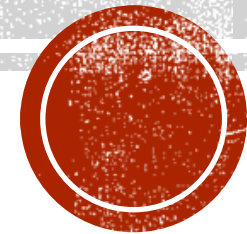




NEUTRON FLUX MEASUREMENTS WITH THRESHOLD DETECTORS



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ARIEL School 2023



OUTLINE

Motivation

Physical background

- Neutron flux, reaction rate, activation
- Typical neutron spectrum of a thermal reactor
- Typical cross section of different reactions

Measurement

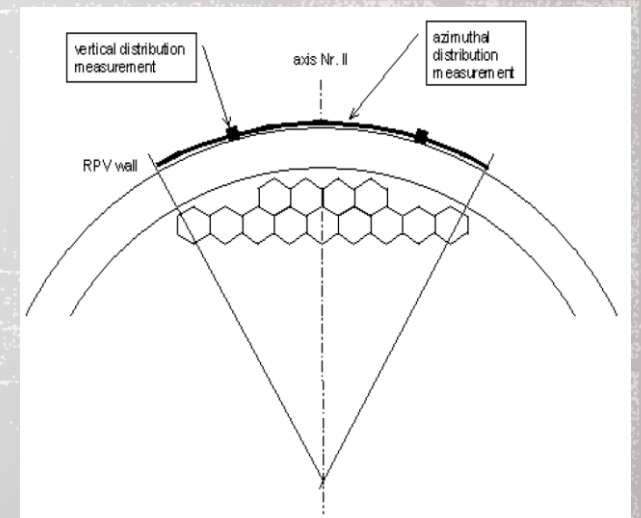
Determination of the neutron spectrum

- Spectrum unfolding
- Information about the correlation matrices

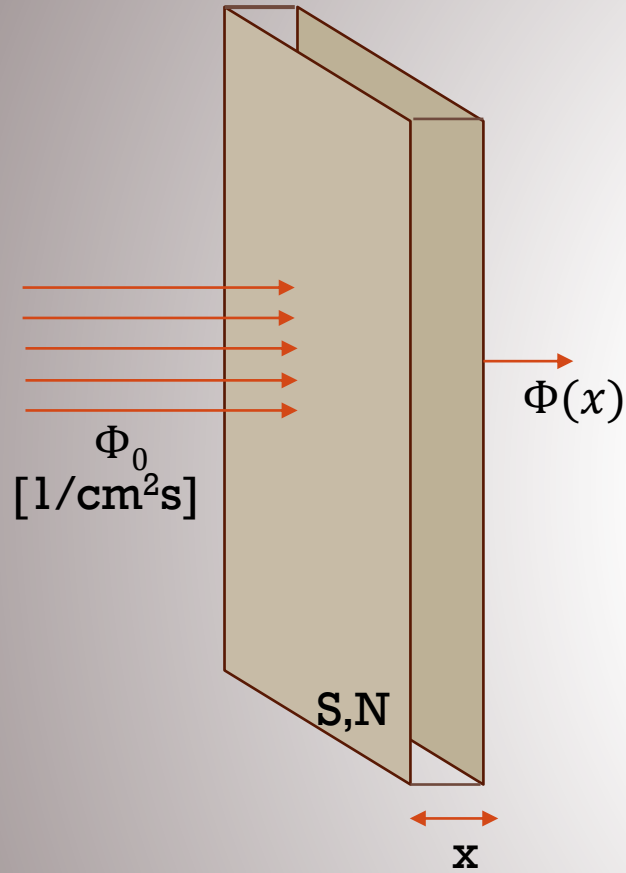
- **Damage** assessment of the vessel:
 - High-energy neutrons may alter the structure of the **steel vessel** by the activation of Fe nuclei
- Experimental nuclear physics:
 - Checking the validity of **neutron transport** codes inside the zone

MOTIVATION

Why is it essential to map the **neutron spectrum** in a nuclear reactor zone?



