

Neutron Energy Dependence of Fission Fragment Yields and Its Applications

Futoshi Minato¹, Kotaro Uzawa², Kazuki Okada²



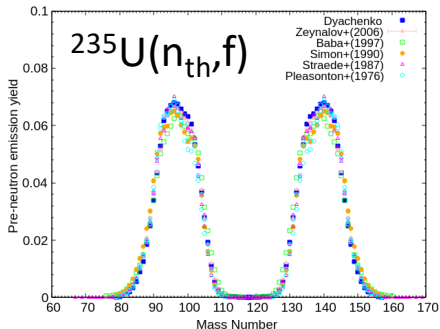
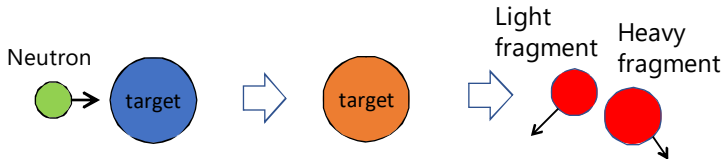
¹Kyushu Univ., ²JAEA



1. Background
2. Toward New Evaluated Data of Fission Fragment Yields
3. Application

This work is supported by JSPS KAKENHI Grant-in-Aid for Transformative Research Areas (26H00410): New Horizons in Negative Muon Science

Fission Fragment Yields



Double Peak Structure
formed by light & heavy fragments

How can we estimate precisely if E_n becomes large?

Applications of Fission Fragment Yields

[1] Energy Applications

Dr. Lile Liu's talk (CIAE) on Tuesday

- Early-Gen. reactors are designed at thermal neutron energy (Light Water)
- Next-generation reactors
 - Fast Breeder Reactors/Accelerator-Driven Reactors/Small Modular Reactors

- Next-Next generation reactors outside boxes

[2] Non-Destructive Analysis of Nuclear Materials

[3] Decommissioning of Reactors

- Avoid Recriticality at Fukushima Plants

[4] Astrophysical applications and Deeper Understanding of Nuclei

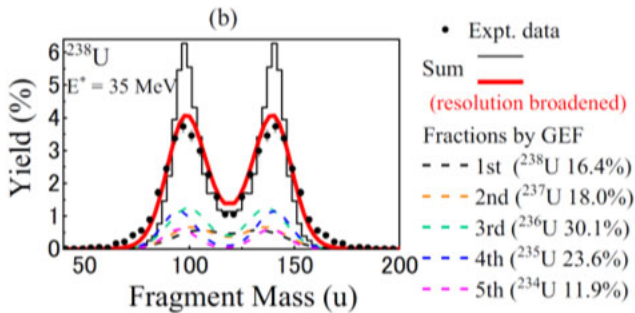
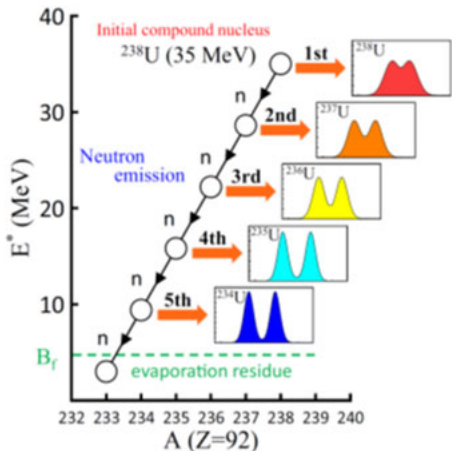


[Tsuchiya, H. et al., J. Nucl. Sci. Tech. 60, 1301 \(2023\)](#)



Multi-Chance Fission

^{238}U fission



S. Tanaka et al., Phys. Rev. C **100**, 064605 (2019)

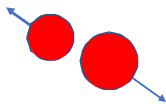
Observables obtained from Fission Fragments

Compound Nuclei



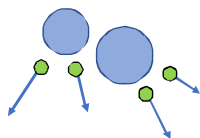
Primary Fragments

Kinetic Energy

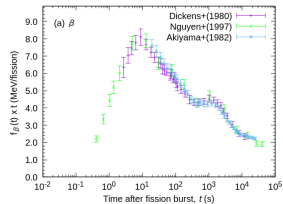
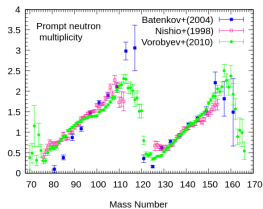
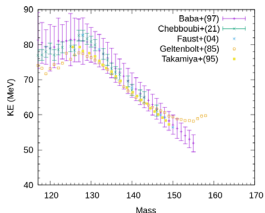
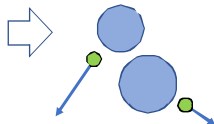


