



**IAEA**

International Atomic Energy Agency  
*Atoms for Peace and Development*

Technical Meeting on the Compilation  
of Nuclear Data Experiments for  
Radiation Characterization  
10-14 October 2022



# Radioactive Decay Calculations from Independent Fission Product Yields

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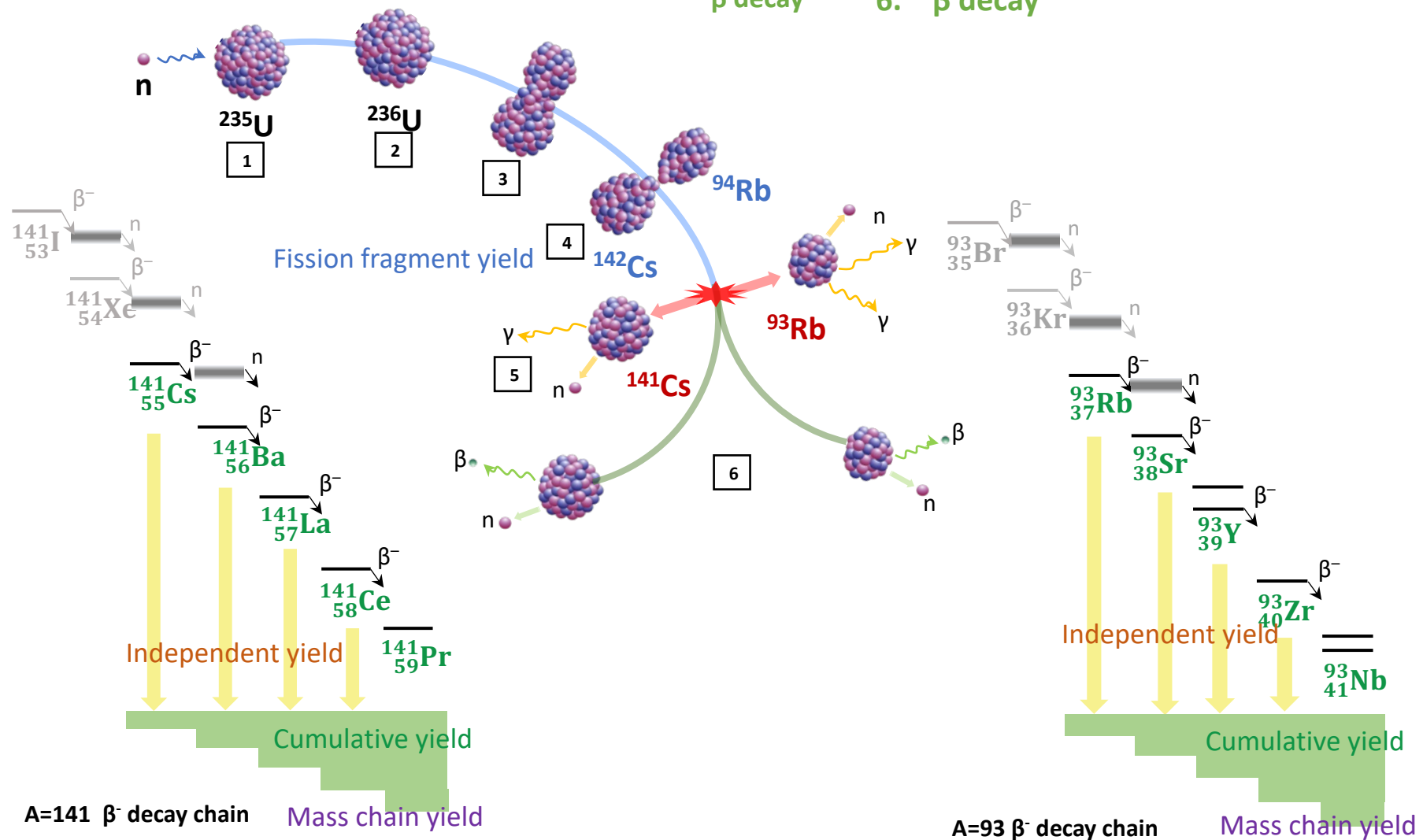
1. Nuclear Data Section, International Atomic Energy Agency
2. Tokyo Institute of Technology
3. Uppsala University



# Introduction

- Nuclear fission, 3 different physics

- Fission physics**
- Capture neutron by  $^{235}\text{U}$
  - Compound nucleus formation of  $^{236}\text{U}$
  - Deformation and elongation
  - Scission
  - Prompt n,  $\gamma$  release**
  - $\beta$  decay**
- Prompt decay**  
 $\beta$  decay



1. Nuclear fission and prompt decay
2. Beta decay from independent FPY
3. Advertisement: Tools from IAEA

# Required consistencies among fission observables

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- Independent fission product yield (MF8 MT454)
  - Number of beta-delayed neutron emissions (MF1 MT455) via Decay data
  - Cumulative fission product yield via Decay data
  - Decay heat via Decay data
- Cumulative fission product yield(MF8 MT459)
  - Decay data
  - Independent fission product yield (MF8 MT454)
  - Number of beta-delayed neutron emissions (MF1 MT455)
- Number of total neutron emissions (MF1 MT452)
  - Number of prompt neutron emissions (MF1 MT456)
  - Prompt neutron spectrum (MF5 MT18)
  - Number of beta-delayed neutron emissions (MF1 MT455)
    - Beta-delayed neutron emission probabilities (branching ratio) in the decay data

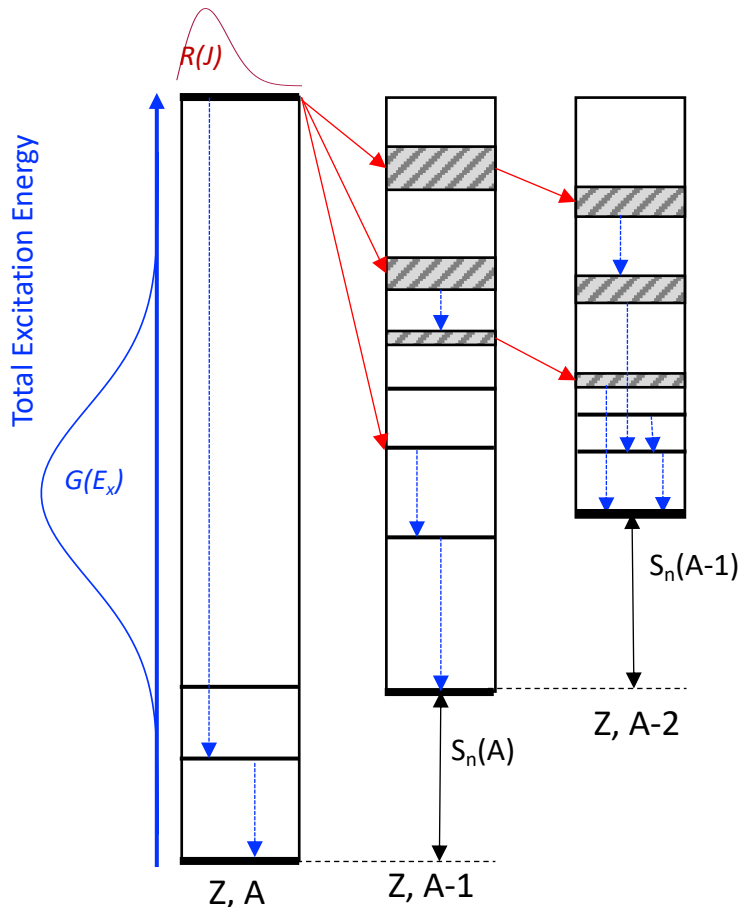
**To ensure consistencies among fission observables, it is important to calculate from fission fragment to beta decay in one flow.**

Identifying Inconsistencies in Fission Product Yield Evaluations with Prompt Neutron Emission  
P. Jaffke, *J. Nucl. Sci. Eng.*,190,258-270 (2018) .



# Deterministic way of Hauser-Feshbach statistical decay of fission fragments in HF<sup>3</sup>D model

- Treating a primary fission fragment as a compound nucleus.
- Generating distributions of primary fission fragment characterized by  $Y(Z, A, E_{ex}, J^\Pi)$  and integrating deterministically for all primary fission fragment pairs (no Monte Carlo sampling required).