[2]



- σ : refers to the probability that a certain reaction takes place

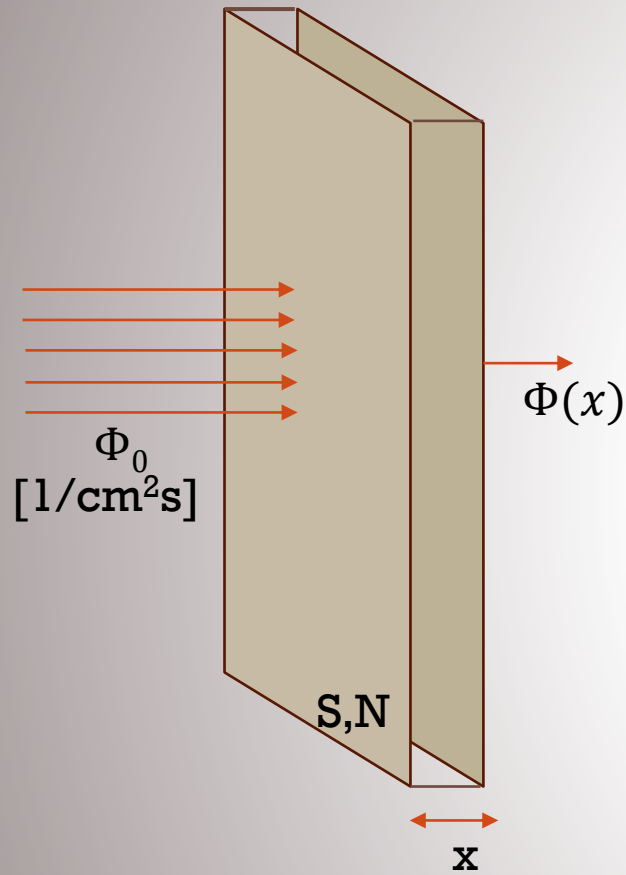
$$\sigma = \frac{R}{\Phi N}$$

- with **R** being the number of reactions taking place per one second

S: surface
N: number of target nuclei

PHYSICAL BACKGROUND

- Neutron flux (Φ)
- Reaction cross section (σ)
- Reaction rate (R)
- Activation ($A_I(t)$)



S: surface
N: number of target nuclei

- σ : refers to the probability that a certain reaction takes place

$$\sigma = \frac{R}{\Phi N}$$

- with **R** being the number of reactions taking place per one second

The cross section depends on the energy of the incident neutron!

$$\sigma(E) = \frac{R}{\Phi(E)N}$$

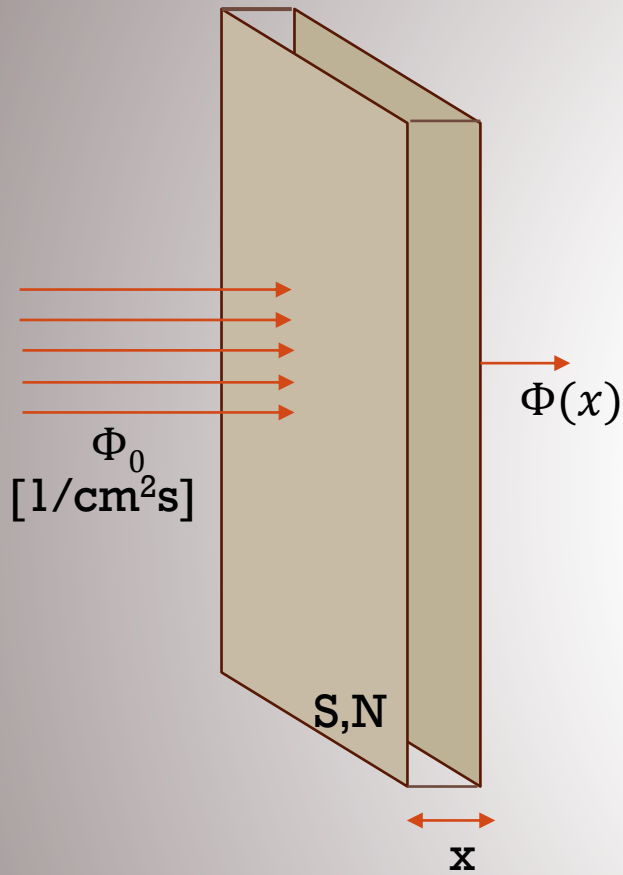
PHYSICAL BACKGROUND

- Neutron flux (Φ)
- Reaction cross section (σ)
- Reaction rate (R)
- Activation ($A_I(t)$)

The cross section depends on the energy of the incident neutron!



