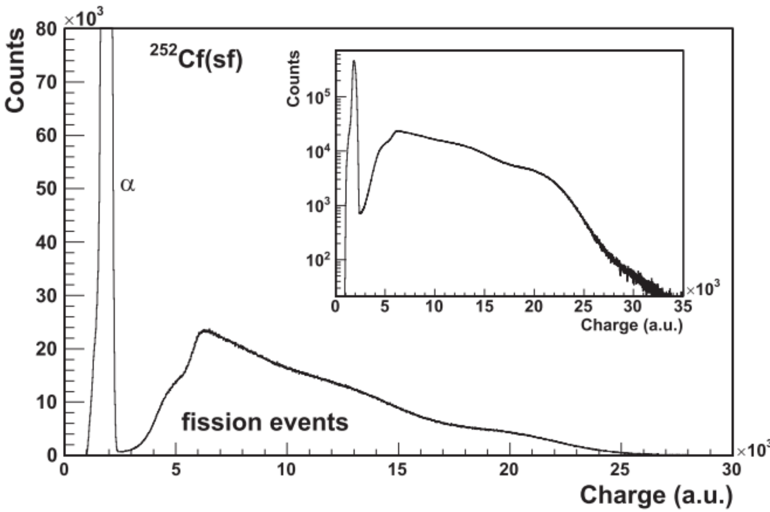
02 Fission for Neutron Detection

Neutron Fission Counter (or Fission Chamber)

- **Neutron detection based on the neutron-induced fission of fissile materials**
- **Typically, in the form of gas counters holding fissile materials**
- **Relatively insensitive to gamma compared to neutron, but background signals due to the alpha decay of fissile materials**



Basic operation principle of a fission chamber
James et al., IEEE Trans. Nucl. Sci. 57 (2010) 3678--3682



The response of the ^{238}U fission counter exposed to ^{252}Cf
J. Taieb et al., Nucl. Instrum. Methods A833 (2016) 1--7

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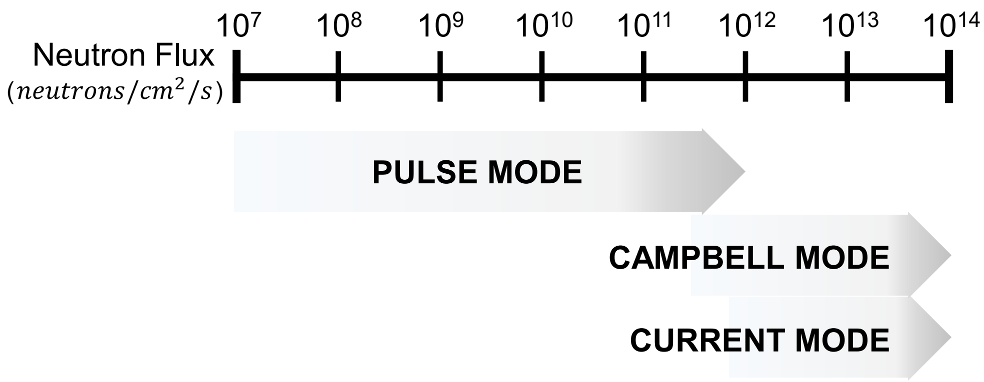
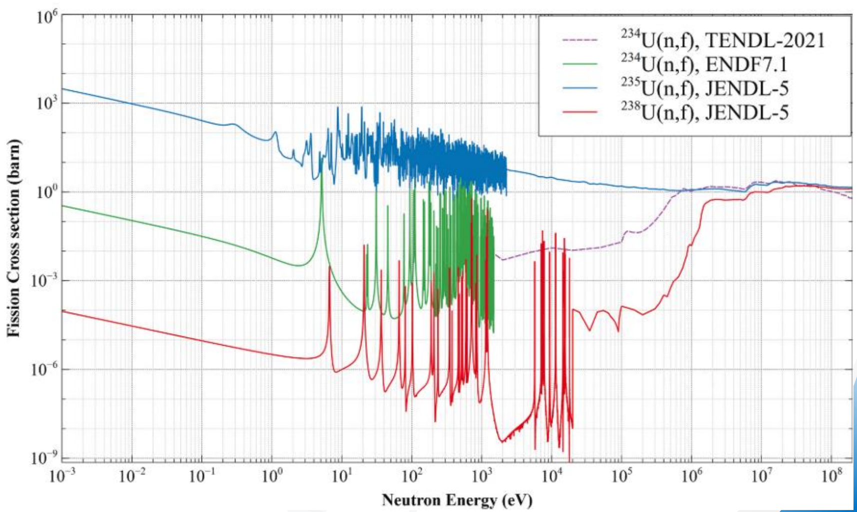
02 Fission for Neutron Detection

Neutron Fission Counter (or Fission Chamber)

- **Covers a wide neutron-flux range depending on the operation mode: pulse, Campbell, and current mode**
- **Detects neutrons in the broad neutron energy range: from a few meV up to a few hundred MeV**
- **Operates under extreme conditions such as nuclear reactors (e.g., high temperature or high radiation fields)**



A new small fission chamber for in core and wide range neutron flux measurement, CEA, Tech. Rep., 2006



Neutron-induced fission cross-sections of uranium isotopes $^{234,235,238}_{92}U$ in ENDF7.1, JENDL-5, and TENDL-2021.