## Neutron emission multiplicity

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

- Distribution of excitation energy,  $G(E)$

$$G(E_x) = \frac{1}{\sqrt{2\pi}\delta_{l,h}} \exp\left\{-\frac{(E_x - E_{l,h})^2}{2\delta_{l,h}^2}\right\}$$

$$\delta_{l,h} = \frac{\delta_{TXE}}{\sqrt{E_l^2 + E_h^2}} E_{l,h}$$

- Probability of nucleus having the state of spin  $J$  and parity  $\Pi$ ,  $R(J, \Pi)$

$$R(J, \Pi) = \frac{J + 1/2}{2f^2\sigma^2(U)} \exp\left\{-\frac{(J + 1/2)^2}{2f^2\sigma^2(U)}\right\}$$

$\sigma^2(U)$ : spin cut-off parameter

$U$ : Excitation energy

$f$ : scaling factor

HF<sup>3</sup>D Model:

Okumura et al. *J. Nucl. Sci. Technol.*,55,1009-1023,(2018)



# Hauser-Feshbach calculations implemented in TALYS

1. Read fission fragment distribution file

$$Y_{ff}(Z, A, E_{ex}, J, \Pi)$$

$Y_{ff}$ : fragment yield  
 Z: fragment charge  
 A: fragment mass

$E_{ex}$ : Excitation energy  
 J: spin  
 $\Pi$ : parity

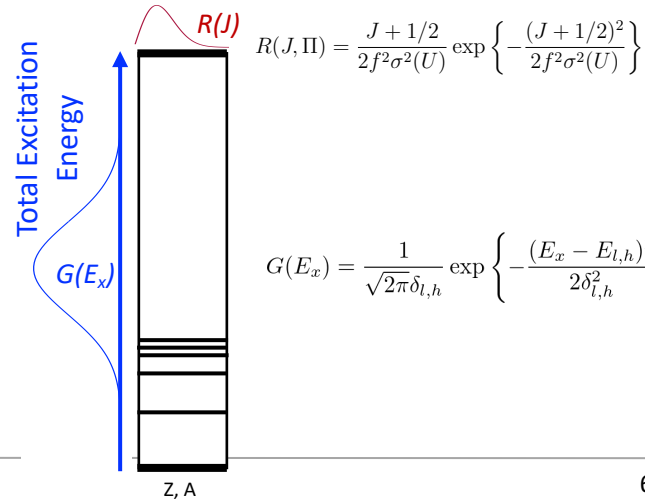
# Z	=	92									
# A	=	236	Fissioning system								
# Ex (MeV)	=	6.55e+00									
# Z1	A1	Zh	Ah	Yield	TKE[MeV]	TXE[MeV]	E1[MeV]	W1[MeV]	Eh[MeV]	Wh[MeV]	
30	74	62	162	3.0000e-06	1.4373e+02	2.5550e+01	9.7733e+00	1.7875e+00	1.5777e+01	5.7377e+00	
30	75	62	161	1.1000e-05	1.4544e+02	2.2786e+01	5.7400e+00	3.1184e+00	1.7046e+01	6.9337e+00	
31	75	61	161	2.0000e-06	1.4076e+02	2.6930e+01	5.7300e+00	5.5013e+00	2.1200e+01	2.4042e+00	
30	76	62	160	5.0000e-05	1.4532e+02	2.6206e+01	6.1234e+00	2.4469e+00	2.0082e+01	6.5358e+00	
:											
46	117	46	119	9.0000e-05	1.6262e+02	3.4208e+01	1.7155e+01	8.5389e+00	1.7053e+01	7.6726e+00	
47	117	45	119	7.0000e-06	1.6130e+02	3.2700e+01	1.9750e+01	7.0597e+00	1.2950e+01	4.2823e+00	
45	118	47	118	7.0000e-06	1.6167e+02	3.1759e+01	1.4299e+01	1.0776e+01	1.7460e+01	8.7686e+00	
46	118	46	118	9.0000e-05	1.6435e+02	3.5416e+01	1.7522e+01	6.7362e+00	1.7893e+01	7.0032e+00	
47	118	45	118	1.1000e-05	1.6072e+02	3.2713e+01	1.6269e+01	5.4600e+00	1.6444e+01	7.6689e+00	

(Z,A) of light fragment  
 (Z,A) of heavy fragment

Mean and width of light fragment  $E_{ex}$  Mean and width of heavy fragment  $E_{ex}$

2. Reconstruct fission fragment distributions ( $G(E_x)$  and  $R(J^\Pi)$ )

3. Run the Hauser-Feshbach statistical decay calculation  
 - neutron and gamma emissions from each fragment





# Fission fragment yield models stored in TALYS (1.96)

## GEF

(ffmodel 1)

Designed with global fitting parameters based on experimental data

F. Nordström, Technical Report UPTeC ES21016, Uppsala university, 2021.

From  ${}_{76}\text{Os}$  to  ${}_{115}\text{Mc}$ , 737 nuclides

## HF<sup>3</sup>D

(ffmodel 2)

Designed with a fully deterministic technique with fitting functions

S. Okumura, T. Kawano, P. Jaffke, P. Talou,  
and S. Chiba, JNST, 55(9),1009–1023, 2018.

${}^{236}\text{U}$ ,  ${}^{239}\text{U}$ , and  ${}^{240}\text{Pu}$ , 3 nuclides

## SPY

(ffmodel 3)

Designed with a statistical scission point  
model using microscopic calculation

J.-F. Lemaître, S. Goriely, S. Hilaire, and J.-L. Sida,  
PRC99, 034612, 2019.

${}^{240}\text{Pu}$ ,  ${}^{241}\text{Pu}$ ,  ${}^{242}\text{Pu}$ , and  ${}^{243}\text{Pu}$ , 4 nuclides

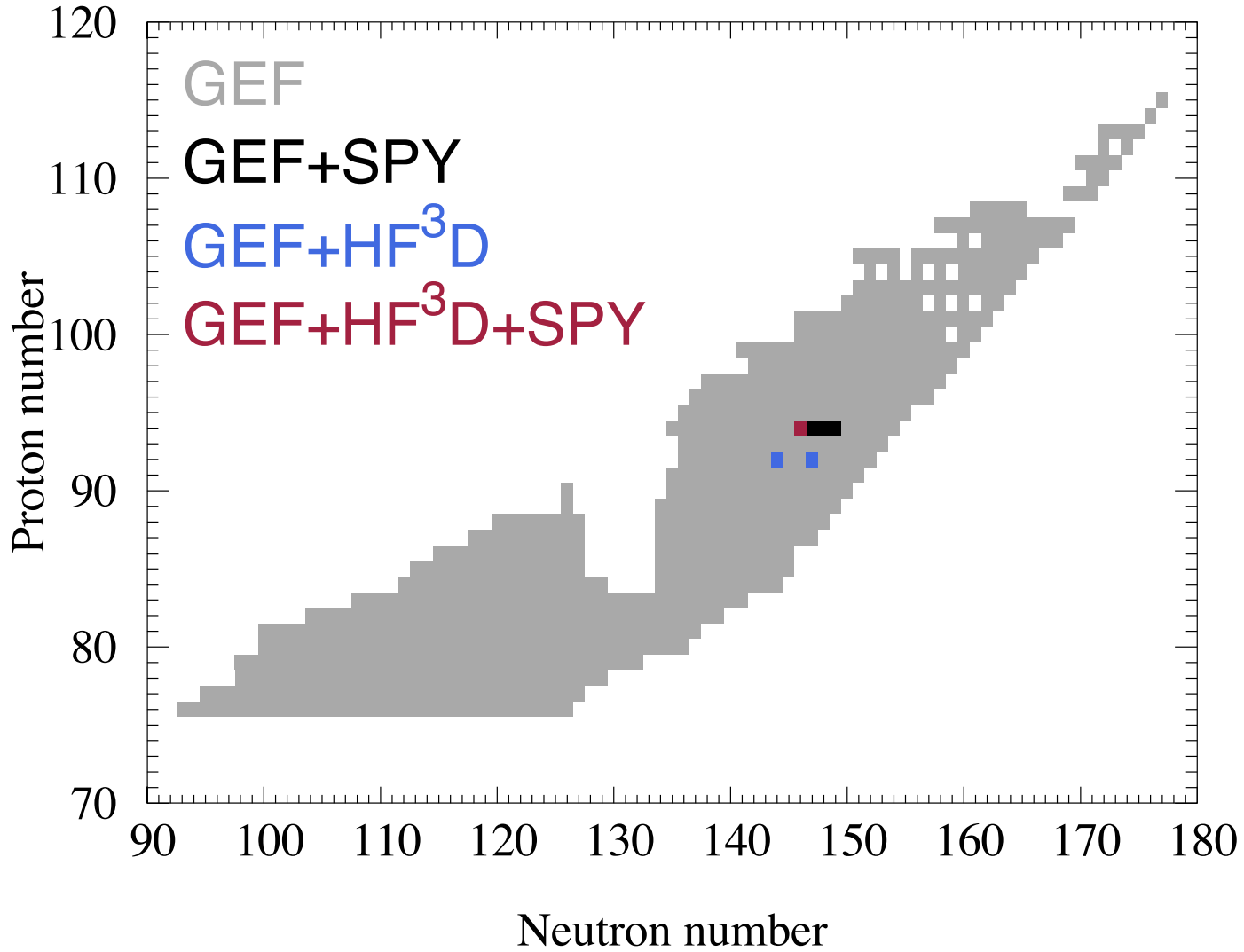
## Local

(ffmodel 0)

Arbitrary fission fragment data provided by users.  
(will be implemented in next update of TALYS)