Post Evaporation Fragments

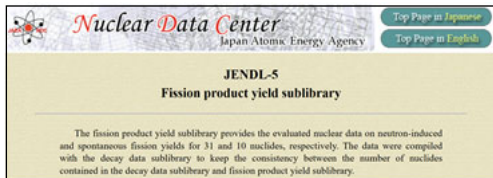
Particle Emissions



β -delayed particles

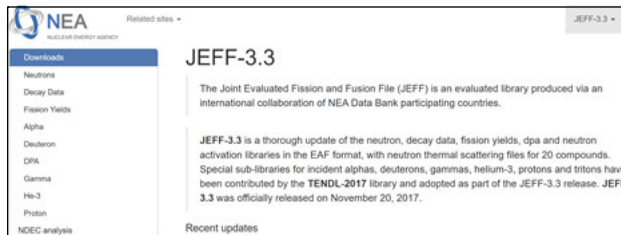


Present Status of Evaluated Fission Fragment Yield (FFY) Data



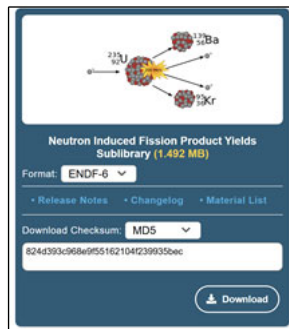
The screenshot shows the Nuclear Data Center website. At the top, there is a logo of a stylized atom and the text "Nuclear Data Center" and "Japan Atomic Energy Agency". There are two buttons: "Top Page in Japanese" and "Top Page in English". The main heading is "JENDL-5 Fission product yield sublibrary". Below this, a paragraph states: "The fission product yield sublibrary provides the evaluated nuclear data on neutron-induced and spontaneous fission yields for 31 and 10 nuclides, respectively. The data were compiled with the decay data sublibrary to keep the consistency between the number of nuclides contained in the decay data sublibrary and fission product yield sublibrary."

<https://www.ndc.jaea.go.jp/index.html>



The screenshot shows the NEA website. The logo "NEA NUCLEAR ENERGY AGENCY" is at the top left. A sidebar on the left lists "Downloads" with categories: Neutrons, Decay Data, Fission Yields, Alpha, Deuteron, DPA, Gamma, He-3, Proton, and NDEC analysis. The main content area is titled "JEFF-3.3" and contains the text: "The Joint Evaluated Fission and Fusion File (JEFF) is an evaluated library produced via an international collaboration of NEA Data Bank participating countries." and "JEFF-3.3 is a thorough update of the neutron, decay data, fission yields, dpa and neutron activation libraries in the EAF format, with neutron thermal scattering files for 20 compounds. Special sub-libraries for incident alphas, deuterons, gammas, helium-3, protons and tritons have been contributed by the TENDL-2017 library and adopted as part of the JEFF-3.3 release. JEFF 3.3 was officially released on November 20, 2017." There is also a "Recent updates" section.

<https://www.oecd-nea.org/dbdata/jeff/jeff33/index.html>

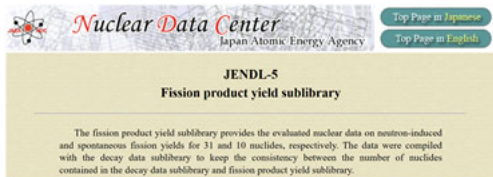


The screenshot shows the NDC website for "Neutron Induced Fission Product Yields Sublibrary (1.492 MB)". It features a diagram of a $^{235}_{92}\text{U}$ nucleus being hit by a neutron, resulting in fission products $^{139}_{54}\text{Ba}$, $^{94}_{36}\text{Kr}$, and $^{95}_{36}\text{Kr}$. Below the diagram, there is a "Format:" dropdown menu set to "ENDF-6", a "Release Notes", "Changelog", and "Material List" link, a "Download Checksum:" dropdown menu set to "MD5", and a text box containing the checksum "824d393c968e9f55162104f239935bec". A "Download" button is at the bottom right.

<https://www.ndc.bnl.gov/endf-releases/?version=B-VIII.1>

Present Status of Evaluated Fission Fragment Yield (FFY) Data

JENDL-5 case



The screenshot shows the Nuclear Data Center logo and the text "Nuclear Data Center Japan Atomic Energy Agency". There are two buttons: "Top Page in Japanese" and "Top Page in English". Below this is a box titled "JENDL-5 Fission product yield sublibrary" with a description: "The fission product yield sublibrary provides the evaluated nuclear data on neutron-induced and spontaneous fission yields for 31 and 10 nuclides, respectively. The data were compiled with the decay data sublibrary to keep the consistency between the number of nuclides contained in the decay data sublibrary and fission product yield sublibrary."