03 Fission Model and Tests

GEANT4 High-precision Neutron Models

Appropriate for most neutron simulations

Physics model includes

- Elastic scattering (thermal neutron scattering for specific nuclides)
- Inelastic scattering
- Capture
- **Fission**

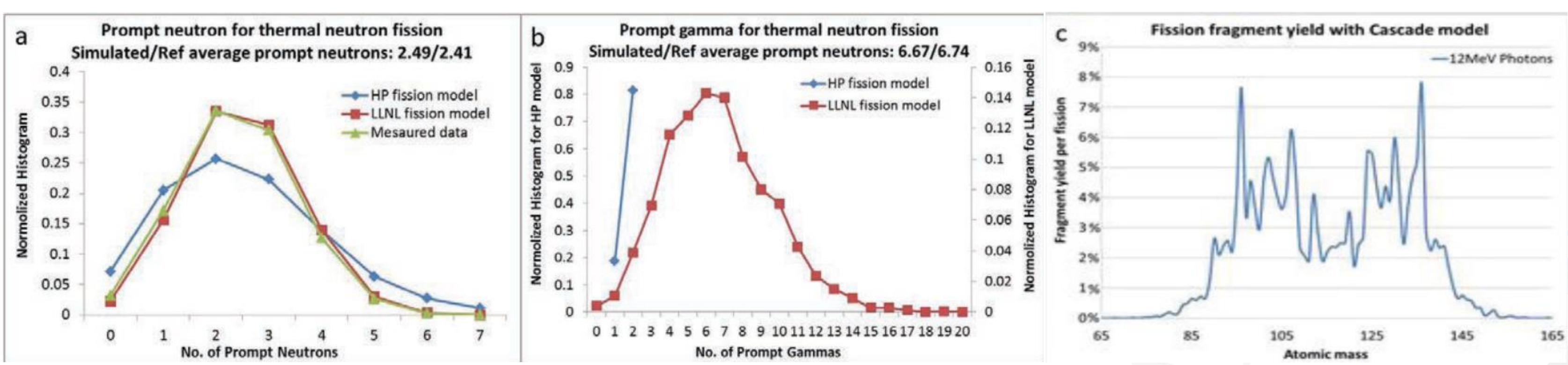
Models based on the evaluated dataset, G4NDL

- Cross sections
- Fission fragment yields and final states

03 Fission Model and Tests

GEANT4 High-precision Neutron Models

- **The HP fission model generates fission observables that are inconsistent with the measurements**
  - Total and kinetic energy, and the multiplicity of particles are not reproduced well with this model
- **Photo-fission is not properly being addressed in GEANT4**



Multiplicity of prompt (a) neutron and (b) gamma for neutron-induced fission of $^{235}_{92}U$, and fission-fragment yields for photo-fission of $^{235}_{92}U$
J. Tan and J. Bendahan, Physics Procedia 90 (2017) 256--265

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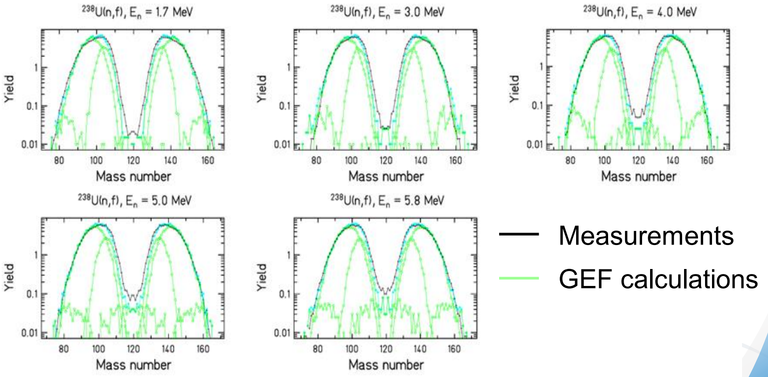
03 Fission Model and Tests

General description of the fission observables (GEF)

[Ref] General Description of Fission Observables, NEA/DB/DOC(2014)1, and https://www.lp2ib.in2p3.fr/nucleaire/nex/gef

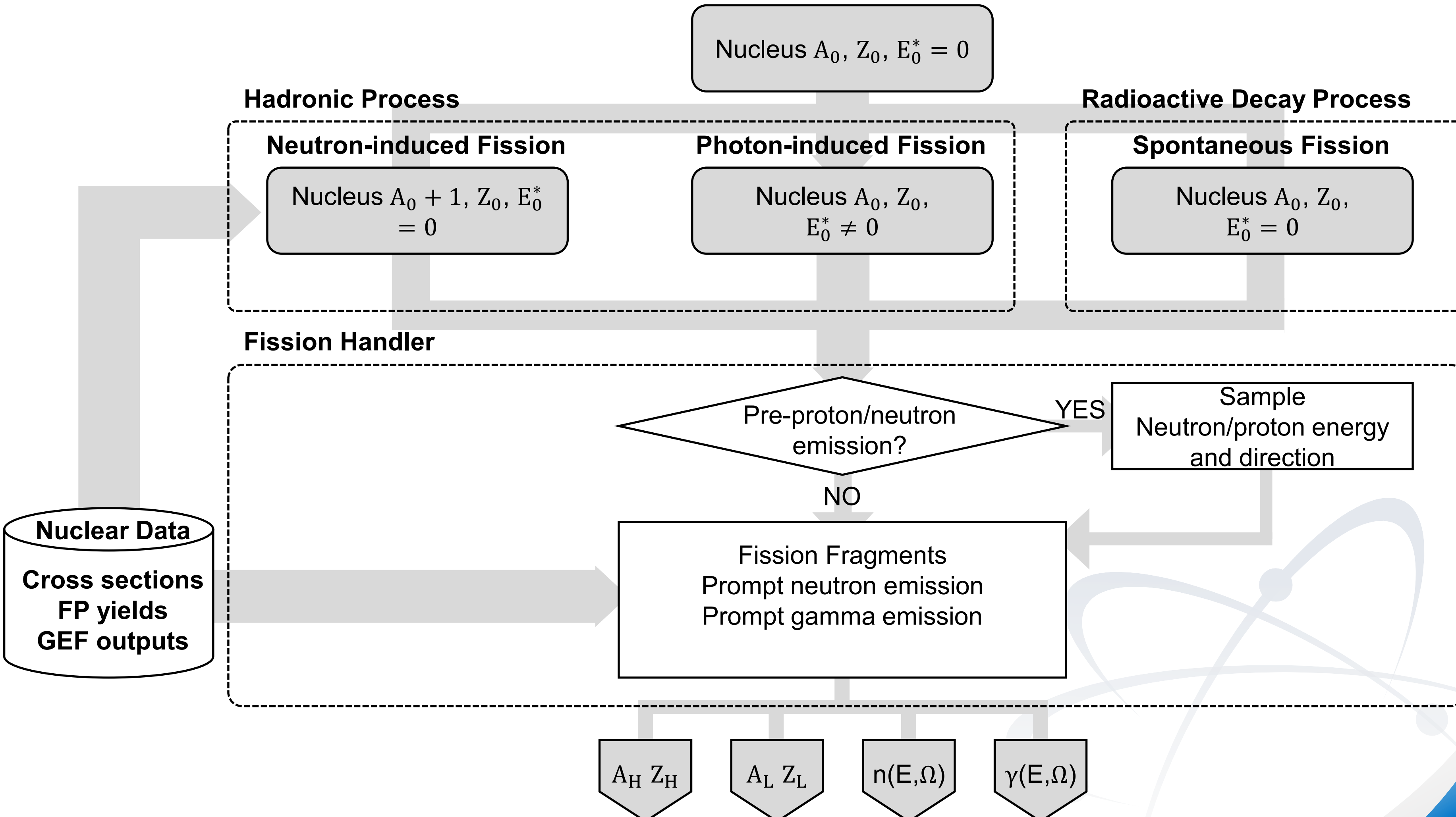
- **The code treats spontaneous and neutron-induced fission at excitation energy up to 100 MeV**
- **Trying to implement a fission model that is able to reproduce physical observables without a complete set of nuclear data**
- **The following quantities of GEF calculations are used as input data to the GEANT4 fission model**
  - Fission fragments yield for photo-fission
  - Multi-chance fission probabilities
  - Prompt-gamma and neutron spectrum
  - Neutron and gamma multiplicity



