Fission of Neutron-rich Nuclei Explored by Nuclear Theory and Experiment
理論と実験で拓く中性子過剰核の核分裂

Modeling the photonuclear reactions within the Hauser-Feshbach Fission Fragment Decay framework

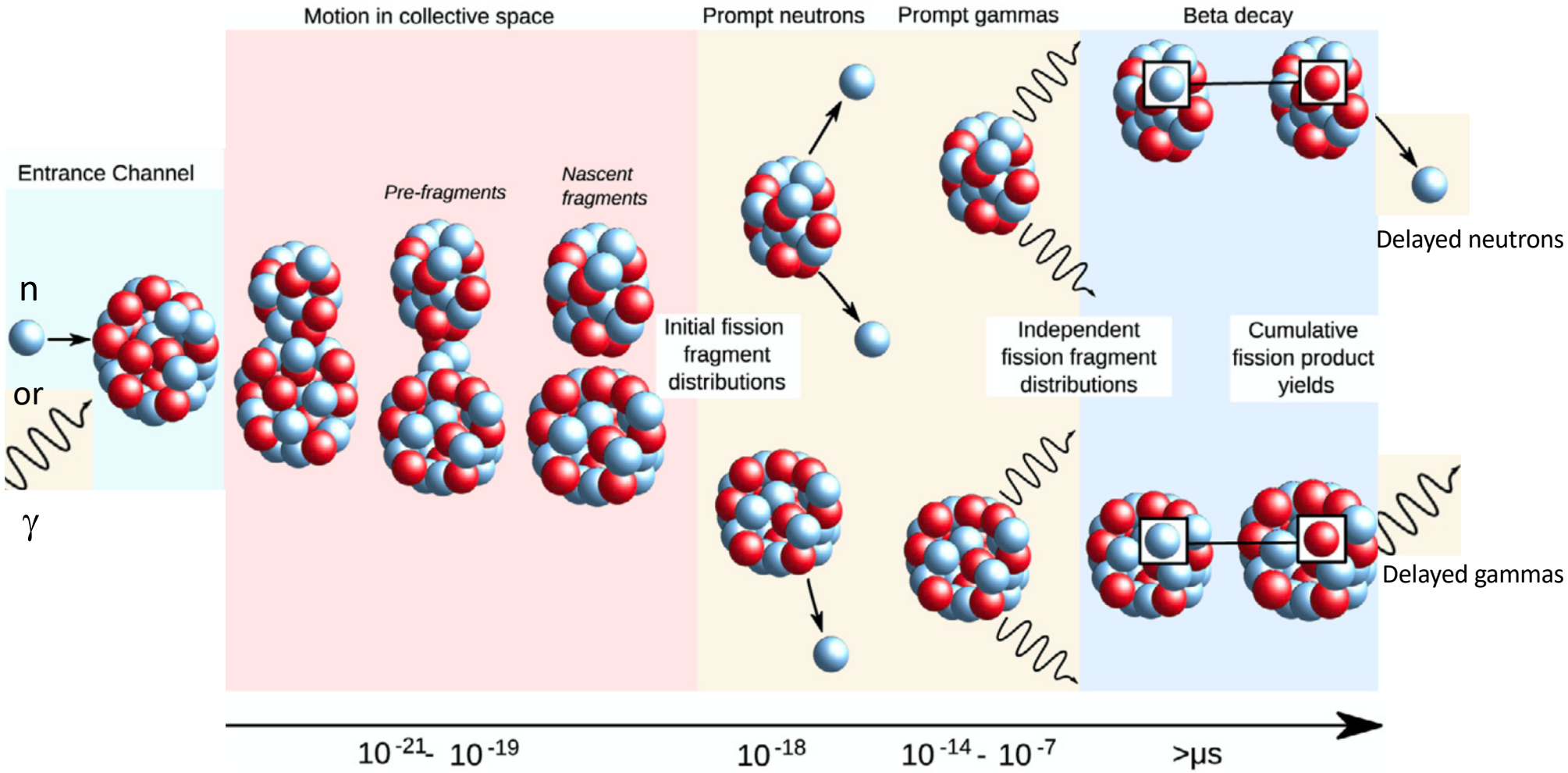
arXiv:2212.08943

T. Kawano[1], A.E. Lovell[1], S. Okumura[2], H. Sasaki[1], I. Stetcu[1], and P. Talou[1]

1 Los Alamos NATIONAL LABORATORY EST.1943

2 IAEA International Atomic Energy Agency

The neutron- or photon-induced fission processes

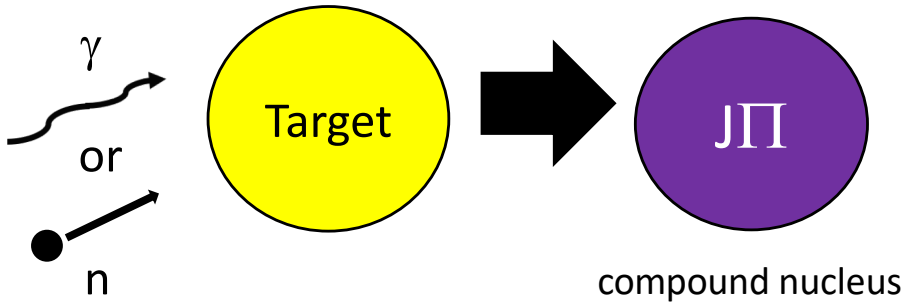


N. Schunck and D. Regnier, Prog. Part. Nuc. Phys. 125 (2022) 103963

Is there some significant difference between neutron- and photo-induced fission processes?