$$\sigma(E) = \frac{R}{\Phi(E)N}$$



- the activity of the irradiated nuclei:
 - $A_I(t)$ gets saturated rapidly when the **half-life** of the irradiated nucleus is **too short**
 $A_I(t \rightarrow \infty) \rightarrow R$ (maximal)

PHYSICAL BACKGROUND

- Neutron flux (Φ)
- Reaction cross section (σ)
- Reaction rate (R)
- Activation ($A_I(t)$)

S: surface

N: number of target nuclei

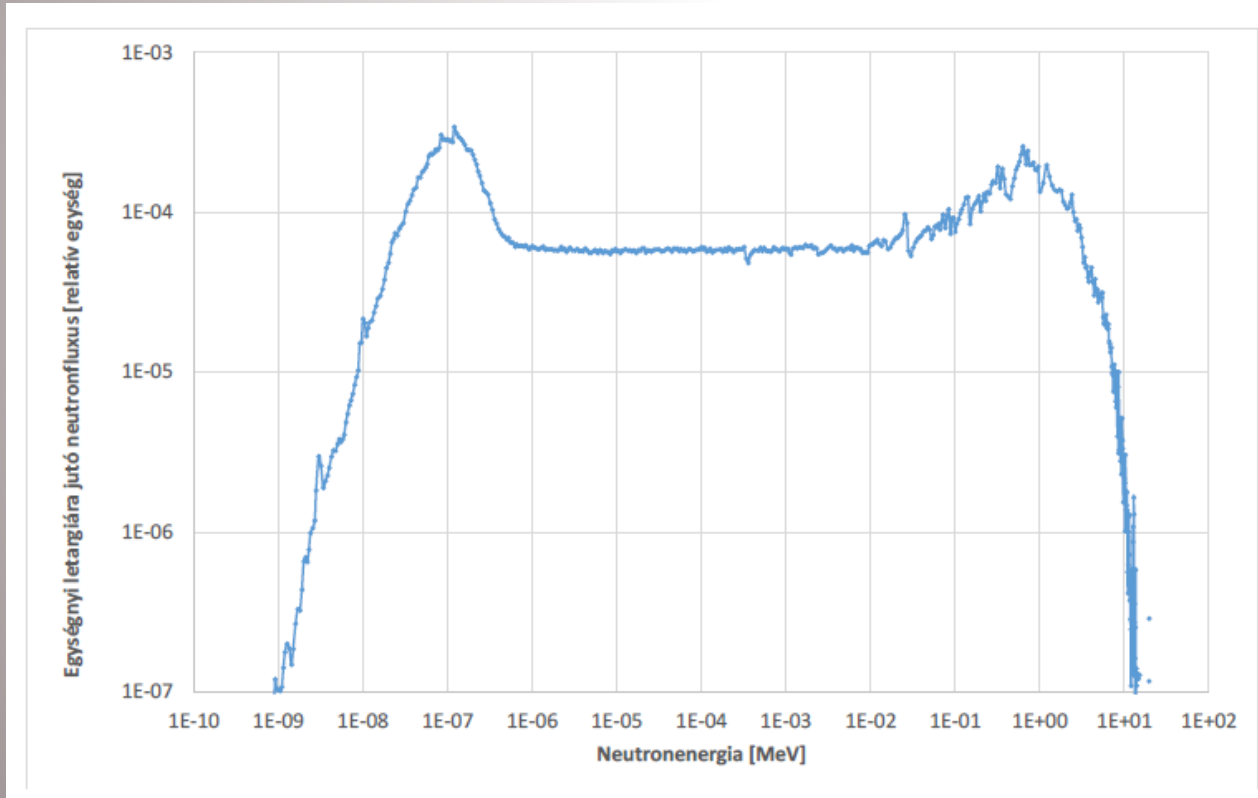
WHAT DO WE MEASURE? —

$$\frac{d\Phi(E)}{dE}; \sigma(E); R$$

The reaction rate

Neutron **spectrum** in a VVER-440 reactor:

$$\frac{d\Phi}{dE}$$



Neutron flux over unit of lethargy -> measure of neutron slowing

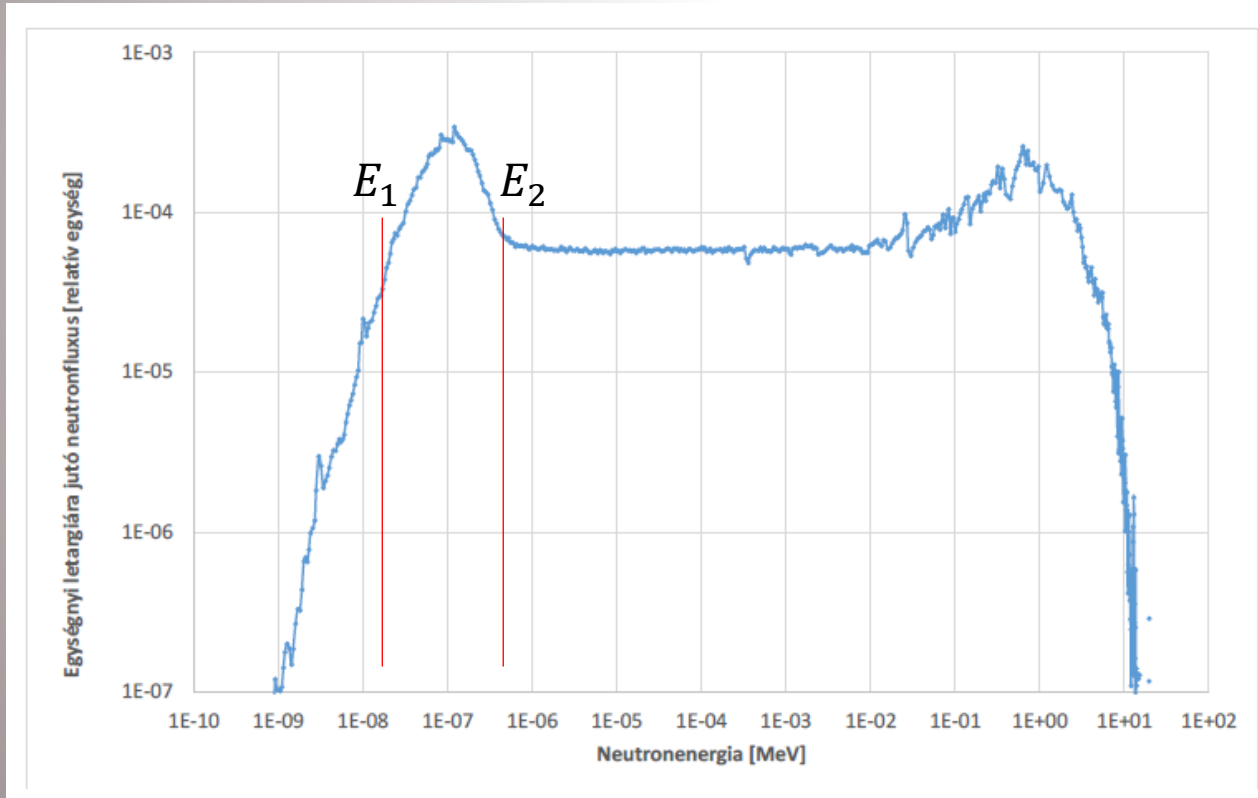
WHAT DO WE MEASURE? —

$$\frac{d\Phi(E)}{dE}; \sigma(E); R$$

The reaction rate

Neutron **spectrum** in a VVER-440 reactor:

$$\frac{d\Phi}{dE}$$



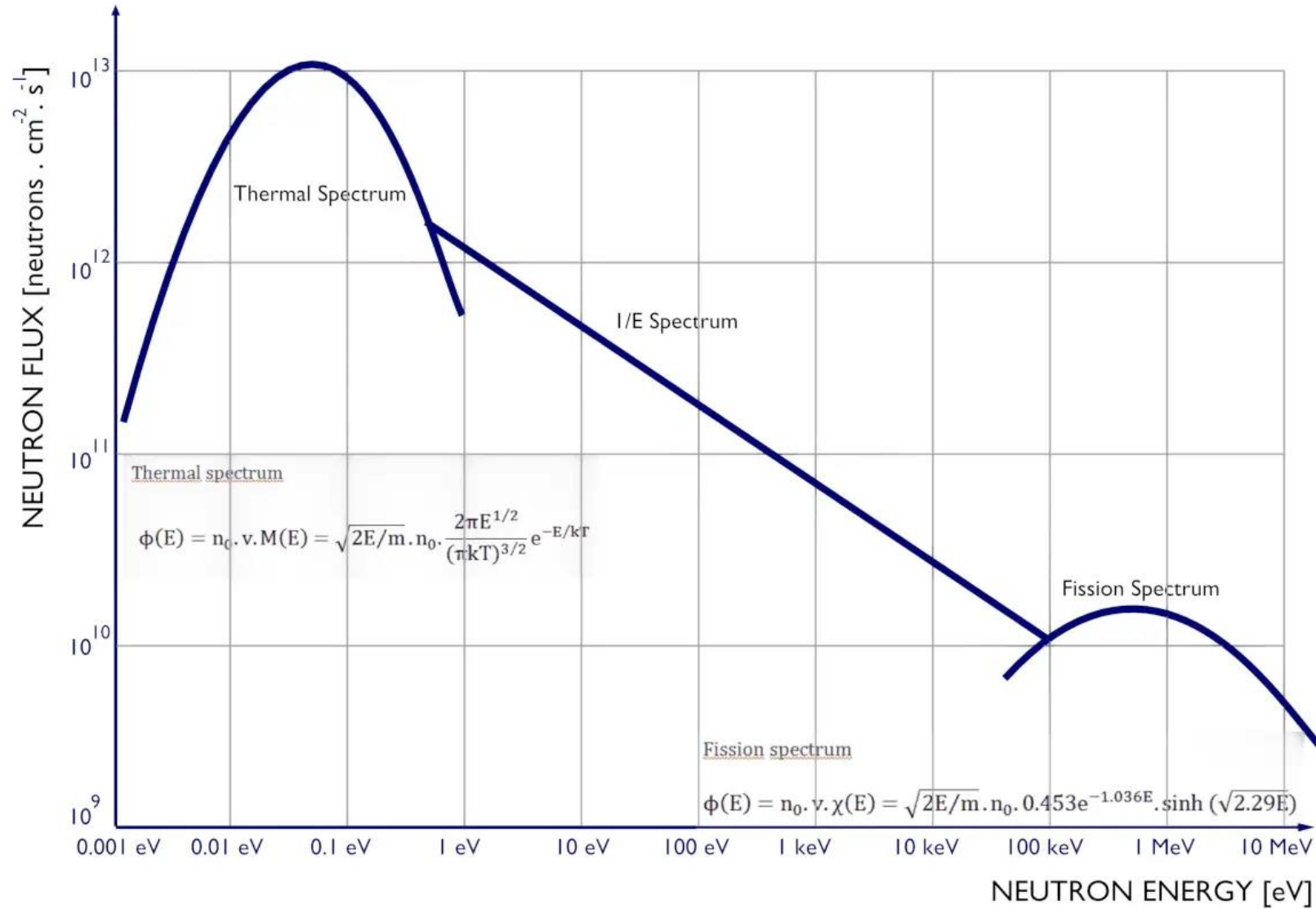
$$dR = \frac{d\Phi(E)}{dE} N \sigma(E) dE$$