Measured pre-neutron mass distributions from neutron-induced fission of U-238, K.-H. Schmidt and B. Jurado

03 Fission Model and Tests

Proposed Fission Model



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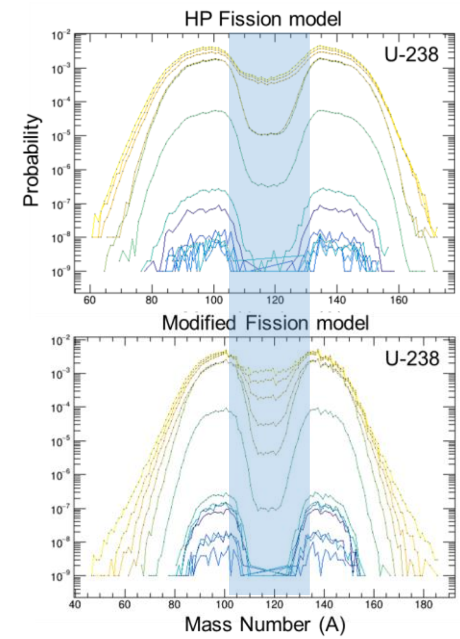
03 Fission Model and Tests

Fission Fragments

- **Generated based on the ENDF card (MT=454)**
  - Dependency on excitation energy gets improved
- **Spontaneous and neutron-induced fission**
  - GEFY-6.1 Fission Yield Libraries
- **Photo-fission**
  - GEF-generated fission product yields at E_x^*



(thermal) neutron-induced fission

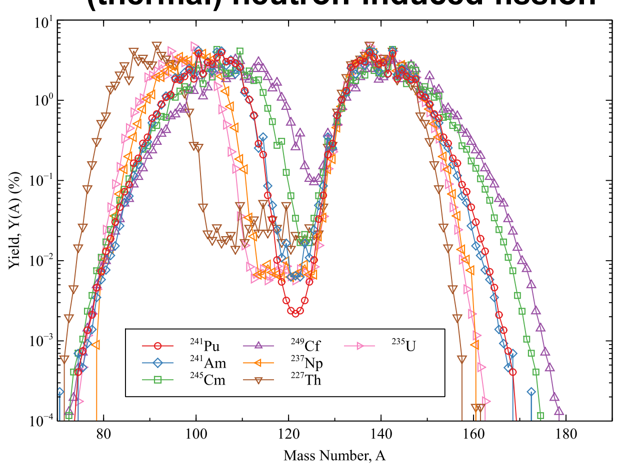
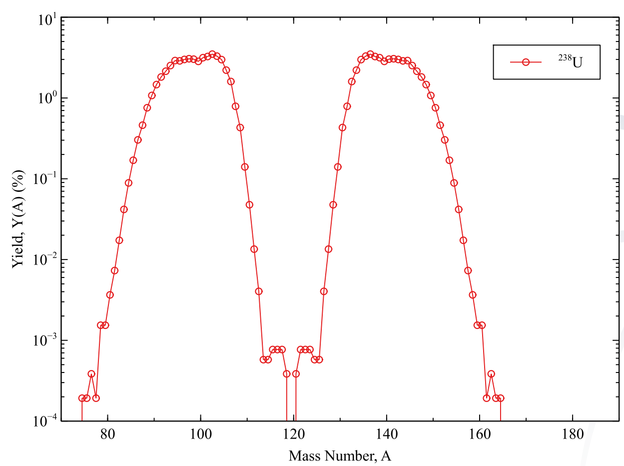
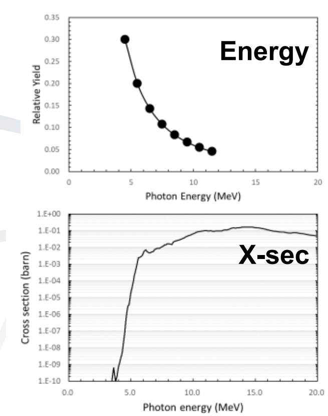


Photo-fission





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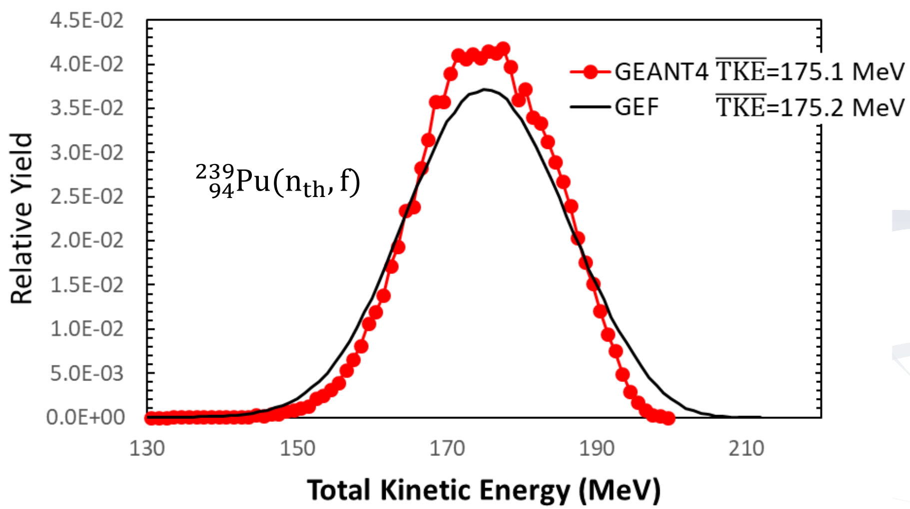
Fission Fragments