# Fission fragment yield models stored in TALYS (1.96)





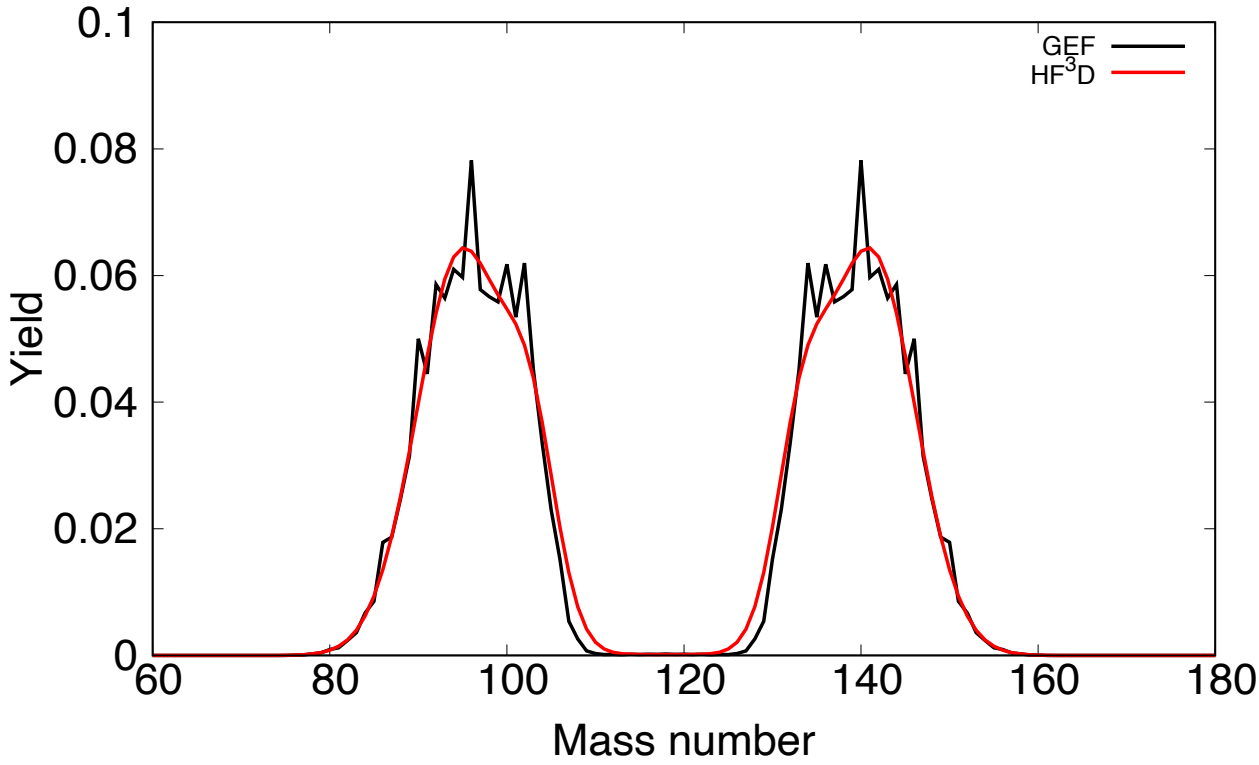


# Calculatable physical quantities

Table 1: Representative fission quantities comparable to experimental data.

Type	Description
$Y_i(A)$	Independent fission yield as a function of mass number
$Y_i(Z, A, M)$	Independent fission yield of all isotopes including meta-stable state
$\bar{\nu}$	Average number of neutrons per fission
$\bar{\gamma}$	Average number of $\gamma$ -rays per fission
$\bar{\nu}(A)$	Average neutron multiplicity as a function of fission product mass
$\bar{\gamma}(A)$	Average $\gamma$ -ray multiplicity as a function of fission product mass
$\langle E_n \rangle$	Average prompt neutron energy
$\langle E_\gamma \rangle$	Average prompt $\gamma$ -ray energy
$\langle E_n \rangle(A)$	Average neutron energy as a function of product mass
$\langle E_\gamma \rangle(A)$	Average $\gamma$ -ray energy as a function of product mass
$P(\nu)$	Neutron multiplicity distribution
$\chi(\nu)$	Prompt fission neutron energy spectrum (PFNS)
$\phi(\gamma)$	$\gamma$ -ray energy spectrum

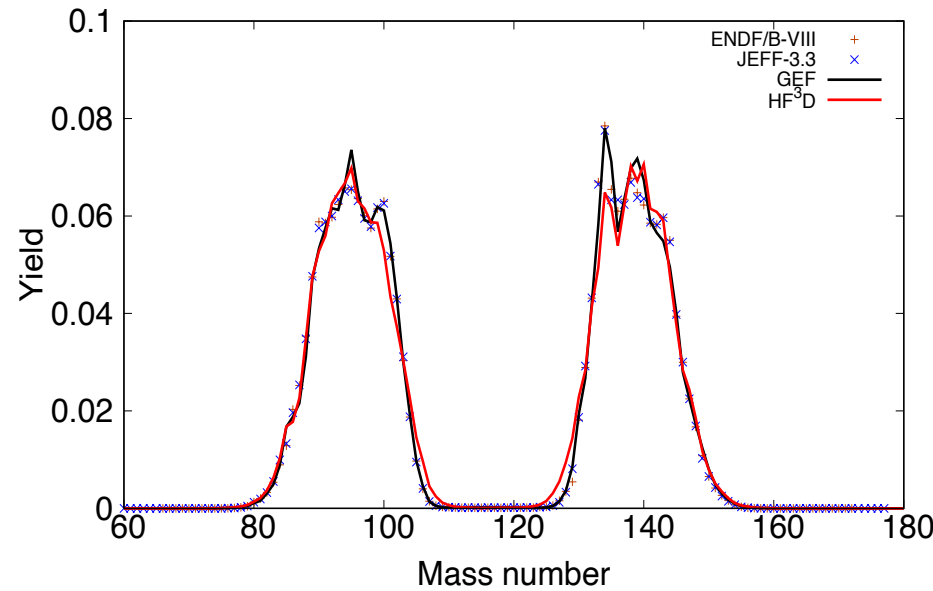
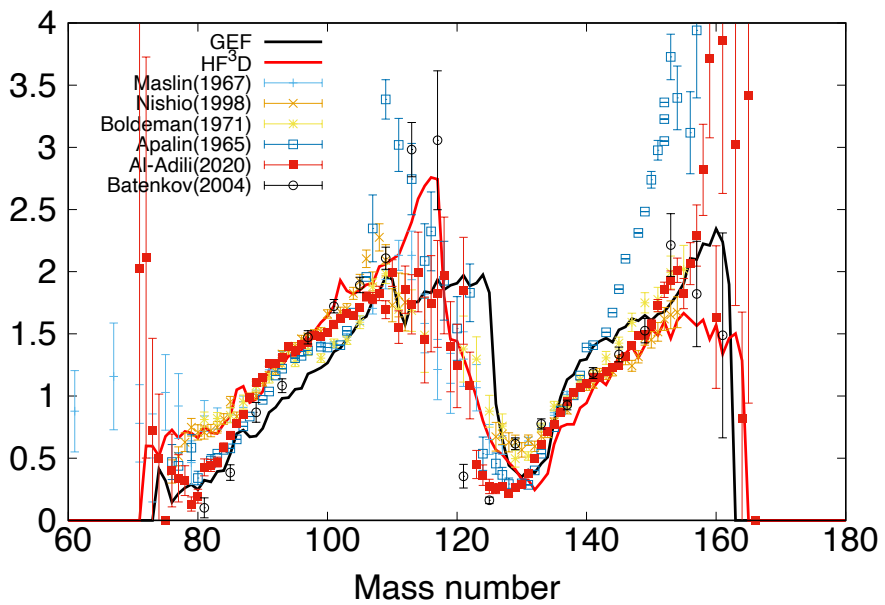
# Fission fragment mass distribution of $^{235}\text{U}+n_{\text{th}}$



Fission fragment mass distribution generated by GEF and HF3D model stored in TALYS fission fragment database



# Calculated $\nu(A)$ and $Y(A)$ for $^{235}\text{U}+n_{\text{th}}$



Calculated  $\nu(A)$  from GEF and HF<sup>3</sup>D model FF distributions and Hauser-Feshbach statistical decay by TALYS