$$R = N \int_{E_1}^{E_2} \frac{d\Phi(E)}{dE} \sigma(E) dE$$

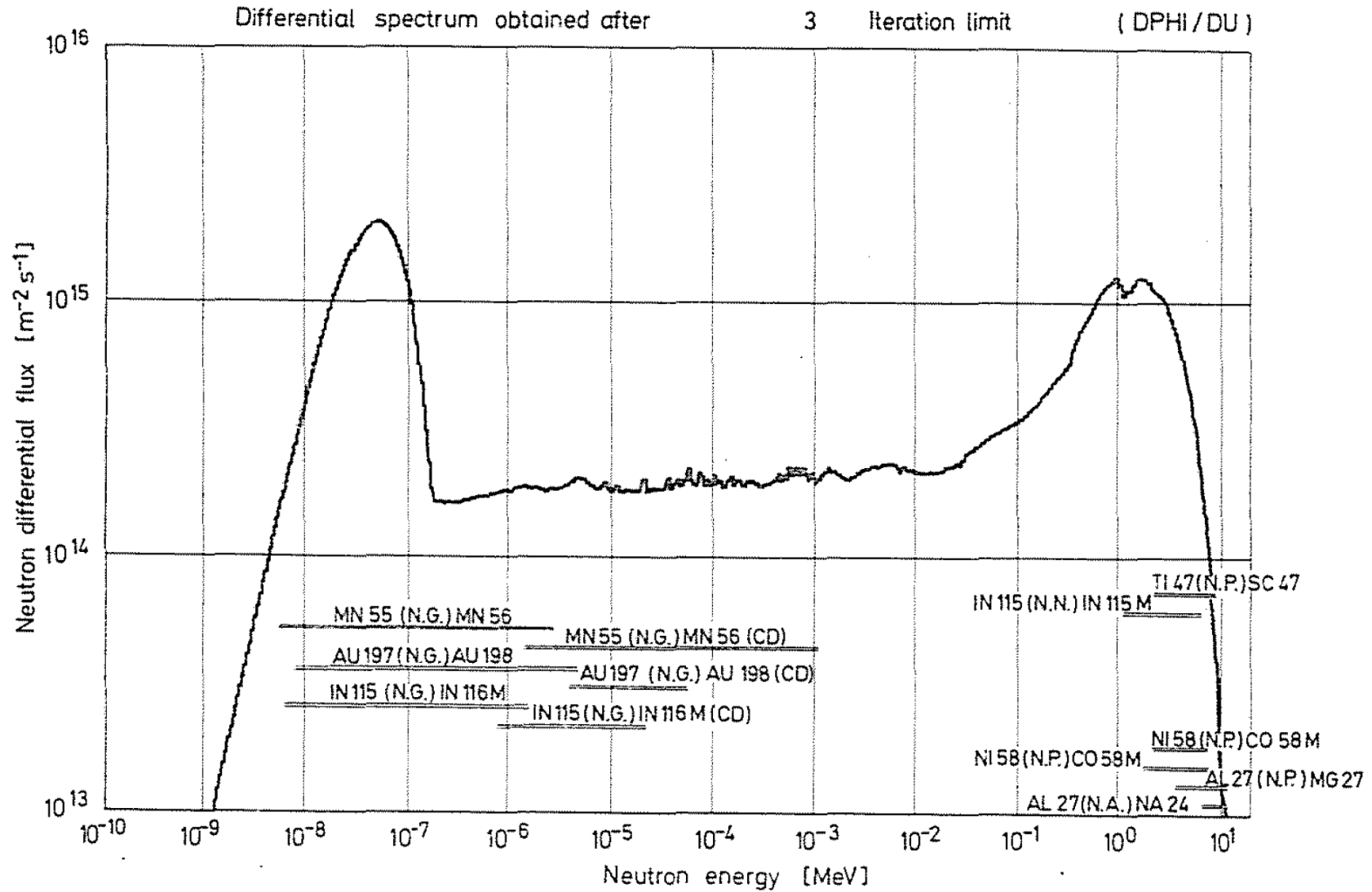
measure and calculate the reaction rate over an energy interval

Neutron flux over unit of lethargy -> measure of neutron slowing

Typical energy regions of the neutron flux spectrum in thermal reactors [2]



Neutron spectrum of a light-water reactor [3]



Cross sections are downloaded from:

Evaluated Nuclear Data File (ENDF) Database Version of 2023-08-25

Software Version of 2023-08-31



News & History

- 2023/08 Updated **JENDL-5** Japanese evaluated nuclear data library (2021) **Errata** including update-13, August 10, 2023 [page]
- 2023/08 New library: **INDEN-Aug2023** evaluations produced by International Nuclear Data Evaluators Network (coord. by the IAEA) [page]
- 2023/03 New software feature: plotting covariances of the average number of neutrons per fission MF31 [example]
- 2023/02 New software tool: **EE-View** - fast experimental-evaluated data viewer [about] → go to SIG:[eeview][eeview1]; DA:[eeview-da]
- 2022/10 New software feature: plotting covariances for angular distributions of secondary particles MF34 [example]

Core nuclear reaction database contain recommended, evaluated cross sections, spectra, angular distributions, fission product yields, photo-atomic and thermal scattering law data, with emphasis on neutron induced reactions. The data were analyzed by experienced nuclear physicists to produce recommended libraries for one of the national nuclear data projects (USA, Europe, Japan, Russia and China). All data are stored in the internationally-adopted ENDF-6 format maintained by CSEWG. See database summary [here].