O. Iwamoto et al., J. Nucl. Sci. Tech. 60, 1 (2023)

- 41 kinds of FFY data
- 10 Spontaneous FFY data
- 31 Neutron-Induced FFY data

Issues:

- **Only at specific 3 neutron energies** Thermal, 500 keV、 14 MeV

We need FFY data besides these conventional neutron energies

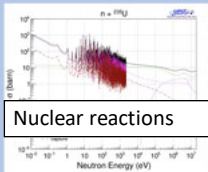
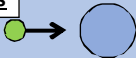
New FFY data to be included in JENDL-5.1

Development of New Code System for Calculating FFY based on “CCONE*”

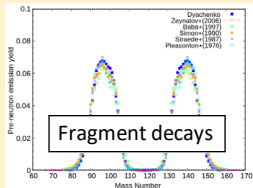
FM, O. Iwamoto, Phys. Rev. C 110, 054311 (2024)

New Framework

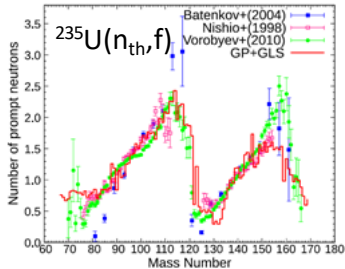
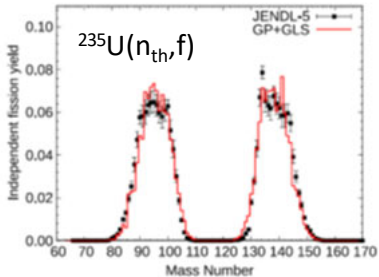
Previous



Nuclear reactions



Fragment decays



INPUT: Primary FFY & TKE \rightarrow Fragment Decays

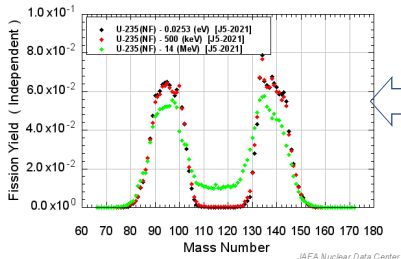
$\rightarrow \langle \nu_p \rangle$, indep./cum. yields, etc.

CCONE: O.Iwamoto et al., Nuclear Data Sheets 131, 259 (2016)

c.f. FIFRELIN, CGMF, FREYA, BeoH/HF³D, TALYS, GEF

INPUT

Primary Fission Fragment Yields & Kinetic Energy



Gaussian
Fitting

Assuming Linear Energy Dependence
of Gaussian parameters
e.g. peak positions, sym. and asym heights

Question:
Parameters truly depend linearly on energy??

Available Experimental data are limited

Solution

A Theoretical Model Calculation Following Physical Background
→ Find appropriate energy dependence of parameters for FFY

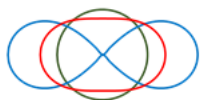
Purpose of our study

(1) Adopt a Langevin model

- ✓ Not necessarily reproduce experimental data
- ✓ It would provide a reasonable energy-dependence

(2) Analyze Langevin FFY and KE at various energies

- ✓ Bring insights on energy-dependence to our calculation (CCONE)



$\alpha = 0.0$

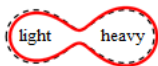
$\alpha = 0.5$

$\alpha = 1.0$



Other shape parameters

α_1



α_2



Cassini parameter
Pashkevich (1971)

α_5

2026/5/11-15

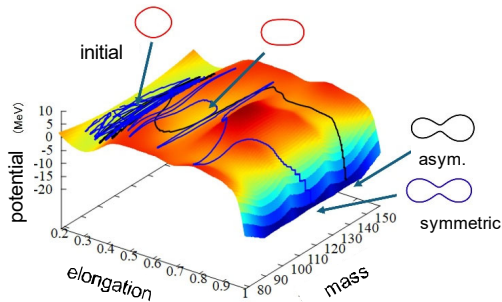
Fission Simulation by 6-dim. Langevin equation

- Represent nuclear shapes with deformation degrees of freedom
- Calculate fission dynamics from their time evolution

HPC@JAEA



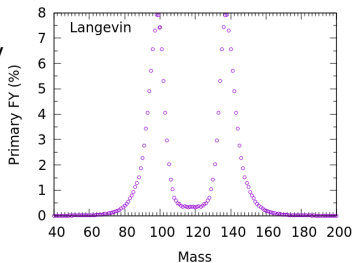
by Kazuki Okada (JAEA)



Langevin Calculation Example (^{236}U)

Primary Fission Fragment

Langevin
 $E^* = 5 \text{ MeV}$
 $^{235}\text{U}(n,f)$



5-Gaussian Function

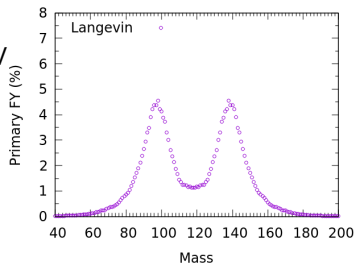
Symmetric component

$$G_0 = \frac{W_0(E)}{\sqrt{2\pi}\sigma_0(E)} \exp\left(-\frac{(A - A_c/2)^2}{2\sigma_0^2(E)}\right)$$