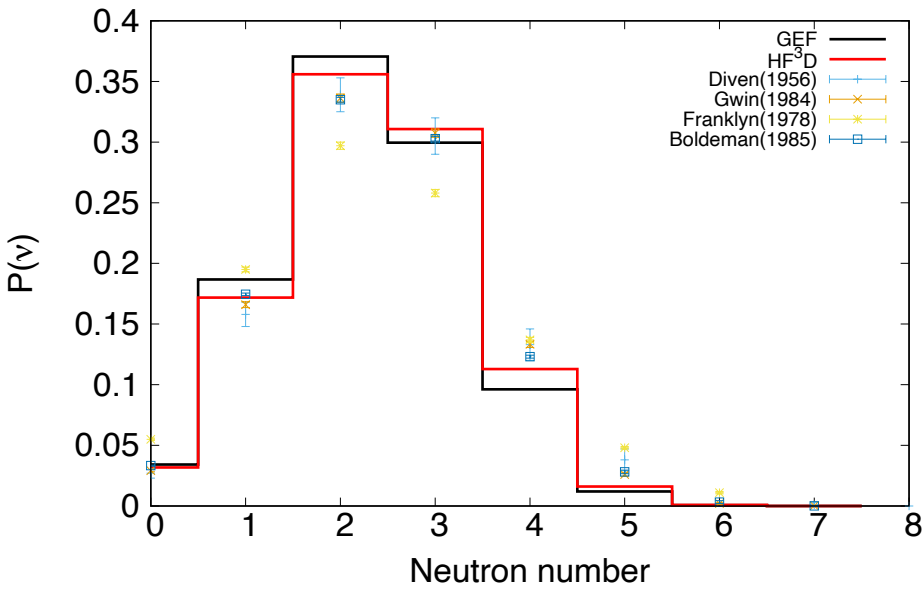
Calculated independent FPY from GEF and HF<sup>3</sup>D model FF distributions and Hauser-Feshbach statistical decay by TALYS

Average number of neutrons/fission

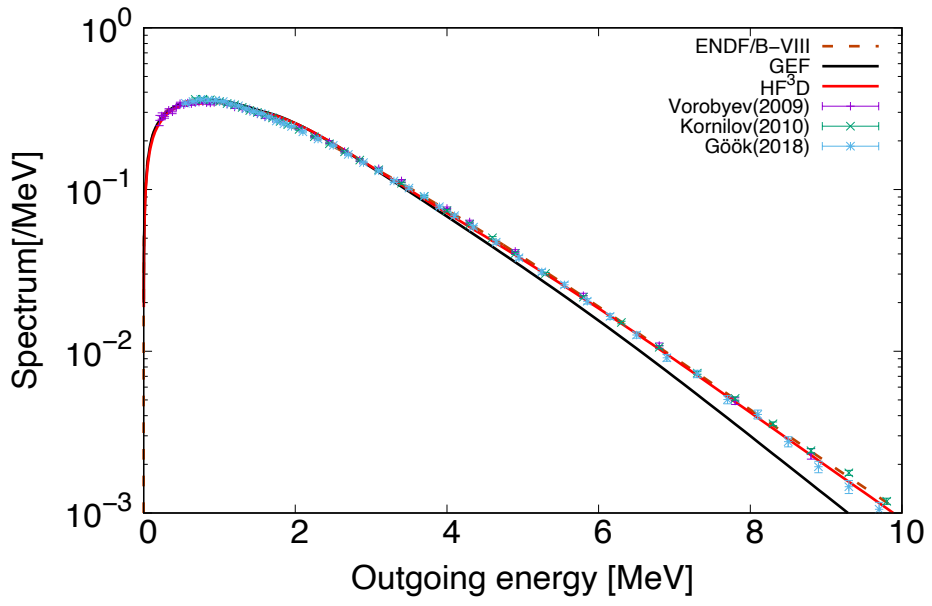
- GEF+TALYS 2.275
- HF<sup>3</sup>D 2.353
- JENDL 2.420



# Calculated P(v) and PFNS for $^{235}\text{U}+n_{\text{th}}$



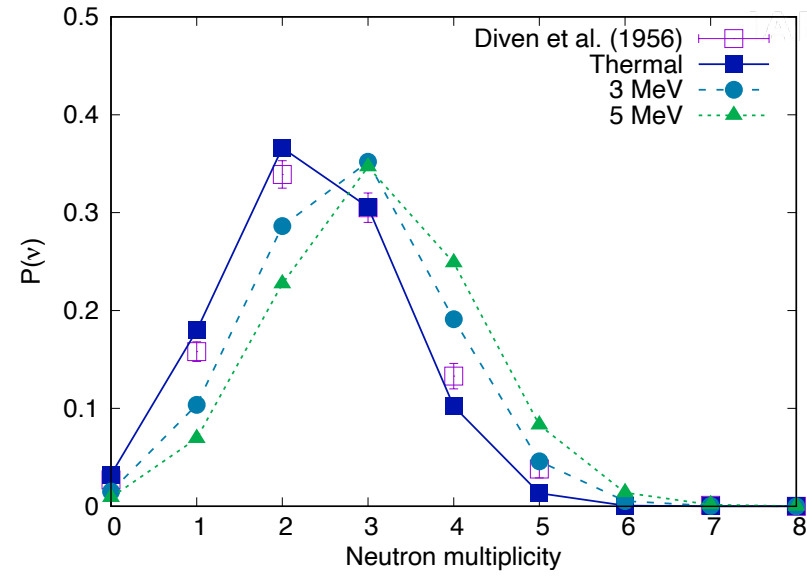
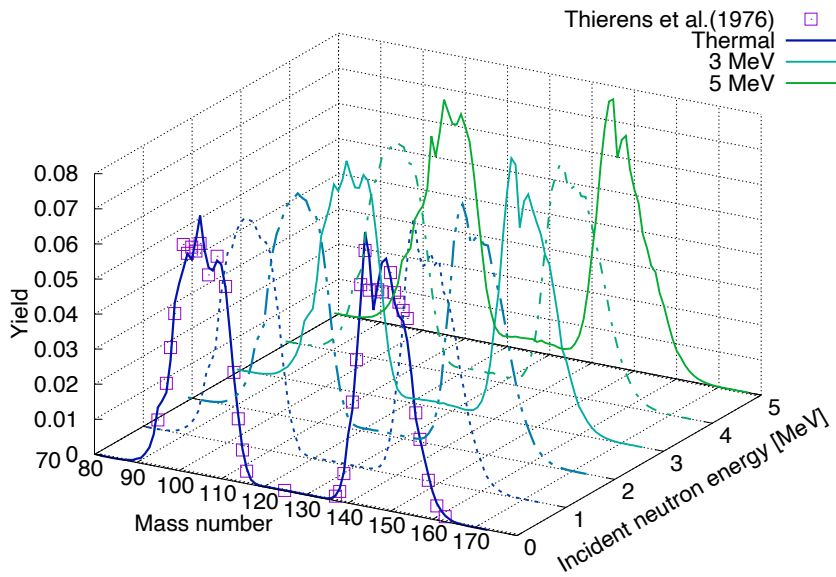
Calculated P(v) from GEF and HF<sup>3</sup>D model FF distributions and Hauser-Feshbach statistical decay by TALYS



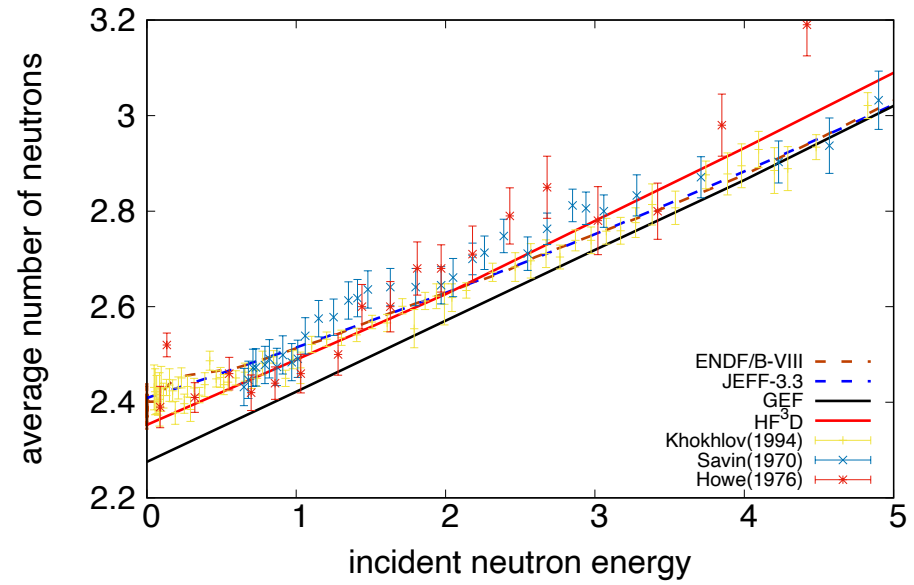
Calculated prompt fission neutron spectrum (PFNS) from GEF and HF<sup>3</sup>D model FF distributions and Hauser-Feshbach statistical decay by TALYS



# Energy dependent fission observables for $^{235}\text{U}+n$



Calculated independent FPY,  $P(\nu)$ , and average  $\nu$  from GEF FF distributions and Hauser-Feshbach statistical decay by TALYS up to 5 MeV



# Acknowledgements

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- The IAEA-NDS acknowledges the internship program “The Nuclear Regulation Human Resource Development Program (ANSET: Advanced Nuclear 3S Education and Training)” entrusted to Tokyo Institute of Technology by the Nuclear Regulation Agency of Japan, for supporting this work.
- T. Kawano (Los Alamos National Lab) for his advice and intensive support on our work.
- A. Al-Adili (Uppsala University) for GEF calculations and data supply.
- S. Goriely (Université Libre de Bruxelles) and J.-F. Lemaitre (CEA) for SPY calculations and data supply.