Standard Request

Examples: [1](#) [2](#) [3](#) [4](#) [5](#) [6](#) [7](#)

Go to: [Advanced Request](#); [ENDF-Database Explorer](#); [EE-View:CS,CS1,DA](#)

Parameters:

Submit

Reset

Target MN-55 >>

Reaction N,G >>

Quantity >>

[More Parameters...](#)

Submit

Libraries: All Selected [Check](#) [Reset](#)

[How to plot](#)

Major Libraries Special Libraries

IAEA Project Libraries Archival

Derived

Options:

Sort by: Reactions Evaluations

Clone Request:

[EXFOR](#)

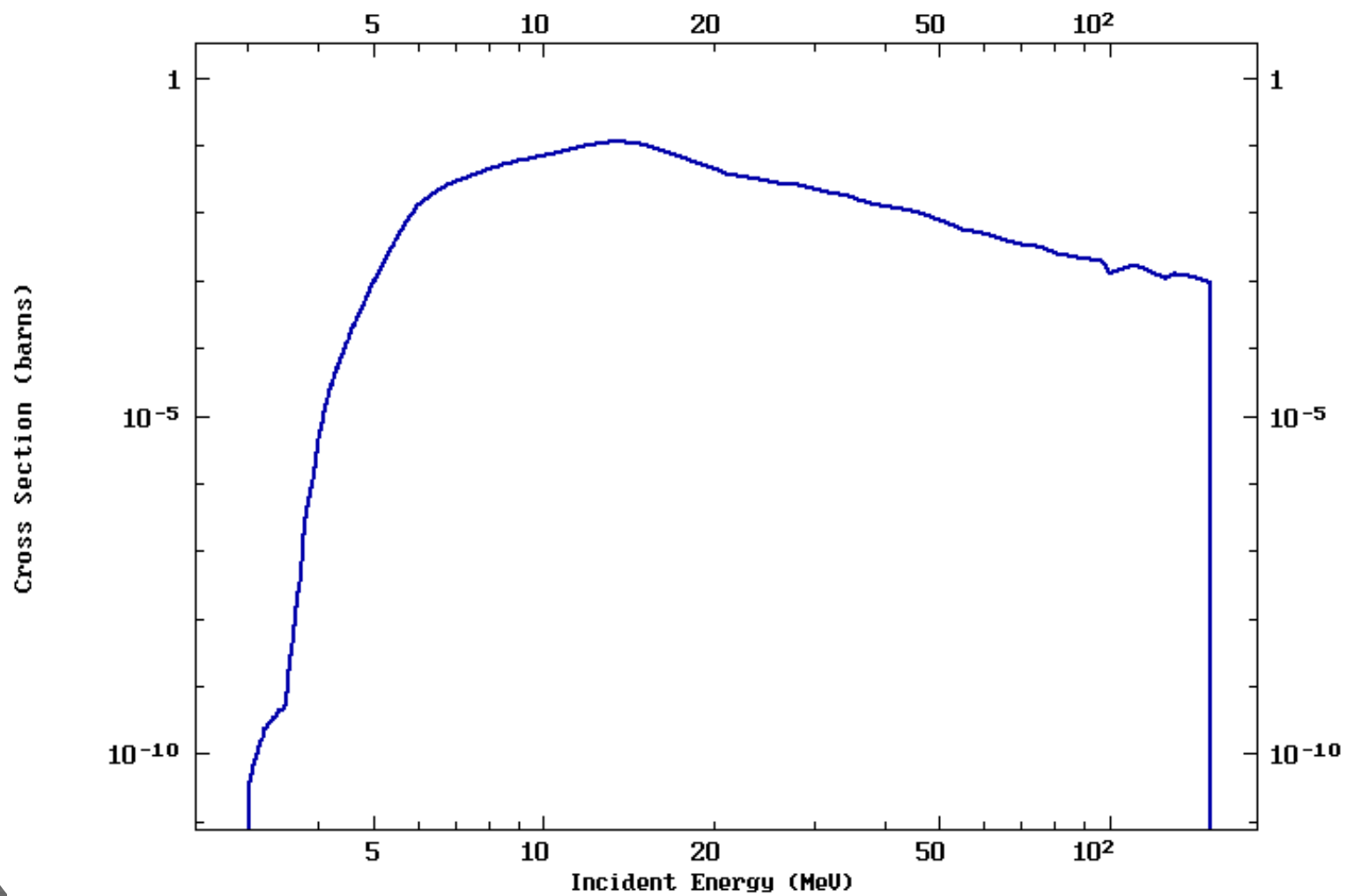
[CINDA](#)