Energy conservation

$$Q = T_A + T_B + T_n + E_\gamma + E_{coll}$$

- $T_{A,B}$= fragments kinetic energy
- T_n= total neutron kinetic energy
- E_γ= total gamma energy
- E_{coll}= collective energy of fragments

[1] K.-H. Schmidt and B. Jurado, NEA/DB/DOC(2014)1
[2] M. Asghar and R.W. Hasse, J. Phys. Colloques 45(1984)C6-455



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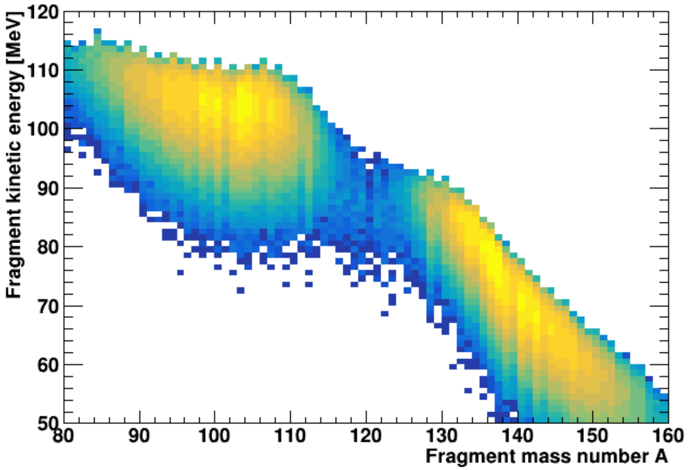
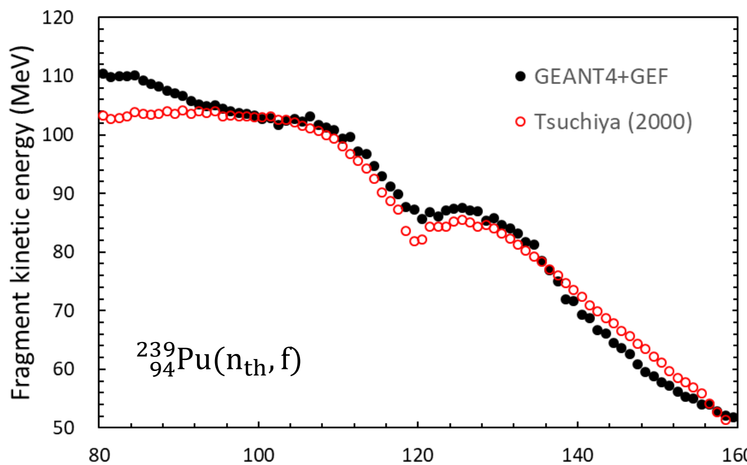
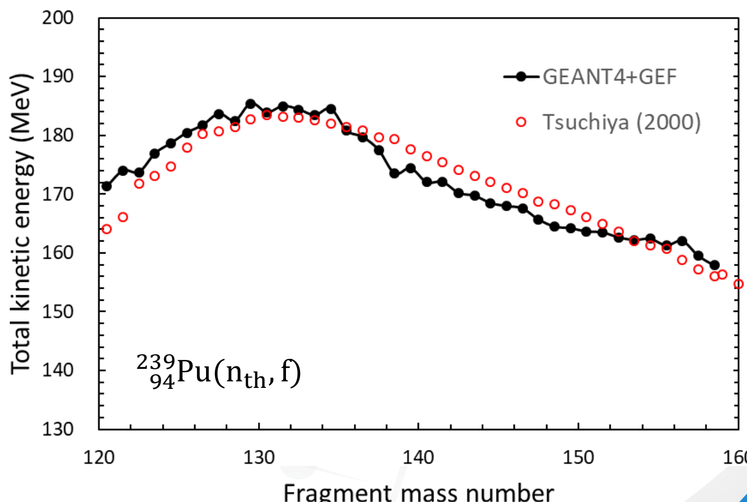
Fission Fragments (Quantum-mechanical features)

Kinetic energy



C.Tsuchiya et al., J. Nucl. Sci. Technol. 37(2000)941





- $^{239}Pu + n_{thermal}$ case
  - A≈120: Strong deformation of mid-shell nuclei
  - A≈132: Close to doubly-magic closed-shell nuclei, weak deformation