Asym. component

$$G_i = \frac{W_i(E)}{\sqrt{2\pi}\sigma_i(E)} \left\{ \exp\left(-\frac{[A - \mu_i(E)]^2}{2\sigma_i^2(E)}\right) + \exp\left(-\frac{(A - [A_c - \mu_i(E)])^2}{2\sigma_i^2(E)}\right) \right\}$$

Langevin
 $E^* = 25 \text{ MeV}$
 $^{235}\text{U}(n,f)$



Energy dependence

height $W_i(E) = \frac{1}{1 + \exp\left[\frac{(E - w_i^a)/w_i^b}{w_i^b}\right]}$

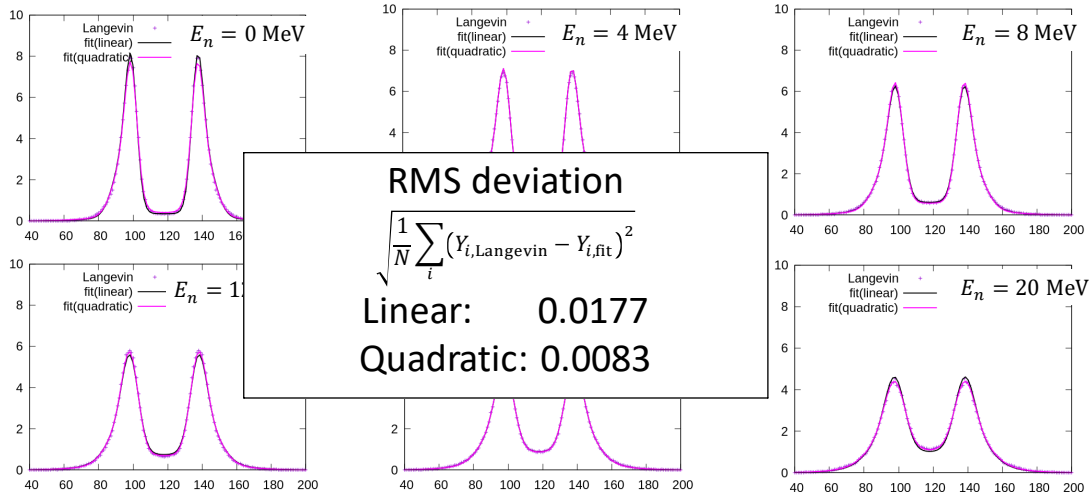
median $\mu_i(E) = \frac{A_c}{2} + \mu_i^0 + \mu_i^1 E + \mu_i^2 E^2$

variance $\sigma_i(E) = \sigma_i^0 + \sigma_i^1 E + \sigma_i^2 E^2 \quad (i = 1, 2)$

$$\sigma_0(E) = \sigma_0^0 + \sigma_0^1 E + \sigma_0^2 E^2$$

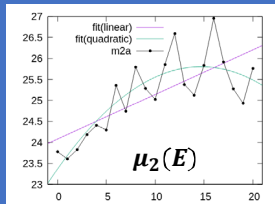
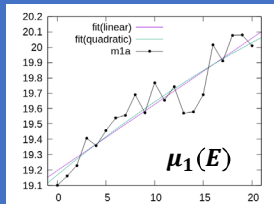
up to quadratic terms

Langevin Model & 5-Gaussian Fitting Result ($n+^{235}\text{U}$)

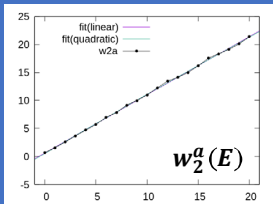
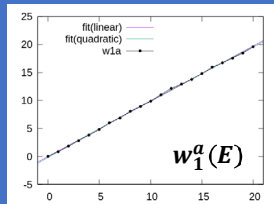


Energy Dependence of Selected Parameters

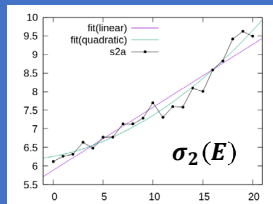
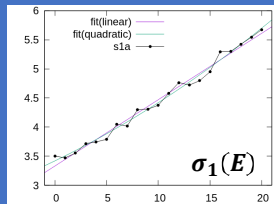
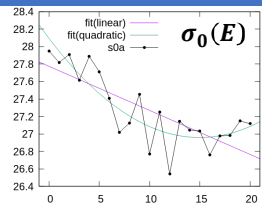
median