Spin and parity of the fissioning compound nucleus

Partial population with the optical model



$$P(E,J,\Pi) = \frac{\sigma(J,\Pi,E)}{\sigma(E)}$$

$$\sigma(E) = \sum_{J\Pi} \sigma(J,\Pi,E) \qquad \sigma(J,\Pi,E) = \frac{\pi}{k^2} g_J \sum_{lj} T_{lj}(E)$$

k … Incoming particle wave number

g_J … Spin factor

T_{lj} …Transmission coefficient

- **Photo-induced reactions**

$$T_{XL}(E) = \frac{2}{2l+1}\left(\frac{E}{\hbar c}\right)^2 \sigma_{XL}(E)$$

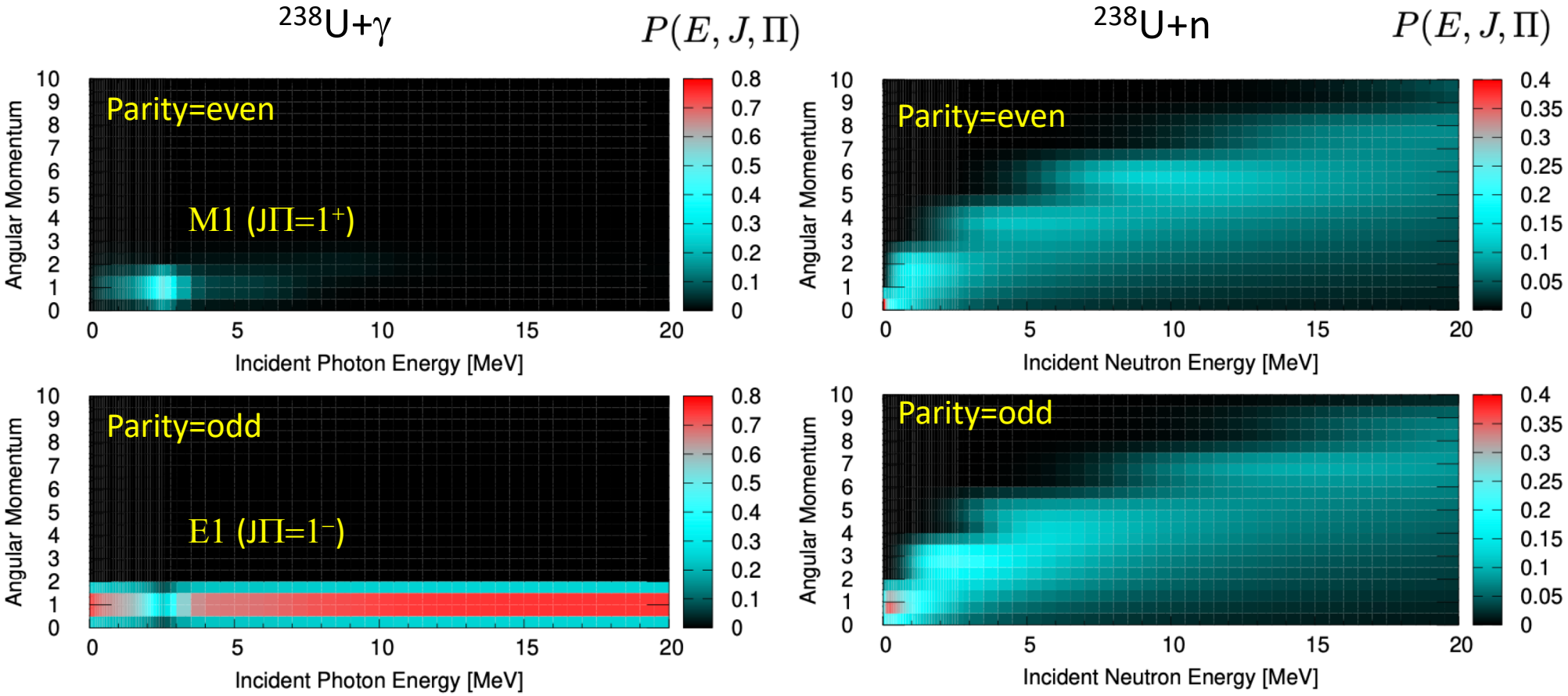
Photoabsorption (XL=E1,M1) with QRPA (H. Sasaki, T. Kawano and I. Stetcu, arXiv:2211.15935)

- **Neutron-induced reactions**

Soukhovitskii et al. PRC72, 024604 (2005)

The results of the spin and parity distributions

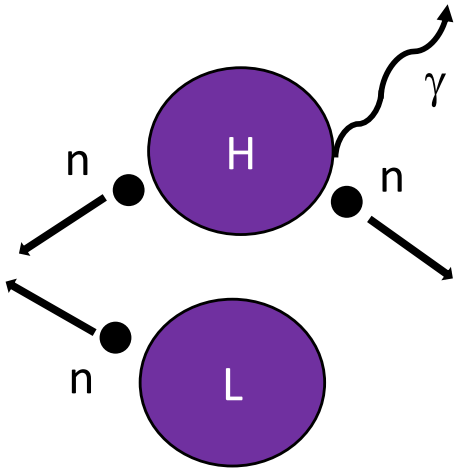
T. Kawano et al., arXiv:2212.08943



The compound states formed by a neutron distribute extensively in the GDR region, while $1^{\pm}$ states are selectively populated by the γ ray incident.