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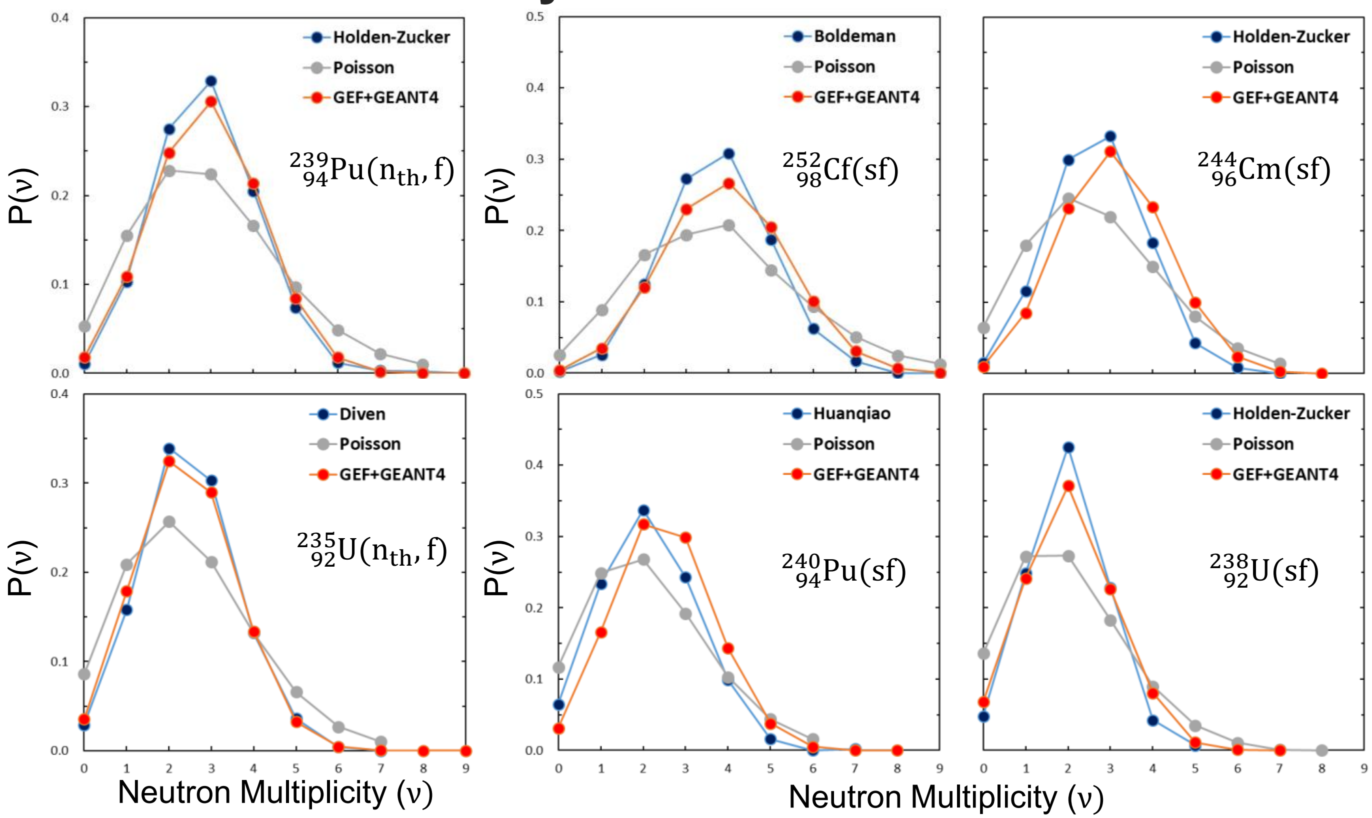
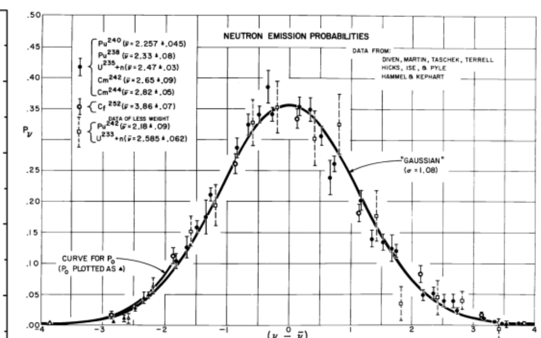
03 Fission Model and Tests

Prompt Neutron Emission

- HPFission model samples multiplicity (ν), assuming ν follows a Poisson distribution with a mean value of ν
- Gaussian distribution that governs neutron emission seems independent of fissioning nucleus, but each ν cannot be described by the Gaussian distribution



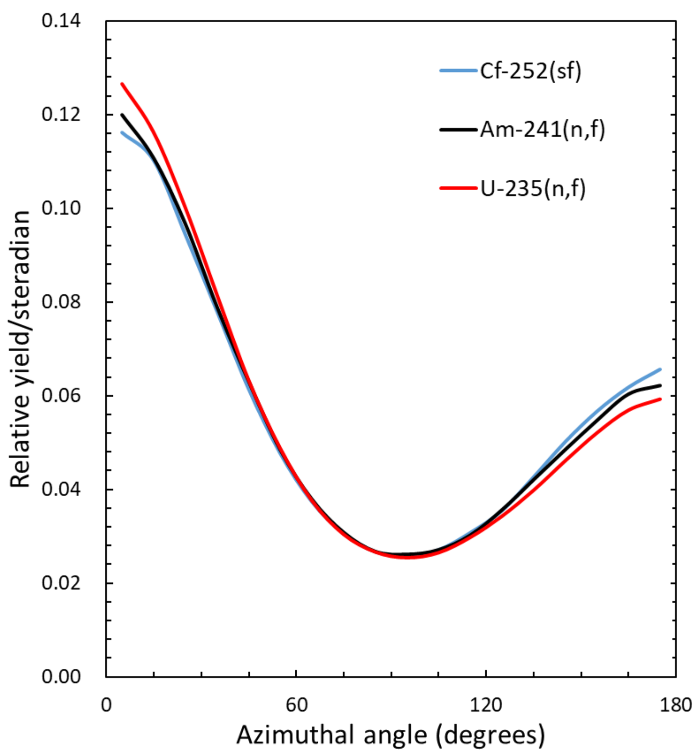


Distribution of fission neutrons
J. Terrell, in Physics and Chemistry of Fission, Vol. 2 (Vienna: IAEA, 1965), p. 3.

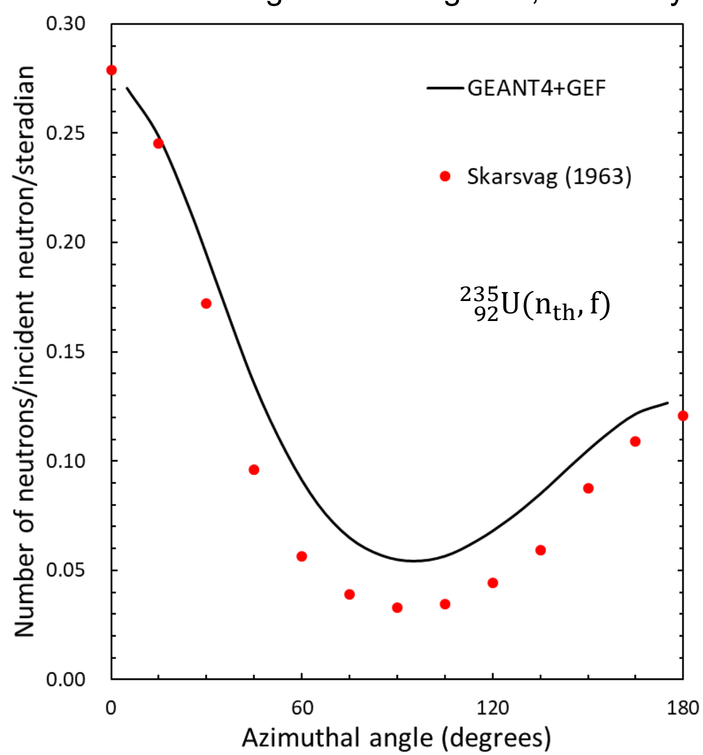
03 Fission Model and Tests

Prompt Neutron Emission

- Isotropic emission from moving fragments
- Asymmetric angular distribution with respect to the fragments due to Lorentz boost
- Angular sampling based on data is available, if needed