# Beta Decay Calculations from Independent Fission Product Yields



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# Standalone beta decay program

- Python 

1. Convert ENDF format decay data library files to

- (1) Simplified format (inspired by the Oyak/Decayfinite code)

```
55 141 0 2.4910000E+01 6.0000000E-02 1.3970950E+02 2 5 1920
1.5473620E+06 1.8786310E+05 1.7248140E+06 5.7510480E+03 7.5359650E+01 3.0848980E+00
1.0000000E+00 0.0000000E+00 5.2560000E+06 1.0000000E+04 9.9965800E-01 2.6533000E-05
1.5000000E+00 0.0000000E+00 7.2100000E+05 1.2000000E+04 3.4200000E-04 1.4000000E-05
```

- (2) JSON format

2. Generate  $\beta$ -decay chains from decay data library

3. Import independent fission product yield file (TALYS output format)

#	Z	A	iso	FP yield	FF yield	FP xs	FF xs
30	74	-1		5.3961E-06	3.0000E-06	1.9191E+00	1.0670E+00
30	75	-1		1.4014E-05	1.1000E-05	4.9841E+00	3.9123E+00
31	75	-1		2.7919E-06	2.0000E-06	9.9294E-01	7.1132E-01

4. Solve the Bateman equations

5. Calculate beta-decay observables from independent yield

- Cumulative fission product yield (at 1000 years time period)
- Decay heat from  $\beta$  and  $\gamma$  rays (time dependent)
- Delayed neutron yield (at 1000 years time period and time dependent)
- Spectrum (Under development)

- Preview decay-chain

- Open source in Github

- Test version: [https://github.com/shinokumura/FPY\\_betadecay](https://github.com/shinokumura/FPY_betadecay)
- Will be moved to Github/IAEA-NDS near future





# Features

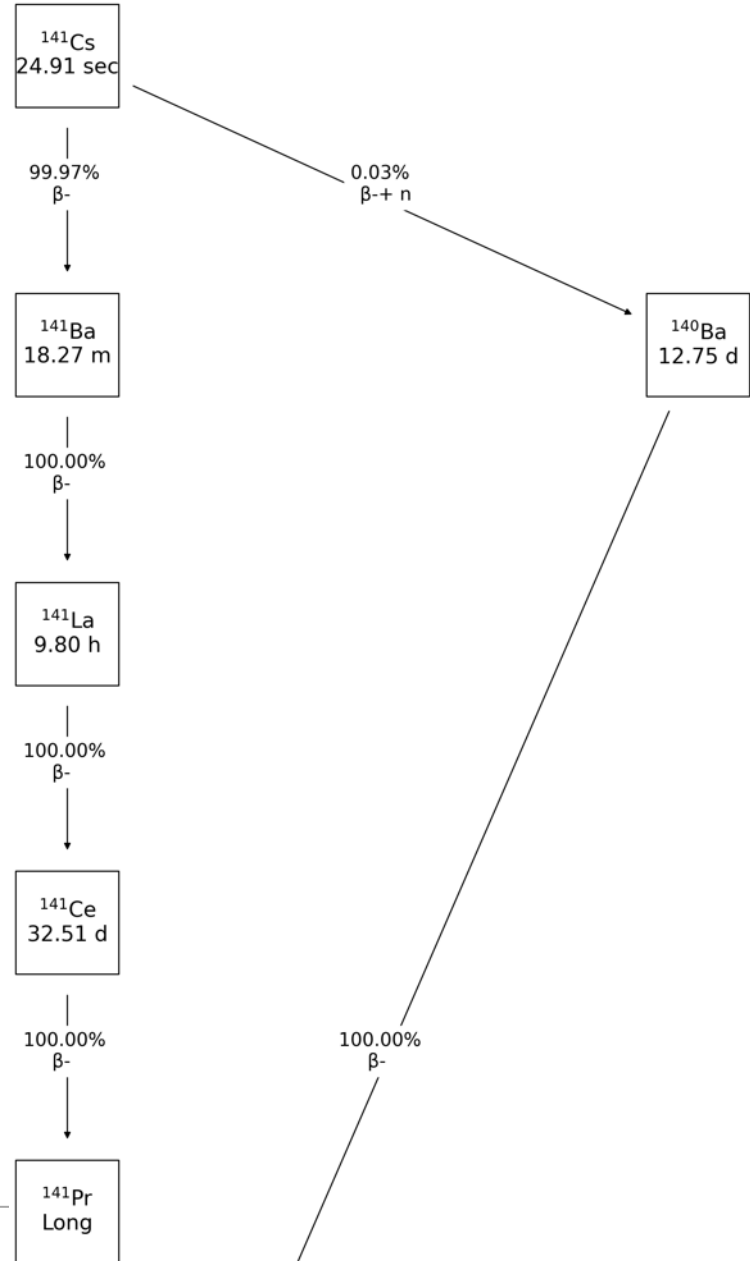
## Decay data

```
"55-Cs-141-00": {
  "Z": "55",
  "ELM": "Cs",
  "MASS": "141",
  "LIS": "00",
  "HL": "2.4910000E+01",
  "LAMBDA": 0.027826,
  "En_beta": "1.5473620E+06",
  "En_gamm": "1.7248140E+06",
  "En_alpha": "7.5359650E+01",
  "DecayInfo": {
    "0": {
      "RTYP": "1.0000000E+00",
      "RFS": "0.0000000E+00",
      "Q": "5.2560000E+06",
      "BR": "9.9965800E-01",
      "DAUGHTER": "56-Ba-141-00"
    },
    "1": {
      "RTYP": "1.5000000E+00",
      "RFS": "0.0000000E+00",
      "Q": "7.2100000E+05",
      "BR": "3.4200000E-04",
      "DAUGHTER": "56-Ba-140-00"
    }
  },
  "daughters": [
    "56-Ba-141-00",
    "56-Ba-140-00"
  ]
},
```

## Decay chain (linearized)

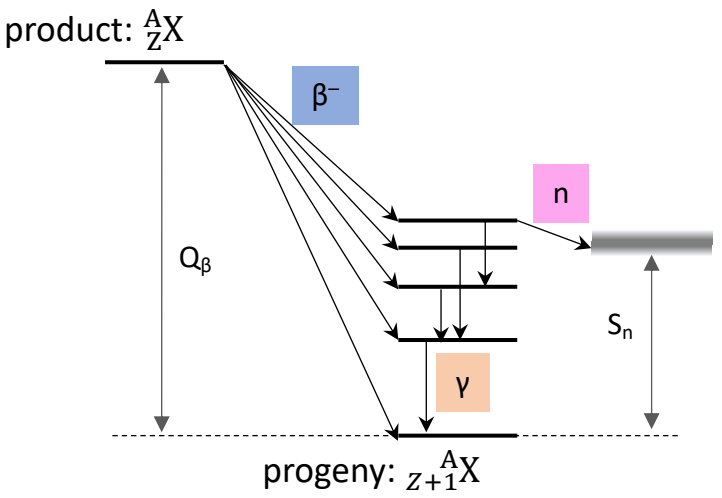
```
"55-Cs-141-00": {
  "1": {
    "chain": [
      "56-Ba-141-00",
      "57-La-141-00",
      "58-Ce-141-00",
      "59-Pr-141-00"
    ],
    "branching": [
      0.999658,
      1.0,
      1.0,
      1.0
    ],
    "rtyp": [
      1.0,
      1.0,
      1.0,
      1.0
    ],
    "lmbds": [
      0.027826,
      0.00063232,
      4.9118e-05,
      2.4676e-07,
      6.9315e-51
    ],
    "en_betas": [
      "1.5473620E+06",
      "9.6628250E+05",
      "9.8713460E+05",
      "1.9438810E+05"
    ],
    "en_gamms": [
      "1.7248140E+06",
      "9.0968270E+05",
      "2.6780420E+04",
      "7.6901970E+04"
    ],
    "2": {
      "chain": [
        "56-Ba-140-00",
        "57-La-140-00",
        "58-Ce-140-00"
      ],
      ...
    }
  },
  ...
}
```

## Decay chain (network diagram plot)





# Decay heat and delayed neutron yield at $E_n = \text{thermal}$



**Decay heat:**

Sum of average energies of  $\beta$  and  $\gamma$  rays from fission products as a function of time following a single fission event.

$$DH_{\gamma,\beta}(t) = \sum \langle E_{\gamma,\beta} \rangle \lambda_{\gamma,\beta} N_i(t) \quad N_i(t): \text{FP Yield at time } t$$

**Delayed neutron:**

Sum of the number of delayed neutron emissions.