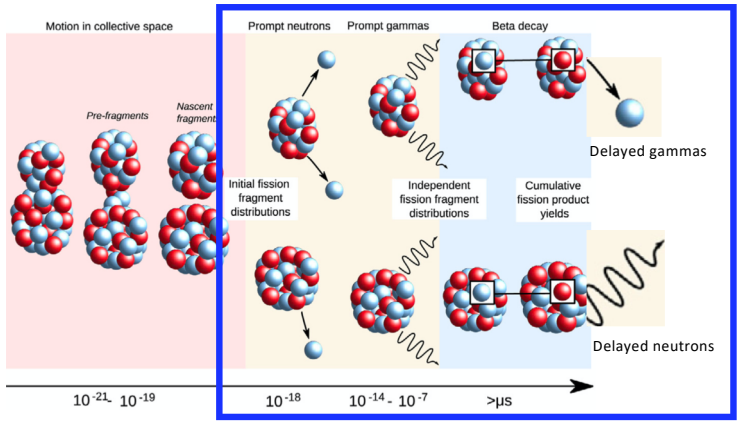
The calculated fission observables after the scission

Hauser-Feshbach decay of fission fragments (HF^{3}D model)



S. Okumura et al.,J. Nuc. Sci. Tech. 55, 1009 (2018)

S. Okumura et al., J. Nuc. Sci. Tech. 59, 96 (2022)



Decays of two fission fragments
→Statistical Hauser-Feshbach Theory

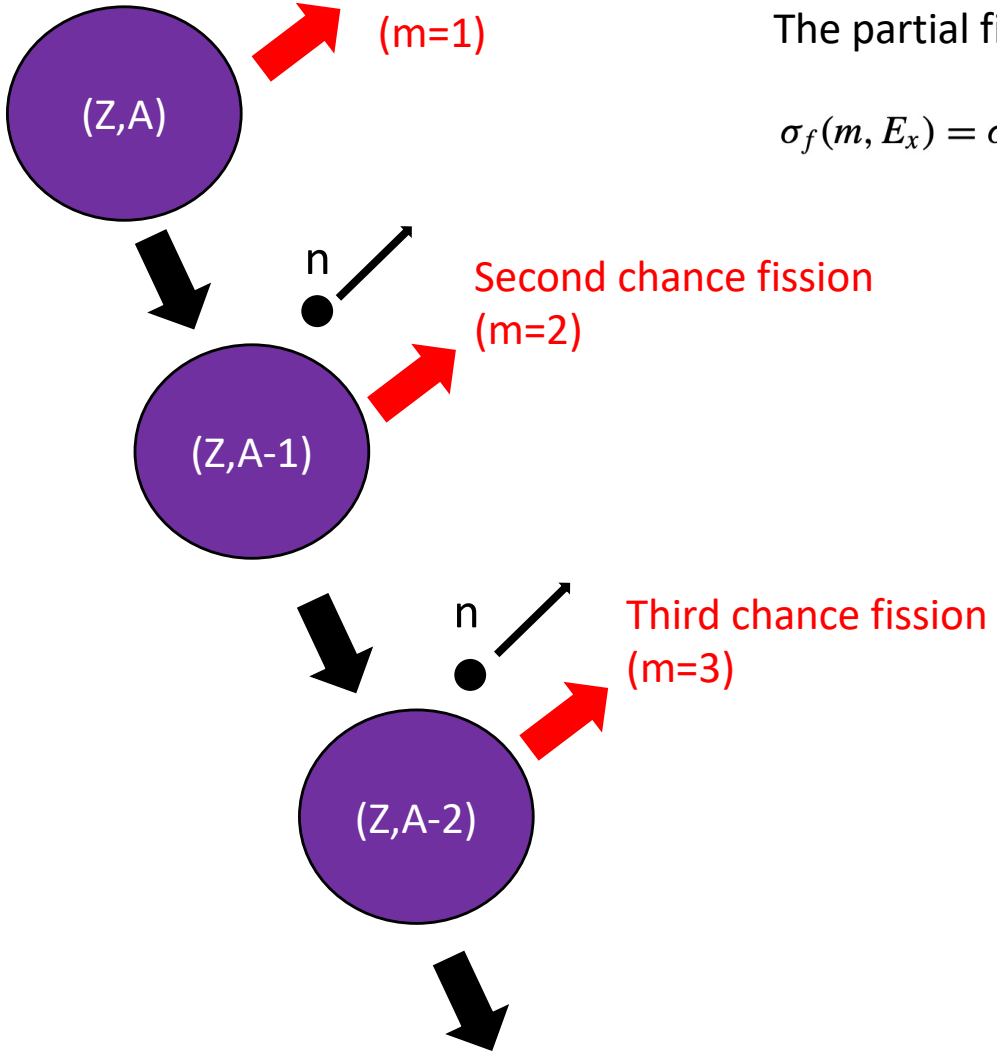
Input

- Spin, parity, and excitation energy for light and heavy fragments L,H $P_{L,H}(E_x, J, \Pi)$
- Mass distribution $Y_P(A)$
- Charge distribution
- Total kinetic energy (TKE) $T(E)$
- Decay data for the β-delayed neutron

Output

- Prompt neutrons
- Prompt γ-rays
- Cumulative fission product yields
- Delayed neutrons