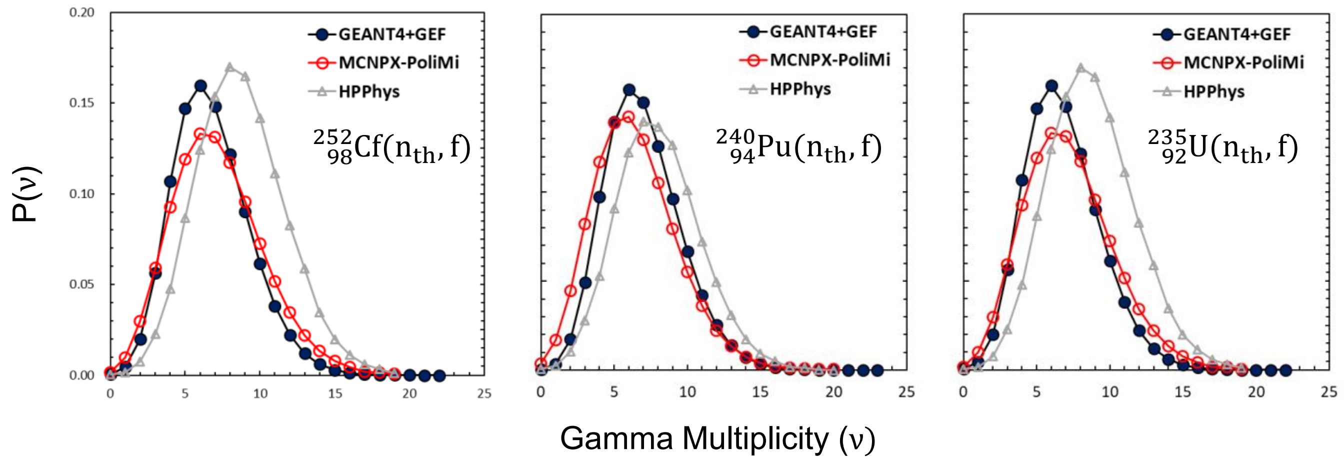
K. Skarsvåg and K. Bergheim, Nucl. Phys. 45(1963)72

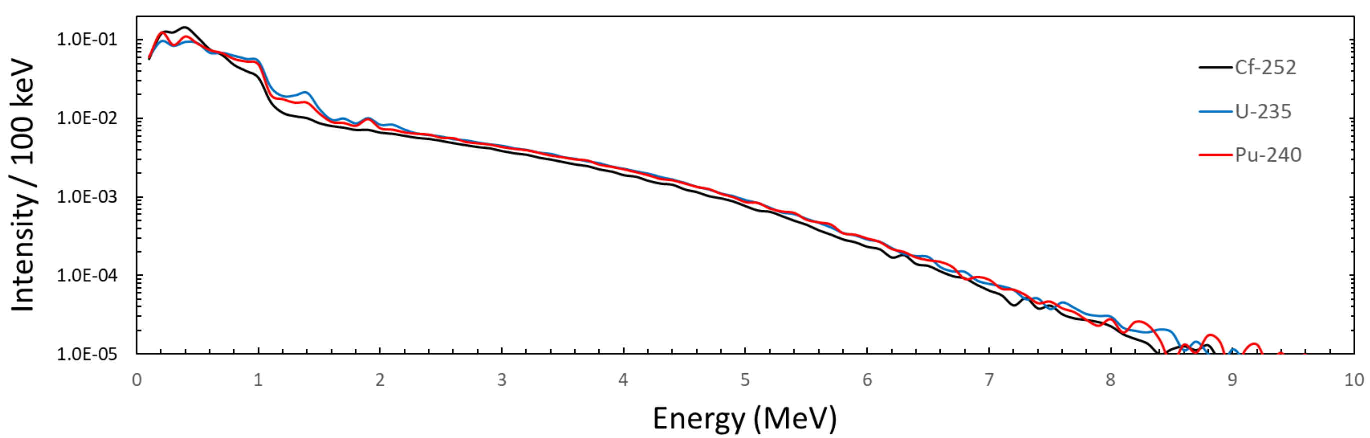


03 Fission Model and Tests

Prompt Gamma Emission

- **HPFission model samples multiplicity (ν), assuming ν follows a Poisson distribution with a mean value of ν(E)**