$$v_d(t) = \sum P_n \lambda_i N_i(t) \quad N_i(t): \text{FP Yield at time } t$$

$$\bar{v}_d = \sum P_n N_i \quad N_i: \text{Cumulative yield}$$

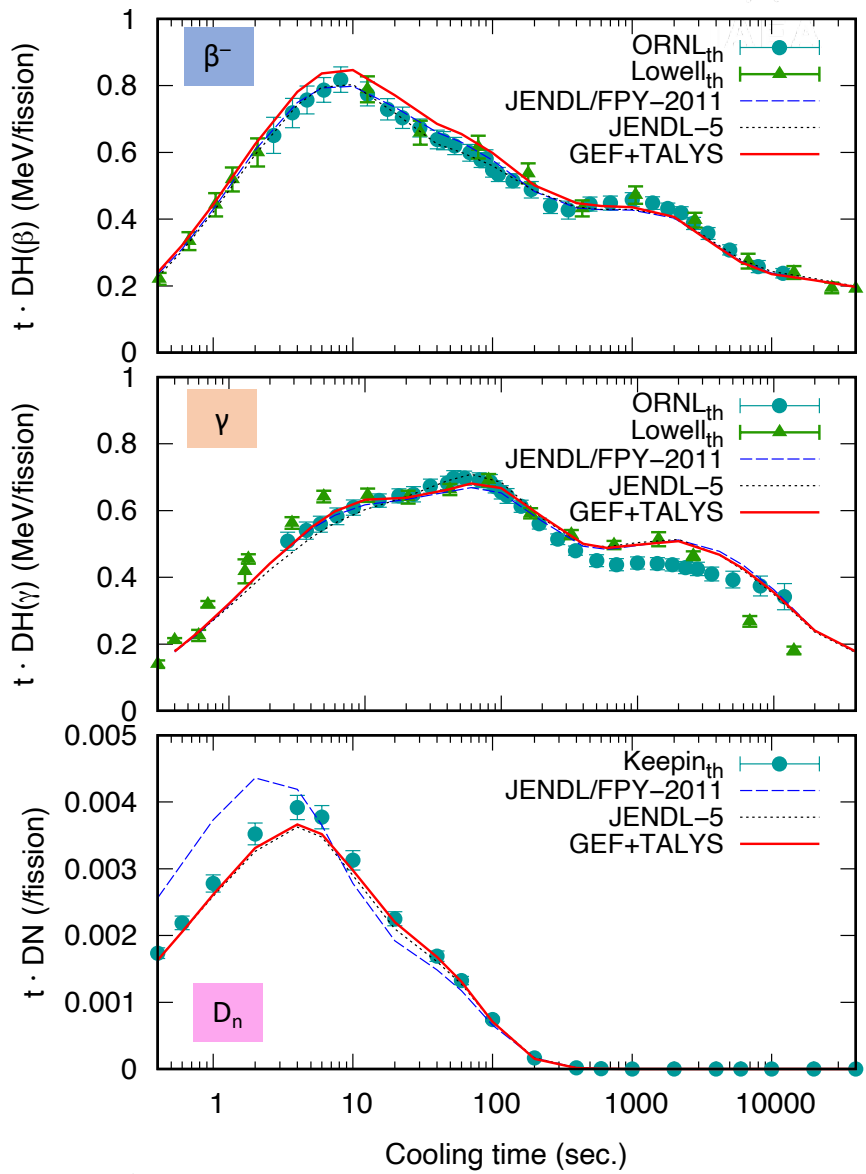


Fig 2.  $\beta$  and  $\gamma$  decay heat and delayed neutron yield burst functions of  ${}^{235}\text{U}$

# Method

## 1. Import calculated independent fission product yields, $Y_{IND}(Z, A, M)$

```

yieldZA1.00E-06.fis
# n + 235U : Z, A Fission yields
# E-incident = 1.00000E-06
#
#
#   Z   A iso   FP yield   FF yield   FP xs   FF xs   Isom. Ratio
30  74 -1   5.3961E-06   3.0000E-06   1.9191E+00   1.0670E+00
30  75 -1   1.4014E-05   1.1000E-05   4.9841E+00   3.9123E+00
31  75 -1   2.7919E-06   2.0000E-06   9.9294E-01   7.1132E-01
30  76 -1   5.7899E-05   5.0001E-05   2.0592E+01   1.7783E+01
31  76 -1   5.5761E-06   3.0000E-06   1.9832E+00   1.0670E+00
32  76 -1   1.9258E-06   2.0000E-06   6.8493E-01   7.1132E-01
30  77 -1   7.2165E-05   4.0001E-05   2.5666E+01   1.4226E+01
30  77  0   5.3674E-05   1.9090E+01   7.4378E-01
30  77  1   1.8490E-05   6.5761E+00   2.5622E-01
31  77 -1   5.7907E-05   4.6001E-05   2.0595E+01   1.6360E+01
29  78 -1   2.1861E-06   3.0000E-06   7.7751E-01   1.0670E+00
  
```

2. Import decay data library
3. Run the radioactive decay calculation



# Energy dependent cumulative yield

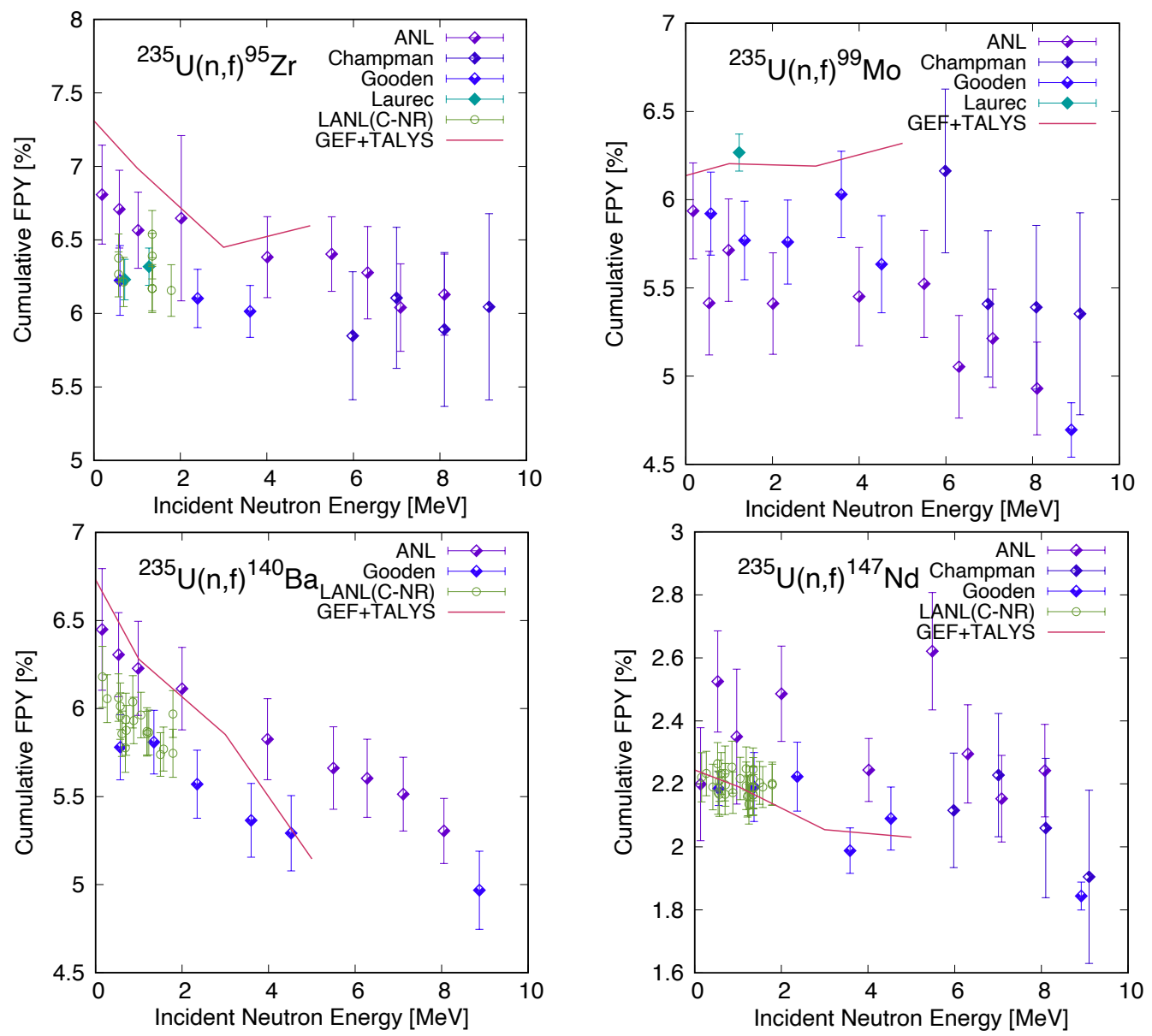
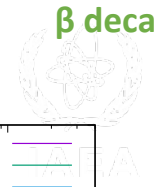


Fig 1. Comparison of cumulative yield of selected fission products showing as function neutron energy