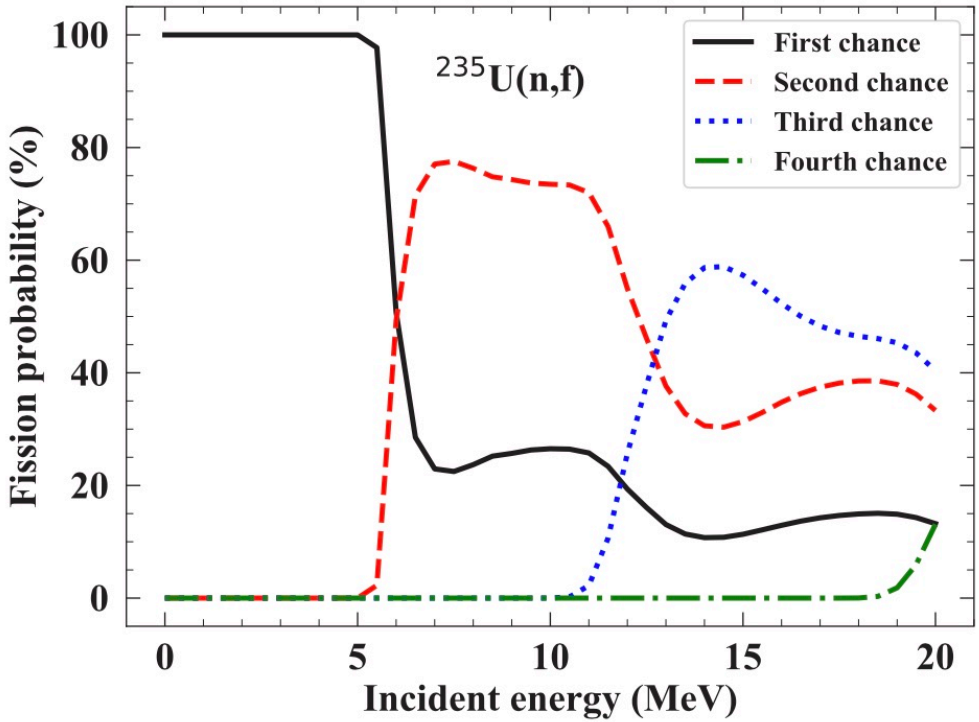
Multichance fission before the scission



The partial fission cross section

$$\sigma_f(m, E_x) = \sigma_P(m, E_x)\frac{T_f(m, E_x)}{T_n + T_\gamma + T_f(m, E_x)}$$

A.E. Lovell et al., PRC 103, 014615 (2021)

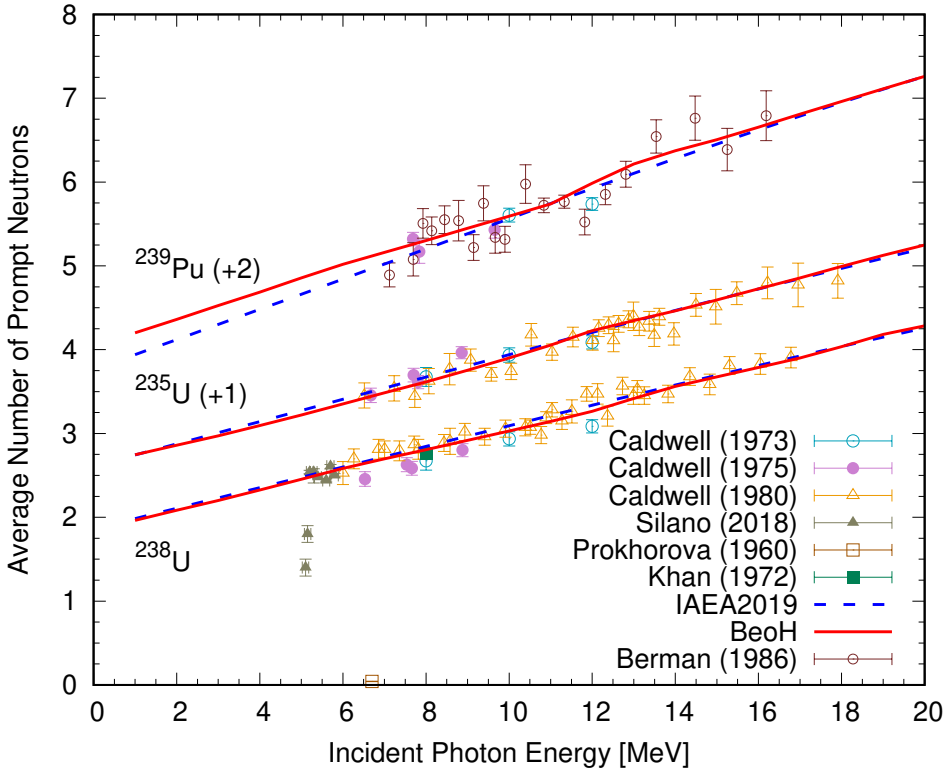


The BeoH module in CoH_3 code extends HF^{3}D model to include the multichance fission

We calculate fission observables for photo-induced reactions with the model parameters obtained in neutron-induced reactions

$\bar{\nu}_p$ and TKE for the photo-fission

T. Kawano et al., arXiv:2212.08943



Target	CN	T_0 [MeV]	T_1	Viola [MeV]
^{235}U	^{235}U	171.5	−0.10	170.4
	^{234}U	171.6	−0.10	170.6
	^{233}U	170.6	−0.20	170.8
^{238}U	^{238}U	171.1	−0.05	169.7
	^{237}U	171.9	−0.05	169.9
	^{236}U	172.8	−0.05	170.1
^{239}Pu	^{239}Pu	182.0	−0.42	176.6
	^{238}Pu	179.0	−0.42	176.8
	^{237}Pu	177.1	−0.20	177.1