height

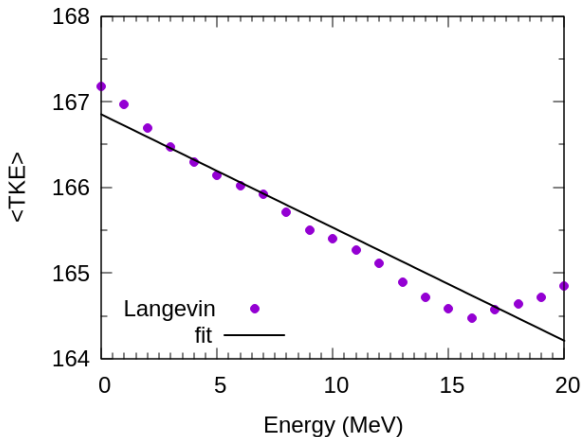


variance



Reproduced by a linear approximation (first order) for $E_n=0-20\text{MeV}$

Kinetic Energy



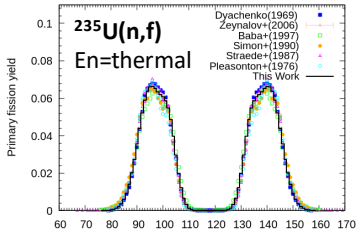
Reproduced by a linear approximation (first order) for $E_n=0-20\text{MeV}$



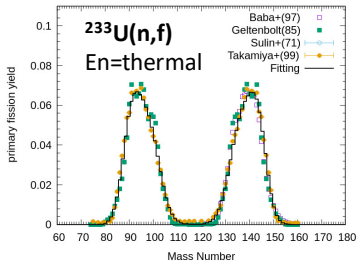
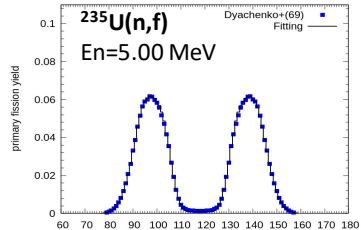
Linear-Energy Dependence!

Re-fitting Parameters with Experimental Data

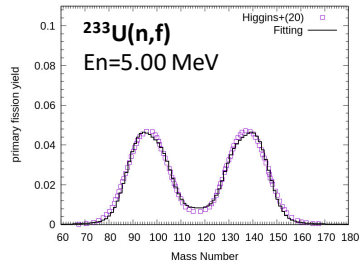
avoid contamination of
2nd-chance fission



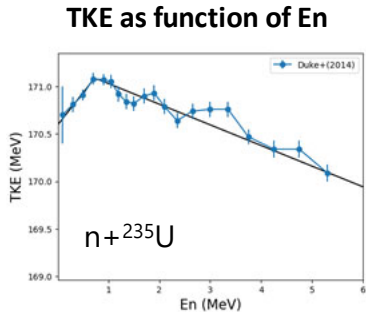
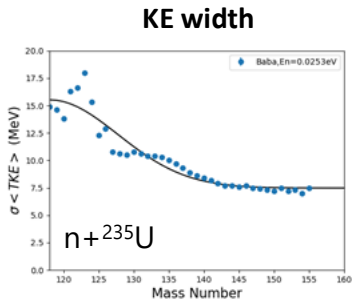
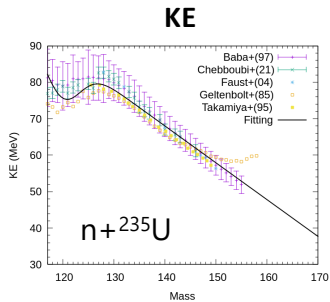
high energy



high energy



Other Parameters concerning Kinetic Energy



$$\text{KE} = (p_0 - p_1 A_h) \left(1 - p_2 \exp\left(\frac{(A_h - A_c/2)^2}{p_3}\right) \right)$$

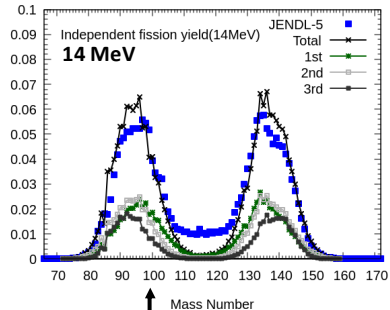
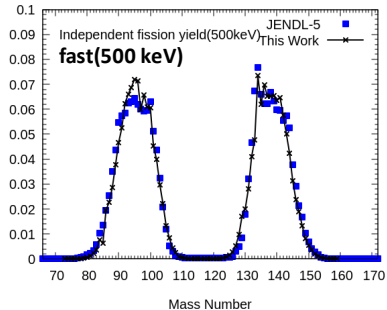
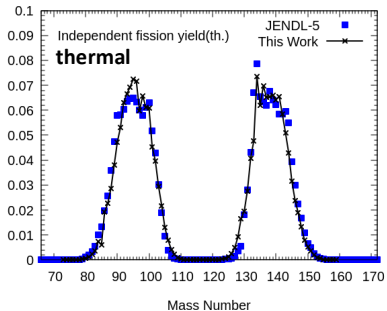
$$\sigma_{\text{TKE}} = s_0 - s_1 \exp\left(-s_2 \left(A_h - \frac{A_c}{2}\right)^2\right)$$