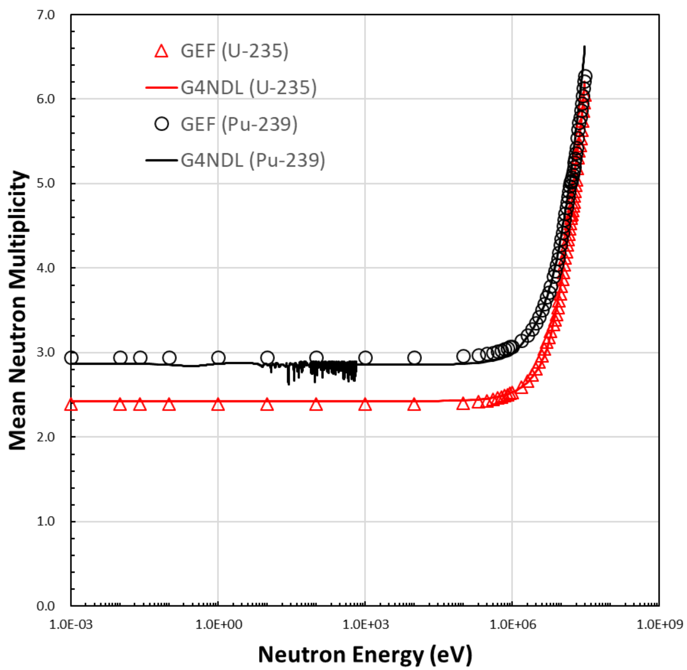


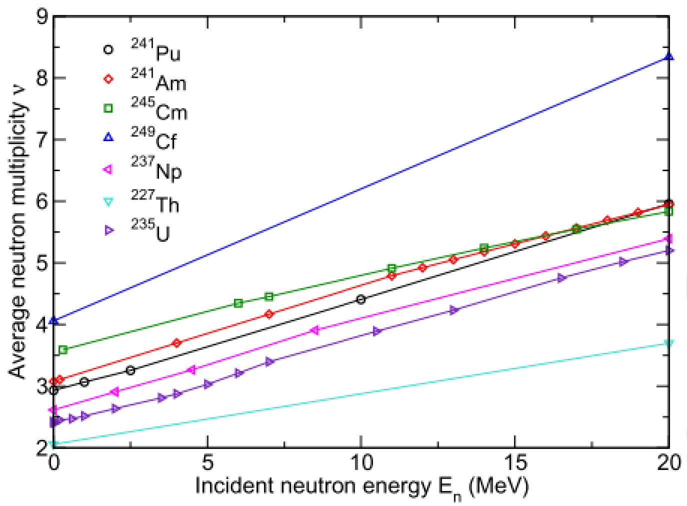


03 Fission Model and Tests

Neutron and gamma emission (n-Fission)

- The higher incident energy causes a larger multiplicity $\bar{\nu}$ because the higher incident energy results in a more excited compound nucleus
- HPFission is based on the evaluated data for $\bar{\nu}$, assuming the multiplicity follows the Poisson distribution
- The GEF multiplicity is tuned in criticality calculations





Neutron multiplicity as a function of incident neutron energy. J. Randrup and R. Vogt (2012)

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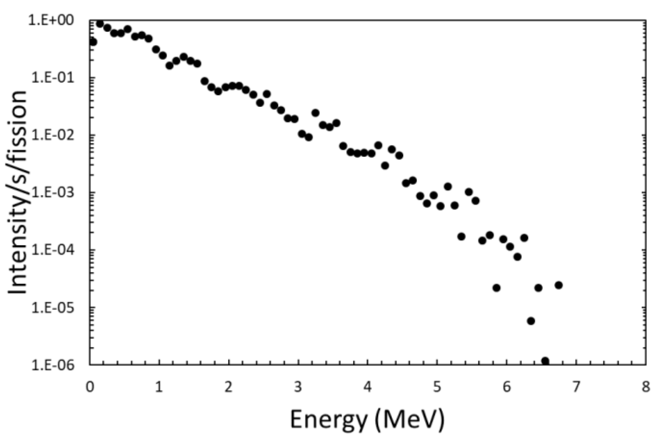
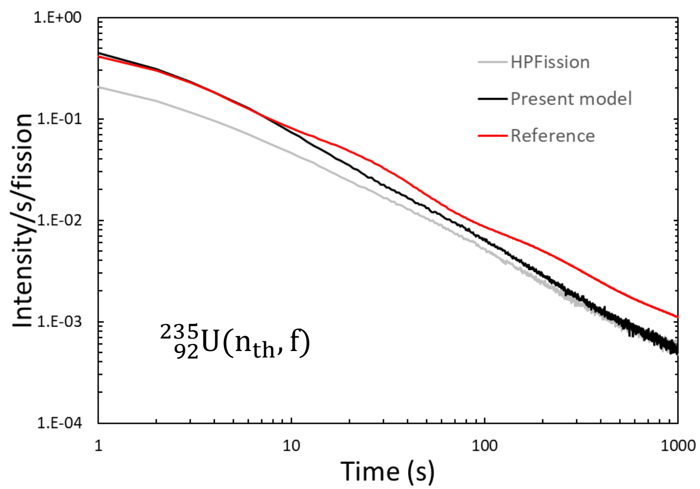
03 Fission Model and Tests

Delayed Neutron and Gamma Emission

- **Delayed neutron and gamma emissions can be handled by the radioactive decay process in GEANT4**
  - However, β-delayed nucleon emission is not implemented yet in the radioactive decay process
  - It seems appropriate for the GEANT4 physics framework to handle delayed neutrons in radioactive decay rather than fission processes
- **Fission fragments solely determine the delayed gamma rays**
  - Decay time and energy correspond to half-life and level scheme of fission fragments





[1] J. Tan and J. Bendahan, Physics Procedia 90(2017)256
[2] T. Gozani, NUREG/CR-0602 (1981)

04 Validation with Criticality

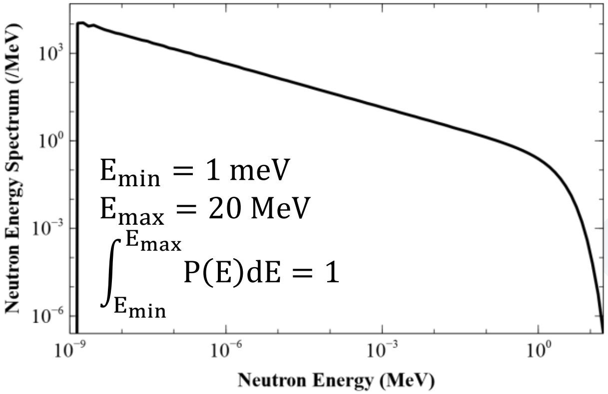
Criticality Calculations

- Simulations were validated for three critical systems: GODIVA, Jezebel, and STACY-30 [International Handbook of Evaluated Criticality Benchmark Experiments]
- Multiplication factors k_{eff} and α were calculated

$$k_{eff} = \frac{n_p(t)}{n_l(t)},$$

where $n(t) = n_0 e^{\alpha t}$ describes the population and loss of fission neutrons in the system

- Primary neutrons:
Watt fission spectrum for ${}^{235}_{92}\mathrm{U}$ sp-Fission