The average number of prompt neutrons

$$\bar{\nu}_p = \sum_{k=1}^{N} Y_k \left(\bar{\nu}_l^{(k)} + \bar{\nu}_h^{(k)} \right)$$

S. Okumura et al.,J. Nuc. Sci. Tech. 55, 1009 (2018)

The contribution from light and heavy fragments

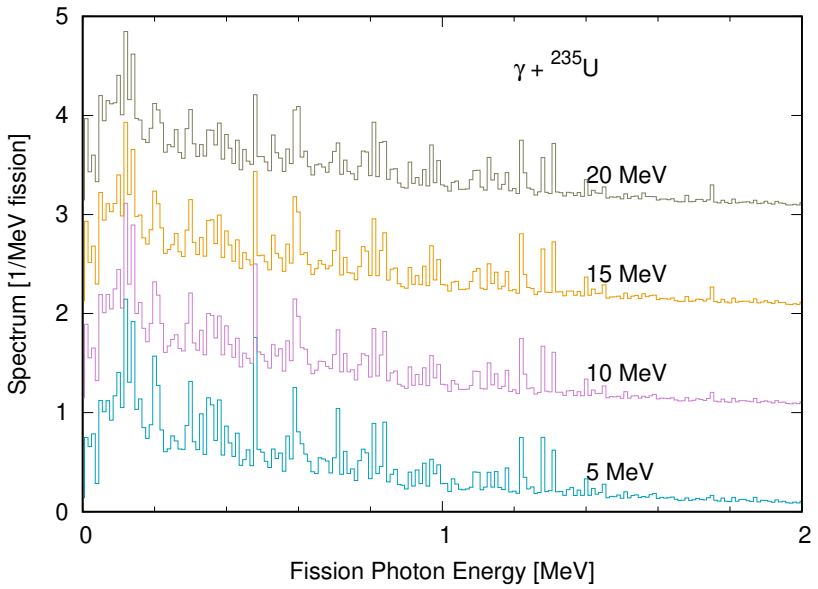
$$\bar{\nu}_{l,h}^{(k)} = \int dE_x \sum_{J\Pi} \int d\epsilon \, R(J,\Pi) G(E_x) \phi_{l,h}^{(k)}(J,\Pi,E_x,\epsilon)$$

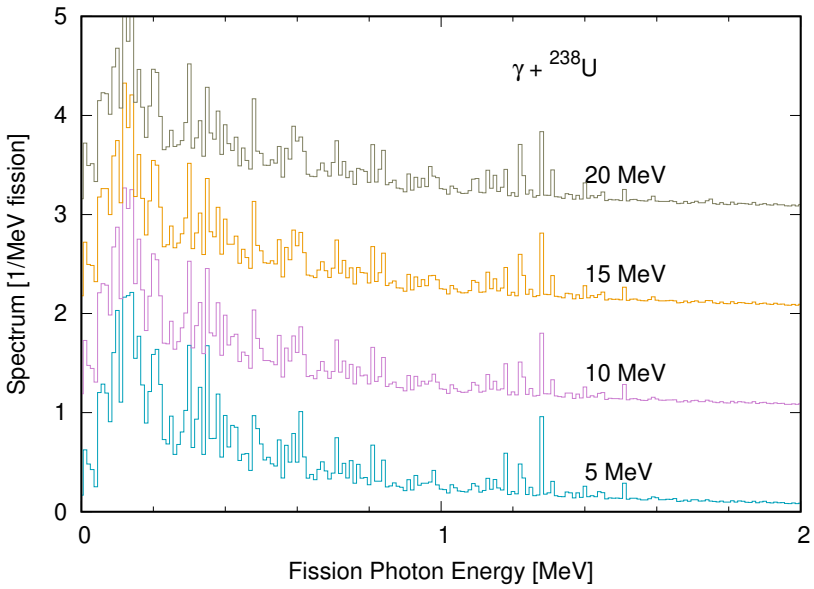
Calculated with Hauser-Feshbach theory

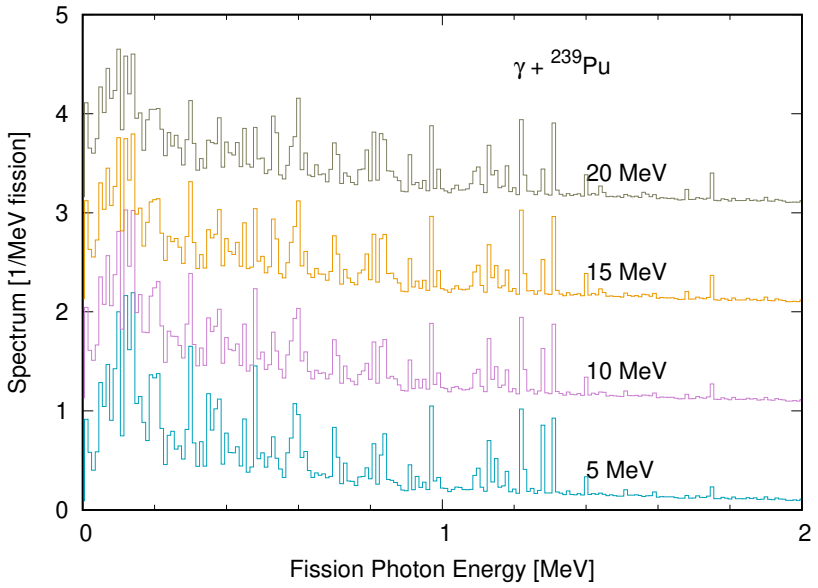
We readjust the TKE to the experimental $\bar{\nu}_p$