$$\text{TKE} = \begin{cases} a + b \times E_n & \text{for } E_n \leq E_0 \\ c + d \times E_n & \text{for } E_n > E_0 \end{cases}$$

carried out the same parameter determination for $^{233,234}\text{U}(n,f)$

Fission Calculation With New Parameters

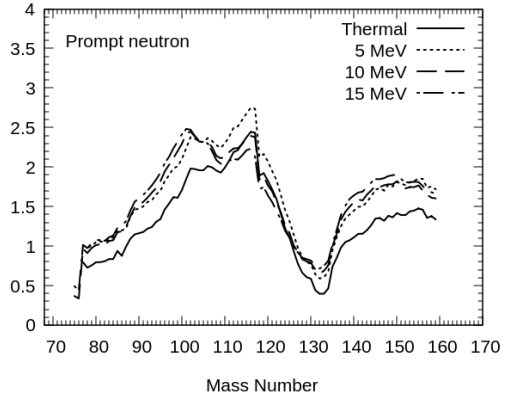
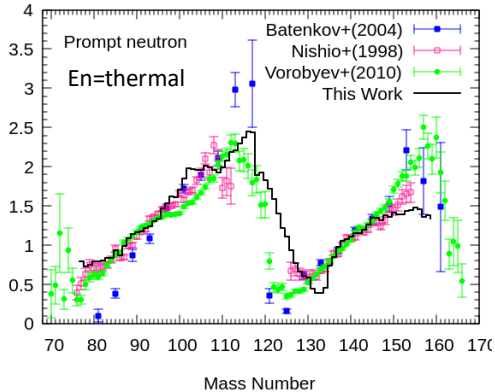
Independent Fission Yields, comparing with JENDL-5



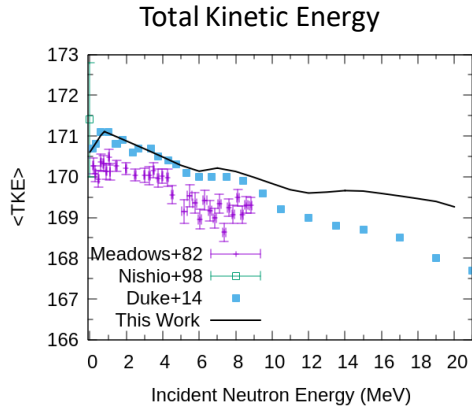
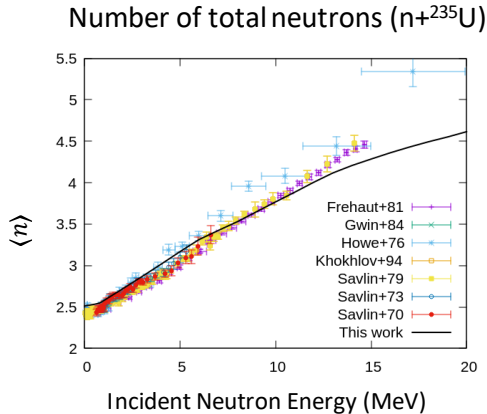
Overestimation in asym.
Underestimation of sym.

Independent Fission Yield Calculation With New Parameters

Calculated prompt neutron multiplicity with experimental data



Independent Fission Yield Calculation With New Parameters



↑
Overestimation above $E_n=8$ MeV remains an issue

$$Q = \text{TXE} + \text{TKE}$$

Applications of Fission Fragment Yields

Applications of Fission Fragment Yields

[1] Energy Applications

Dr. Lile Liu's talk (CIAE) on Tuesday

- Early-Gen. reactors are designed at thermal neutron energy (Light Water)
- Next-generation reactors
 - Fast Breeder Reactors/Accelerator-Driven Reactors/Small Modular Reactors

- Next-Next generation reactors outside boxes

[2] Non-Destructive Analysis of Nuclear Materials

[3] Decommissioning of Reactors

- Avoid Recriticality at Fukushima Plants

[4] Astrophysical applications and Deeper Understanding of Nuclei

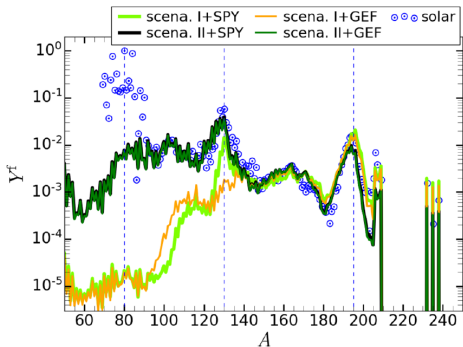


[Tsuchiya, H. et al., J. Nucl. Sci. Tech. 60, 1301 \(2023\)](#)