# Energy dependent decay heat and delayed neutron

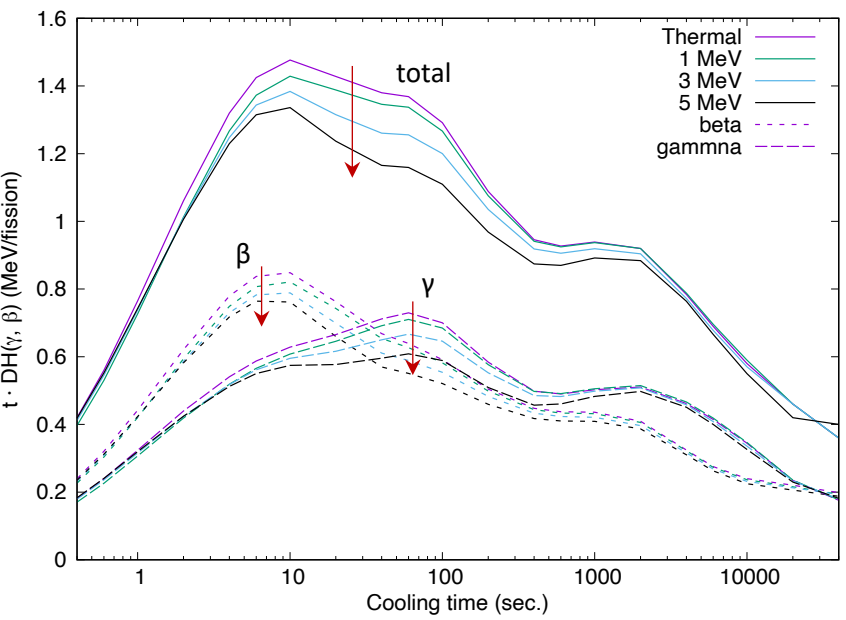


Fig 3. Comparison of total decay heat (—:total, dashed: β and γ) burst functions of <sup>235</sup>U for various neutron energies

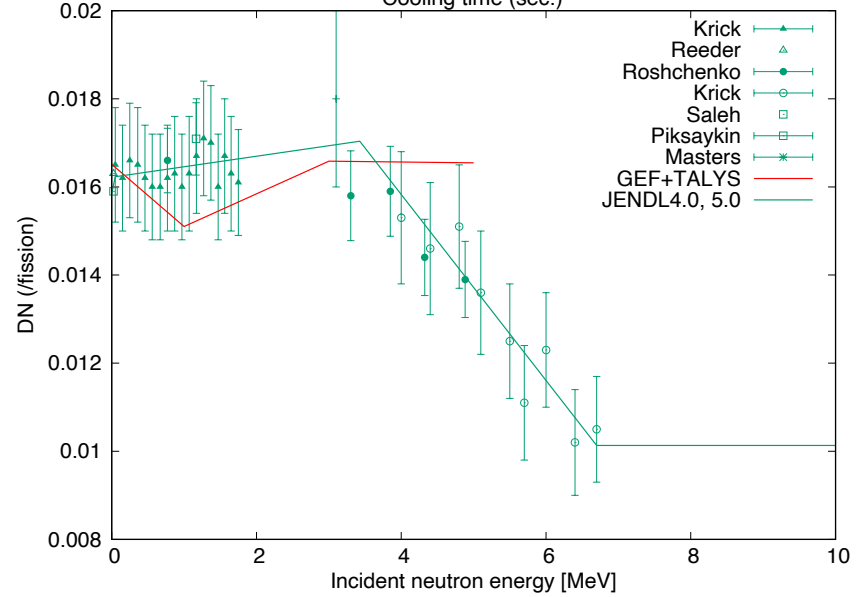
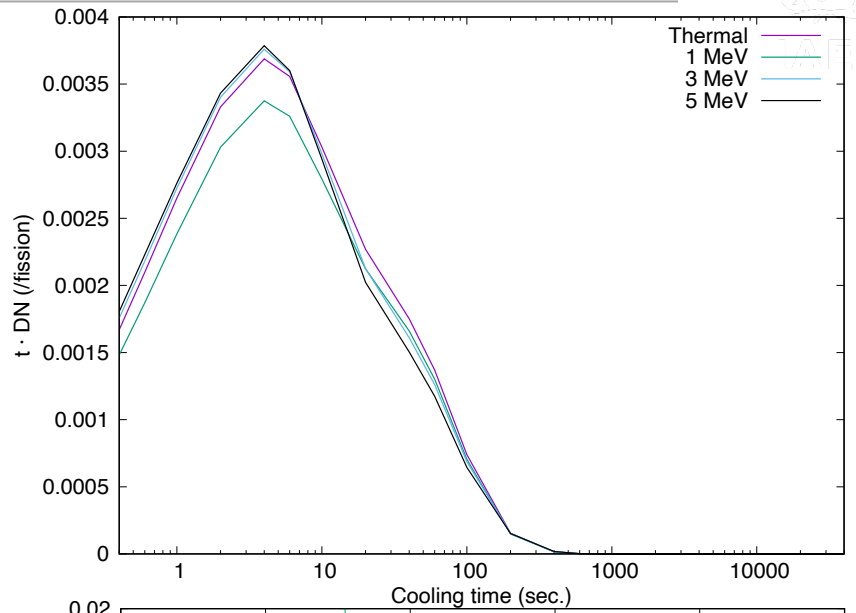


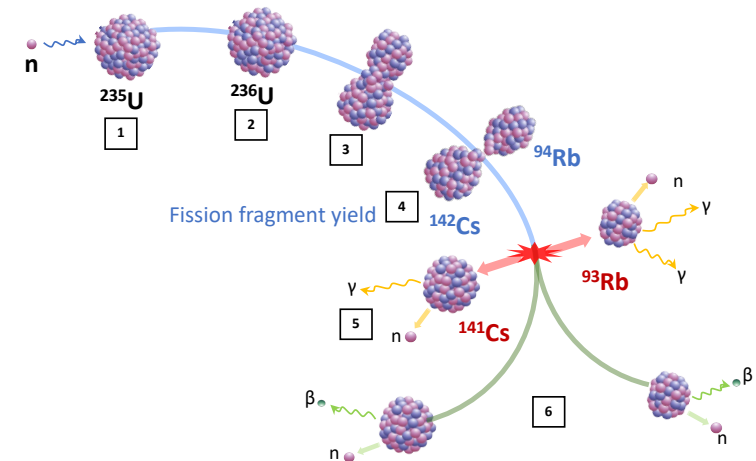
Fig 4. Incident neutron energy dependence of average delayed neutron yield

## (1) TALYS<sup>[1]</sup> fission fragment de-excitation

- Fission fragment distributions by GEF<sup>[2]</sup>, HF<sup>3</sup>D<sup>[3]</sup>, SPY<sup>[4]</sup>, and user's own model
- Application of the Hauser-Feshbach theory to the fission fragment de-excitation process
- Calculate independent fission product yield, prompt neutron and gamma observables
- Code comparisons, multi-chance fission implementation is underway

## (2) Beta-decay observables from beta-decay of fission products

- Cumulative fission product yield
- Decay heat from  $\beta$  and  $\gamma$  rays
- Delayed neutron yield



Details is published in the IAEA NDS report

<https://nds.iaea.org/publications/nds/iaea-nds-0239/>

- [1] Koning A.J., Hilaire S., Duijvestijn M.C. AIP Conference Proceedings. 2005;769(1):1154–1159.
- [2] Schmidt K.H., Jurado B., Amouroux C., Schmitt C. Nuclear Data Sheets. 2016;131:107 – 221.
- [3] Okumura S., Kawano T., Jaffke P., Talou P., Chiba S. JNST. 2018;55(9):1009–1023.
- [4] Lemaitre J.F., Goriely S., Hilaire S., Sida J.L., Phys Rev C. 2019 Mar;99:034612.



# Some Tools and Developments



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# Easy-to-use nuclear data plotter: Dataexplorer



- Plot, data table view, and tabulated data download option
  - Evaluated cross section with experimental data: <https://nds.iaea.org/dataexplorer/xs>
  - Residual production with experimental data: <https://nds.iaea.org/dataexplorer/rp>
  - Fission yields: <https://nds.iaea.org/dataexplorer/fy>

LIBRARIES-2021 Data Explorer
Tips

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Cross Section
Multiple Cross Sections (Libs. only)
Residual Production Cross Section
Fission Yield

Fission yields from ENDFTABLES and EXFORTABLES

Target element: U

Target mass: 238

Reaction: n,f

Fission yield type: Cumulative

Incident Energy: MeV

x

x

x

U238(n,f) at E:MeV, found 39 Y(A) and 91 Y(Z,A) experimental dataset(s).

Linear  Log

Y(A) data.

Dataset List
Raw Data
Download Data Files

Add more data to the chart by selecting dataset from the following table.

<input type="checkbox"/>	Author	Year	#Entry	Points	E_inc[eV]
<input type="checkbox"/>	filter data...				
<input checked="" type="checkbox"/>	Nagy	1978	10798002	9	1.5000e+6

Display at A: 132

Linear  Log

Y(Z,A) data.

Dataset List
Raw Data
Download Data Files

Add more data to the chart by selecting dataset from the following table.