$$T(E) = T_0 + T_1 E_\gamma$$

The calculated prompt fission γ-ray spectra for photo-fission



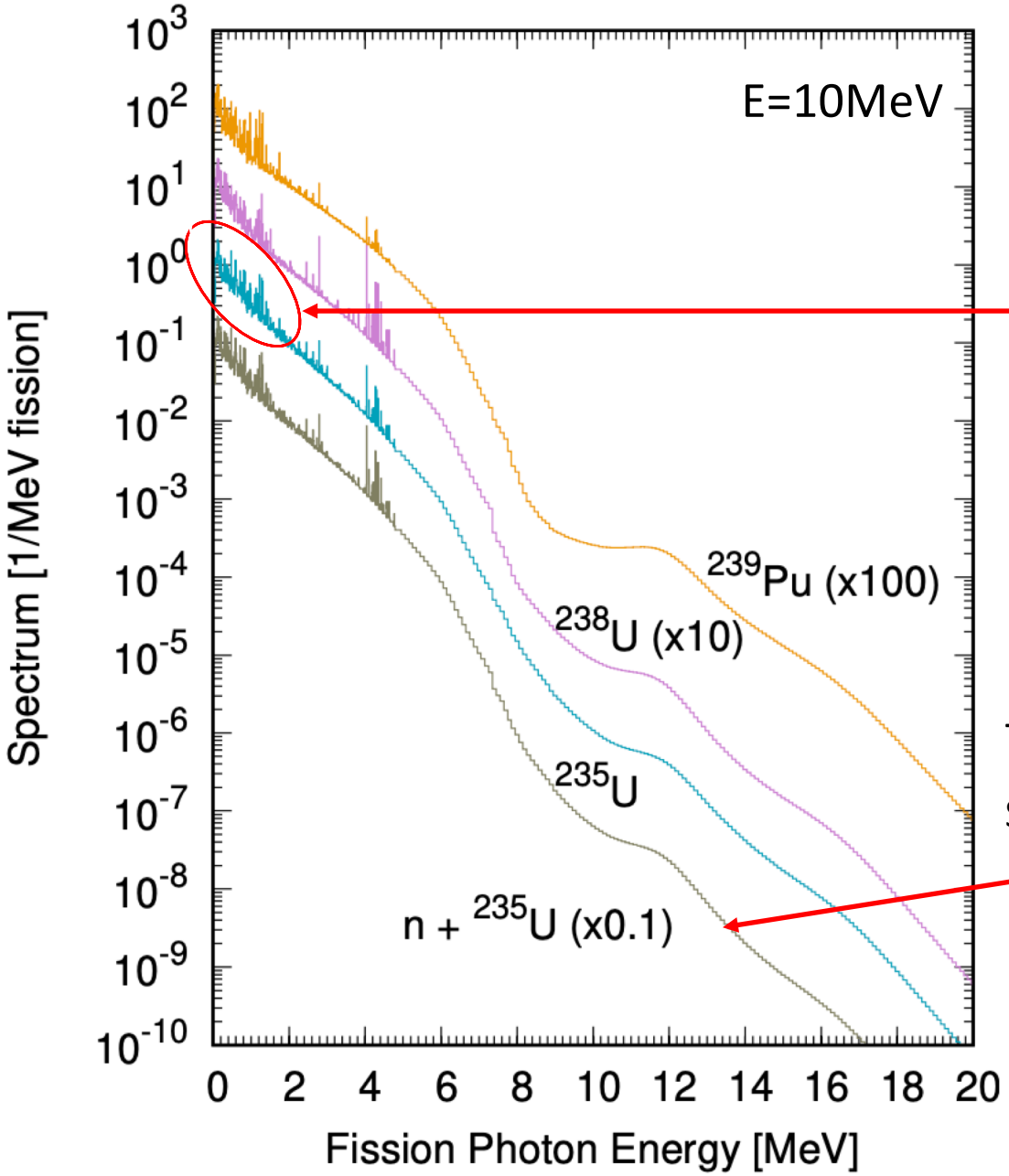


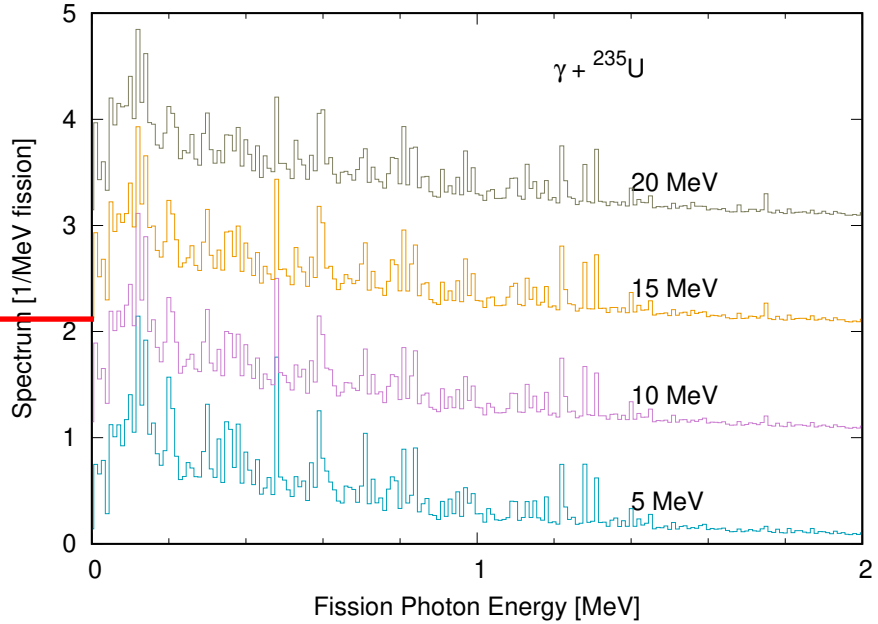


Many prominent discrete prompt fission γ-ray lines are seen in the energy spectra