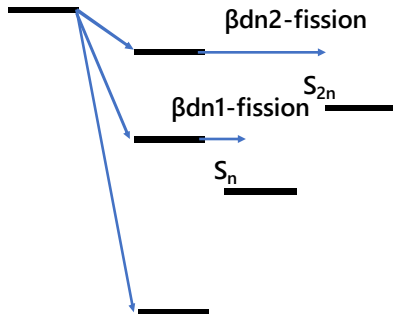
Astrophysical Applications

- Spontaneous fission
- Neutron-induced fission
- β -delayed fission

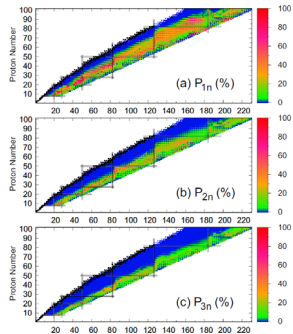


J.-F. Lemaître, PHYSICAL REVIEW C 103, 025806 (2021)

β -delayed fission (β df)



FM, T. Marketin, N. Paar, PRC104, 044321 (2021)
 FM, PRC106, 024306 (2022)



→ Nobuya Nishimura's talk (today)
 Langevin + CCONE calculation (KiLM)

Other Application



JSPS KAKENHI Grant-in-Aid for Transformative Research Areas

New Horizons in Negative Muon Science: A Transdisciplinary Integration of Knowledge Bridging Matter, the Universe, and Humanity

Negative Muon Unstable
Nuclear Physics GL: M. Takamine (ISC)

Negative Muon Nuclear
Data For Society GL: Y. Yamaguchi (JAEA)

Plan to Muon Induced Fission

→ Research potential to reduce radioactive waste in a different way

Muon Induced Fission

μ^-

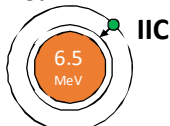
1. μ -capture
delayed fission

2. Fission following
IIC (FFIIC)

X-ray,
Auger

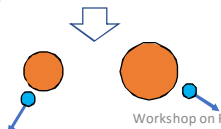


31.6%*



6% 94%

Depend on time-scale of fission



C. Ross, A.S. Umar Phys. Rev. C **112**, L011601 (2025)

TABLE I. Results for ^{240}Pu , ^{256}Fm , and ^{258}Fm systems. For details see text.

System	^{240}Pu	^{256}Fm	^{258}Fm
Charge asymmetry	1.29	1.15	1.0
Mass asymmetry	1.30	1.16	1.0
P_L (no friction)	5.2%	20.6%	50.0%
f (MeV/fm c)	456	550	562
E_{diss} (MeV)	21.94	29.60	18.41
P_L (friction)	6.5%	16.6%	50.0%

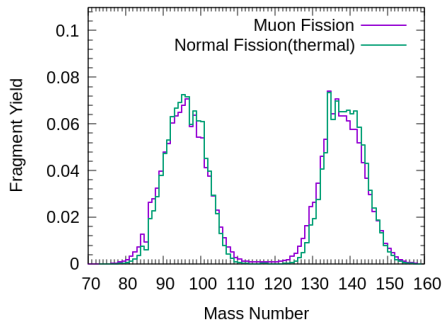
weaker Coulomb field

*F. F. Karpeshin, Phys. of Part. Nuclei Letters, 22, 251 (2025)

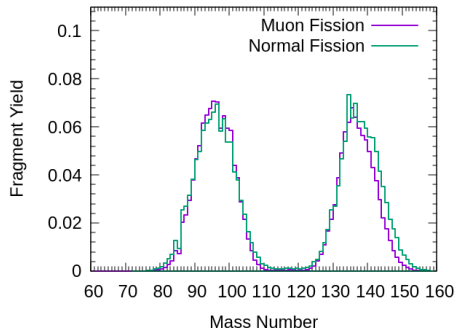
Inverse Internal Conversion (IIC)
 $^{238}\text{U}: 2p_{3/2} \rightarrow 1s$ $E^* = 6.5$ MeV, 31.6%