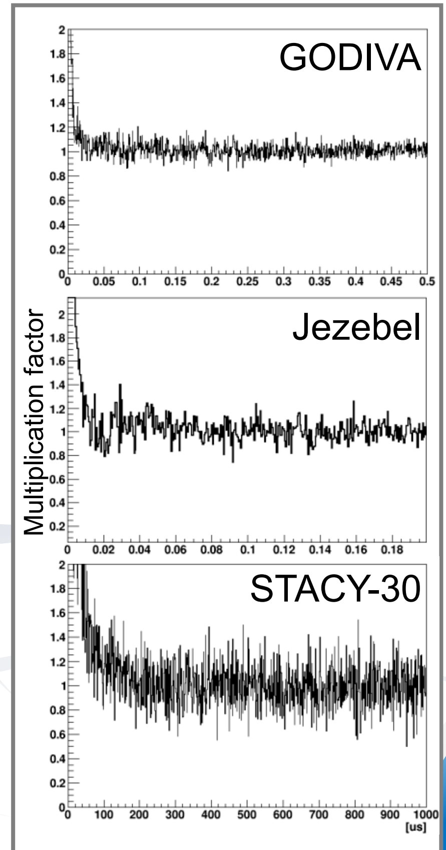
04 Validation with Criticality

Criticality Calculation Results

- The criticality and alpha are found to be very sensitive to the neutron multiplicity (in unpredictable ways)
- Fine-tuning of multiplicity gives better criticality results
- Delayed neutron emission may be required for calculations on a longer time scale

k_{eff}	Benchmark	**This work**
GODIVA	1.0000±0.0010	**1.007**
Jezebel	1.0000±0.0020	**1.002**
STACY-30	0.9973±0.0009	**0.994**

Rossi α [10^4 generations/s]	Benchmark	**This work**
GODIVA	111±2	**183**
Jezebel	64±1	**42**
STACY-30	0.0127±0.0003	**0.016**



05 Summary

- **Neutron fission counter is a valuable tool for counting neutrons over a broad energy domain**
- **New fission model has been developed in GEANT4, enabling extensive studies on spontaneous, neutron-induced fissions, and photo-fission**
- **The model was validated with experimental data for several nuclides in terms of fission fragments, secondary particle productions**
- **Criticality calculations for the well-known criticality systems with the model show good results**
- **The GEF-based fission model allows users to study various fissile and fissionable nuclides as new candidates for sensitive materials in neutron measurements**

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THANK YOU

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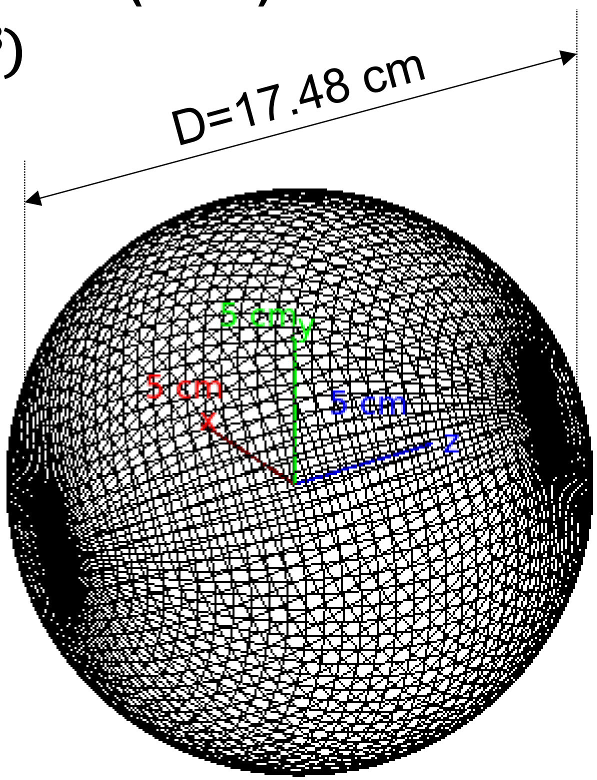
04 Simulation Results

Criticality calculation: GODIVA

- **Handbook ID: HEU-MET-FAST-001**
- **Bare sphere of highly-enriched Uranium (HEU)**
- **Material composition ($\rho = 18.74\ \mathrm{g/cm^3}$)**
  - U-234 1.02%
  - U-235 93.71%
  - U-238 5.27%
- **Simulation time: 500 ns**
  - A timing cut-off was applied to reduce CPU costs
  - Otherwise, there is a possibility that calculations do not be completed for $\boldsymbol{k_{eff} \geq 1}$



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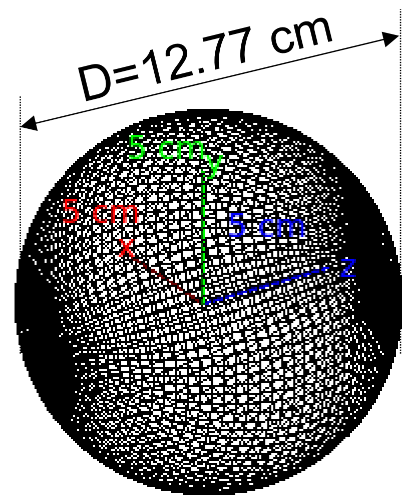
04 Simulation Results

Criticality calculation: Jezebel

- **Handbook ID: PU-MET-FAST-001**
- **Bare sphere of Plutonium**
- **Material composition (ρ=15.61 g/cm^3)**
  - ^{nat}Ga 3.413%
  - Pu-239 91.951%
  - Pu-240 4.346%
  - Pu-241 0.290%
- **Simulation time: 500 ns**



04 Simulation Results

Criticality calculation: STACY-30

- **Handbook ID: LEU-MET-SOL-THERM-007**
- **Low-enriched Uranium solution thermal system**
- **Material composition ($\rho=1.4571\ g/cm^3$)**
  - H 6.569%
  - N 4.495%
  - O 68.982%
  - U-234 0.016%
  - U-235 1.989%
  - U-236 0.002
  - U-238 17.947%
- **Thermal scattering on the following nuclides was considered**
  - Hydrogen, nitrogen, U-235, U-238
- **Simulation time: 2 ms**