Sometimes a peak in the spectrum is produced by a single discrete transition, while one histogram bin may include a few γ lines in many cases

The calculated prompt fission γ-ray spectra at E=10 MeV





Thermal-neutron-induced fission on ^{235}U

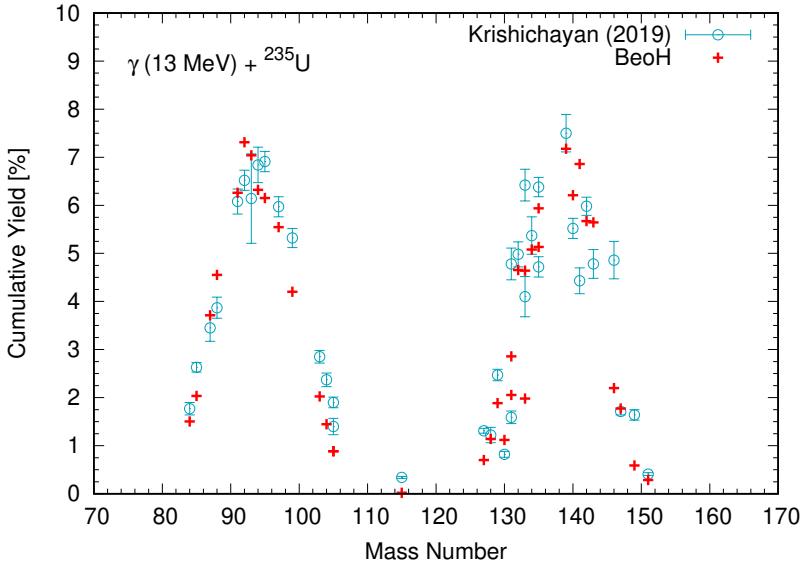
S. Okumura et al., J. Nuc. Sci. Tech. 59, 96 (2022)

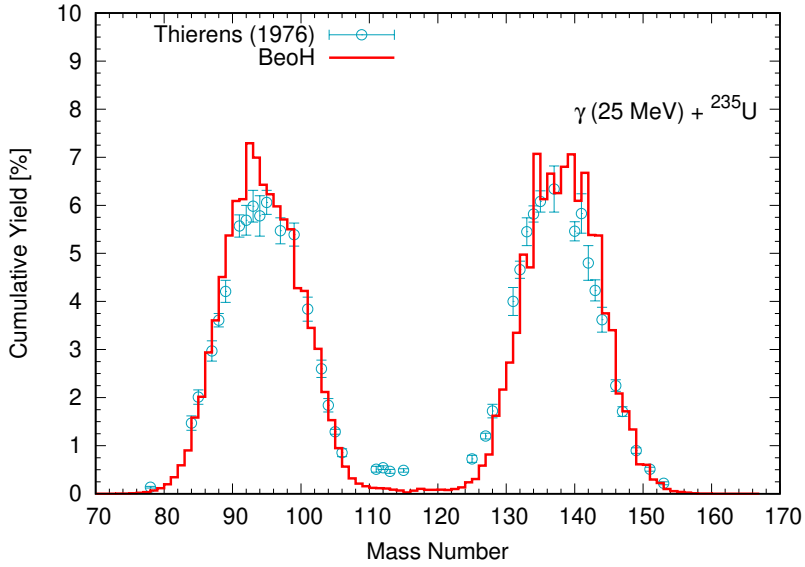
Cumulative fission product yields for photo-fission