Muon Induced Fission

1. μ -capture delayed fission



2. Fission following IIC (FFIIC)



Summary

Fission Fragment Yield data at Various Energies are highly demanded

Limited number of experimental data

Not established energy dependence parameters in model codes

Energy Dependence of parameters was analyzed by Langevin Model

Linear Dependence is Reasonable

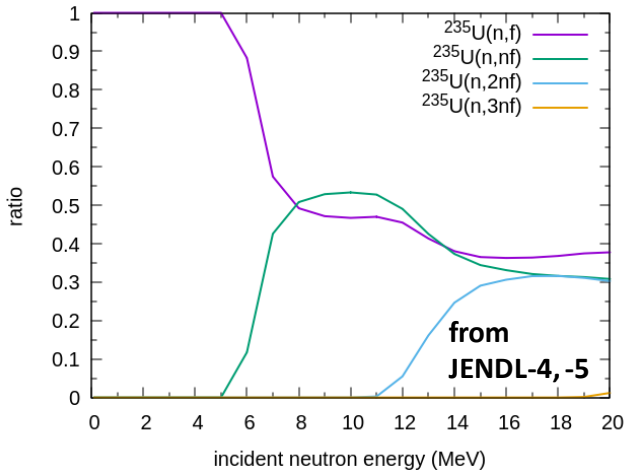
Refit the parameters with experimental Data

and calculate Fission Fragment Yields and Other observables

Well works for $E_n < 8$ MeV, but need further tunings

**FFY data for wide energy region have
a potential to open new science!**

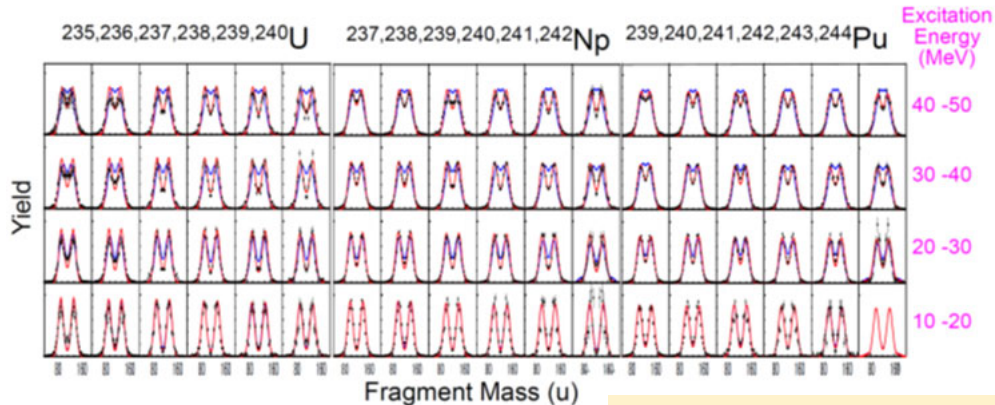
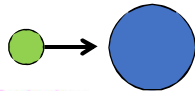
Multi-Chance Fission (Calculation)



Energy Dependence of Fission Fragment Yields

K. Nishio, J. Physics: Conf. Series 1643 (2020) 012151

^{18}O $^{232}\text{Th}, ^{238}\text{U}, ^{237}\text{Np}$

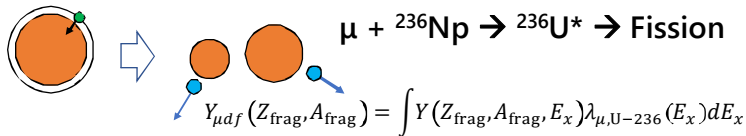


Terminating Shell Effect with increasing Energy

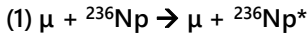
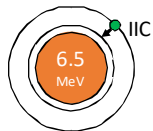
Muon Induced Fission

$Y(Z, A, E_x)$: Post neutron emission yields

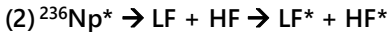
1. μ -capture delayed fission



2. Fission following IIC (FFIIC)-- 3 step --



$$Y_{\text{IIC}}(Z_{\text{frag1}}, A_{\text{frag1}}) = \int Y(Z_{\text{frag1}}, A_{\text{frag1}}, E_x) \lambda_{\text{IIC}}(E_x) dE_x$$



$$Y'_{\text{IIC}}(Z_{\text{frag1}}, A_{\text{frag1}}, \epsilon_x) \quad \text{Random-Phase-Approximation}$$

$$= Y_{\text{IIC}}(Z_{\text{frag1}}, A_{\text{frag1}}) \times \lambda_{\mu\text{-cap}}(Z_{\text{frag1}}, A_{\text{frag1}}, \epsilon_x)$$



$$Y_{\text{FFIIC}}(Z_{\text{frag2}}, A_{\text{frag2}}) = \begin{cases} P_L \int Y'_{\text{IIC}}(Z_{\text{frag1}}, A_{\text{frag1}}, \epsilon_x) R_{\mu}(Z_{\text{frag2}}, A_{\text{frag2}} | Z_{\text{frag1}}, A_{\text{frag1}}, \epsilon_x) d\epsilon_x \\ P_H \int Y'_{\text{IIC}}(Z_{\text{frag1}}, A_{\text{frag1}}, \epsilon_x) R_{\mu}(Z_{\text{frag2}}, A_{\text{frag2}} | Z_{\text{frag1}}, A_{\text{frag1}}, \epsilon_x) d\epsilon_x \end{cases}$$

CCONE