<input type="checkbox"/>	Author	Year	#Entry	Points	E_inc[eV]
<input type="checkbox"/>	filter data...				
<input checked="" type="checkbox"/>	Gudkov	1983	48878002	10	1.0100e+6

[https://nds.iaea.org/dataexplorer/fy?fissile\\_element=U&fissile\\_mass=238&inc\\_pt4=n&inc\\_energy=MeV&fy\\_type=Cumulative](https://nds.iaea.org/dataexplorer/fy?fissile_element=U&fissile_mass=238&inc_pt4=n&inc_energy=MeV&fy_type=Cumulative)



- IAEA-NDS Github
  - <https://github.com/IAEA-NDS>
- EXFOR master files:
  - [https://github.com/IAEA-NDS/exfor\\_master](https://github.com/IAEA-NDS/exfor_master)
- EXFOR dictionary in JSON:
  - [https://github.com/IAEA-NDS/exfor\\_dictionary](https://github.com/IAEA-NDS/exfor_dictionary)

# IAEA-NDS website renewal



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## IAEA Nuclear Data

The IAEA Nuclear Data Section provides fundamental nuclear data for energy and non-energy applications, as well as atomic data for fusion energy research. Nuclear reaction, structure and decay data describe the a process in which the nucleus of an atom is changed by being split apart or joined with the nucleus of another atom, and the lifetimes and decay modes of unstable isotopes, including the spectrum of emitted radiation.

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**Meeting and Event**

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**Learn how to use EXFOR**

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**NDS on Github**

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[Go to Github →](#)

### News

Updates of nuclear data related news.

- JENDL-5 Japanese evaluated nuclear data library has been released from JAEA [2021-12]**  
JENDL-5 Has been released from Japan Atomic Eenergy Agency.
- GRUCON-2021 ENDF data processing code package (includes source code) [2021]**  
New version of GRUCON is available.
- Empire-3.2.2/2021.11 - nuclear reaction model code system for data evaluation [2021]**  
New version of Empire is available

Opening & Introductory Lecture: Measurements of neutron-induced fission ...  
International Centre for Theoretical Physics  
**JOINT ICTP-IAEA SCHOOL ON "NUCLEAR DATA MEASUREMENTS FOR SCIENCE AND APPLICATIONS"**  
Opening & Introductory Lecture: Measurements of neutron-induced fission for fundamental Nuclear Physics and Nuclear Technology  
Organizers (S. Simakov, IAEA) & 1st Lecture Nicola Colonna (INFN-Sezione di Bari)  
19 October 2015

IRDF

Published January 1, 2020 | Version II

**International Reactor Dosimetry and Fusion File (IRDF-II, January, 2020)**

Trkov, A.; Griffin, P.J.; Simakov, S.; Greenwood, L.R.; Zolotarev, K.I.; Capote, B.; Aldama, D.L.; Destouches, C.; (Skip) Kahler, A.C.; Konno, C.; Kostal, M.; Maierle, M.; Malambu, F.M.; Ohta, M.; Radulovic, V.; Sato, S.; Schulz, M.; Simeckova, E.; Vavtar, I.; Wagemans, J.; White, M.; Yashima, H.

### Description

#### Overview

The new International Reactor Dosimetry and Fusion File (IRDF-II) addresses neutron dosimetry needs for fission and fusion applications for incident neutron energies from 0 to 60 MeV. The library entries, enumerated in the Table I, include 119 metrology reactions with covariance information and corresponding decay data. The library also includes 4 cover cross sections of B, B-10, Cd and Gd used to support self-shielding corrections, 5 metrology metrics used by the dosimetry community, and 7 cumulative fission products yields. Several reference neutron fields for library validation are also provided. Finally, recommended radionuclide masses and elemental abundances to be used for dosimetry applications are also included. The dosimetry library can be used in a broad range of applications from lifetime management and assessments of nuclear power reactors to other neutron metrology applications such as boron neutron capture therapy, therapeutic use of medical isotopes, nuclear physics measurements, and reactor safety applications. Library evaluations are based mainly on comprehensive experimental data, therefore the reaction library also represents an ideal benchmark collection for validation and improvement of theoretical nuclear reaction modelling.

#### Additional Description

- Technical info
- Table of contents

#### Files

Name	Size	Preview	Download
IRDF-II_sp_ENDF.zip	279.0 kB	<input type="checkbox"/>	<input type="checkbox"/>
IRDF-II_TAB.zip	20.5 MB	<input type="checkbox"/>	<input type="checkbox"/>

#### Versions

Version	Published
Version II	Jan 1, 2020
Version 1.05	Oct 9, 2014
Version 1.04	Jun 24, 2014
Version 1.02	Jul 14, 2012
Version 2002	Jan 1, 2002

[View all 6 versions](#)

#### Keywords and subjects

IRDF Dosimetry

#### Related Publication

INDC Reports: <https://nds.iaea.org/publications/nds/indc-nds-0528>

INDC Reports: <https://nds.iaea.org/publications/nds/indc-nds-0548>

INDC Reports: <https://nds.iaea.org/publications/nds/indc-nds-0584>

INDC Reports: <https://nds.iaea.org/publications/nds/indc-nds-0657>

INDC Reports: <https://nds.iaea.org/publications/nds/indc-nds-0616>

INDC Reports: <https://nds.iaea.org/publications/nds/indc-nds-0668>

#### Details

**Resource type**  
Evaluated Nuclear Data Library



*Thank you for your  
attention.*



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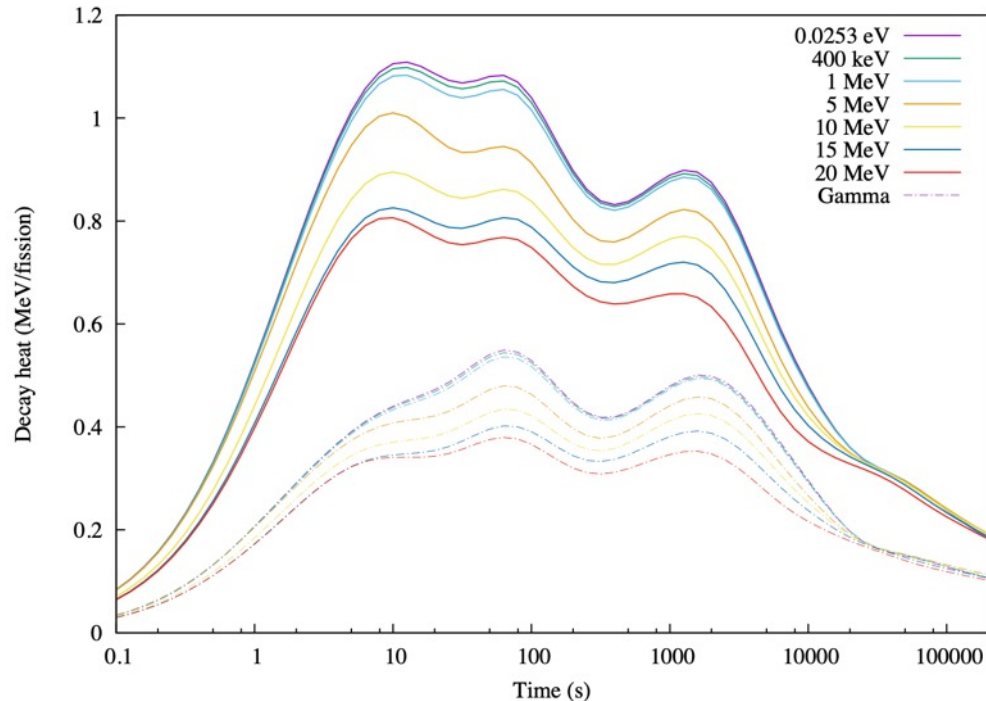


Figure 7: Comparison of total decay heat burst functions of  $^{239}\text{Pu}$  for various neutron energies. All simulations use GEF-4.2 nFY with ENDF/B-VII.1 decay data.

- The asymmetric distributions of fission products for well-known fissiles become considerably more broad at higher neutron energy. As a result, the dominant nuclides for some thermal response function, which are the most likely fission products, will have less production in exchange for increased production from the 'shoulders' of the fission yield distribution.
- The general change in the response function will be a decrease across all time periods, potentially with some new response from a previously minor nuclide. This can be seen in the neutron-energy-dependent decay heat curves from fission pulses calculated with GEF-4.2 fission yields. Two examples are shown in Figures 6 and 7:  $^{235}\text{U}$  and  $^{239}\text{Pu}$ , respectively.

The time evolution of nuclide yield undergoing a linear decay chain is governed by a set of a first-order differential equation, called Bateman equations.

The Bateman equations for radioactive decay case of  $i$ -nuclide series in linear chain describing nuclide yield are as follows:

$$\frac{dN_1}{dt} = \lambda_1 N_1$$

$$\frac{dN_i}{dt} = \lambda_{i-1} N_{i-1} - \lambda_i N_i \quad (i = 2, n)$$

where  $\lambda_i$  is the decay constant of  $i$ th nuclide. By assuming zero yields of all progeny after time  $t$ , the yield of  $n$ th nuclide in the specific decay chain is given by:

$$N_n(t) = \frac{N_1(0)}{\lambda_n} \sum_{i=1}^n \lambda_i c_i e^{(-\lambda_i t)}$$

$$c_n = \sum_{j=1, j \neq n}^n \frac{\lambda_j}{\lambda_j - \lambda_i},$$