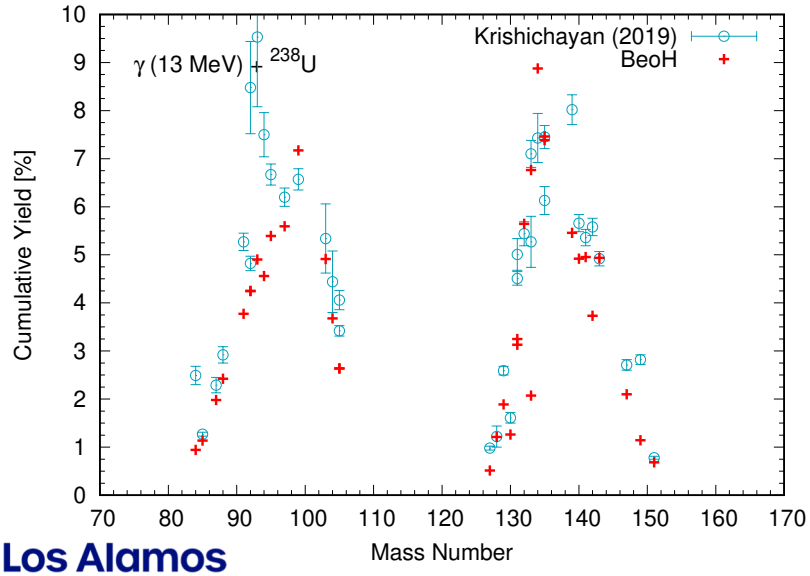
Mono-energetic photon beam at 13 MeV

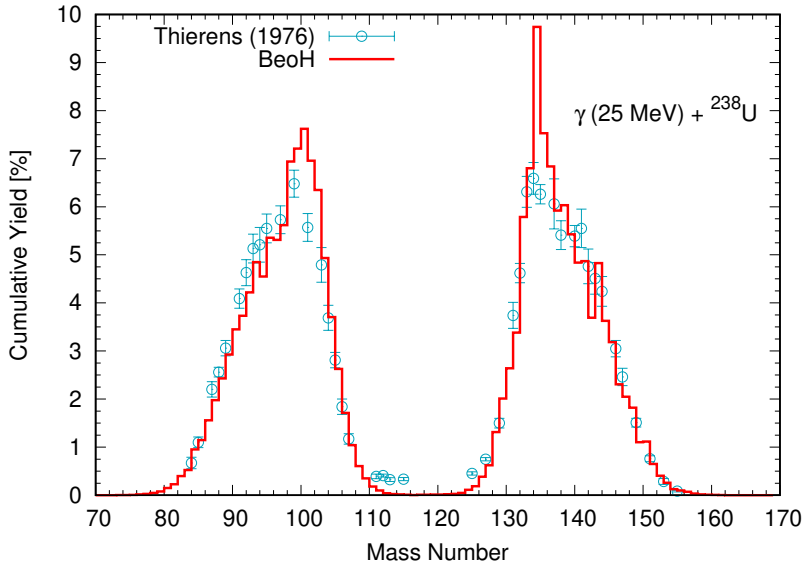
Bremsstrahlung photon source (<25MeV)

$$\overline{Y}_C(A) = \int \sum_Z w(E_\gamma) Y_C(Z, A, E_\gamma) dE_\gamma$$









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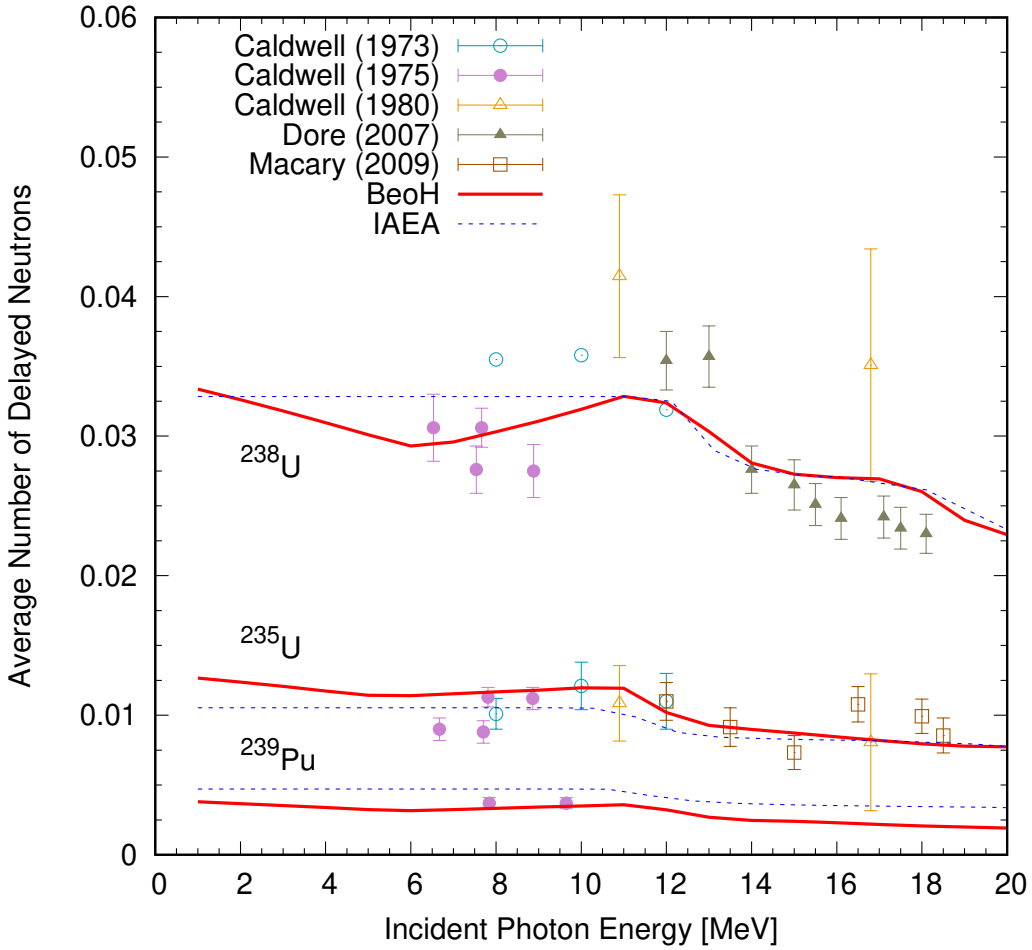
Average numbers of delayed neutrons $\overline{\nu}_d$ for photo-fission



Our calculation of photo-fission well reproduces the experimental data with model parameters of the neutron-induced fission

→ This is in contrast to the very different $J\Pi$ populations of fissioning compound states for the neutron and γ-ray induced reactions

Summary

- We calculate spin and parity distributions of the fissioning compound nucleus for both neutron- and photo-induced reactions

- We calculate fission observables for the photo-induced reactions on actinides with BeoH and compared with available experimental data

- Our calculation shows an excellent reproduction of the delayed neutron yields by employing the model parameters obtained for the neutron-induced fission cases

- This supports a traditional assumption that the photo-fission might be similar to the neutron-induced fission at the same excitation energies regardless of the spin and parity of the fissioning systems