Feedback:

[Comments/Questions?](#)

Energy-dependent cross section of the reaction: $^{56}\text{Fe}(n,\gamma)^{56}\text{Mn}^*$

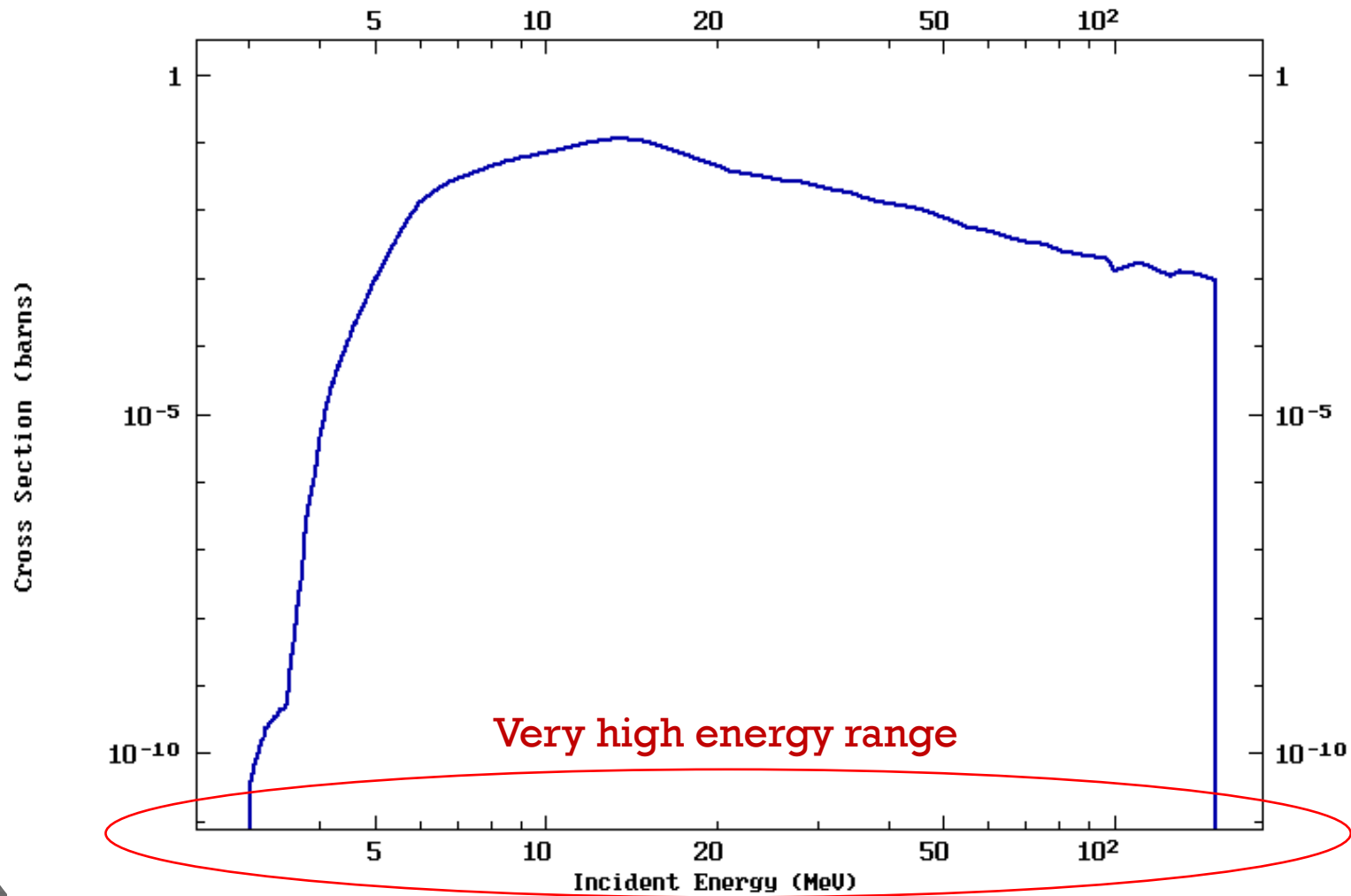
ENDF Request 6063, 2023-Sep-20,17:16:57



Energy-dependent cross section of the reaction:



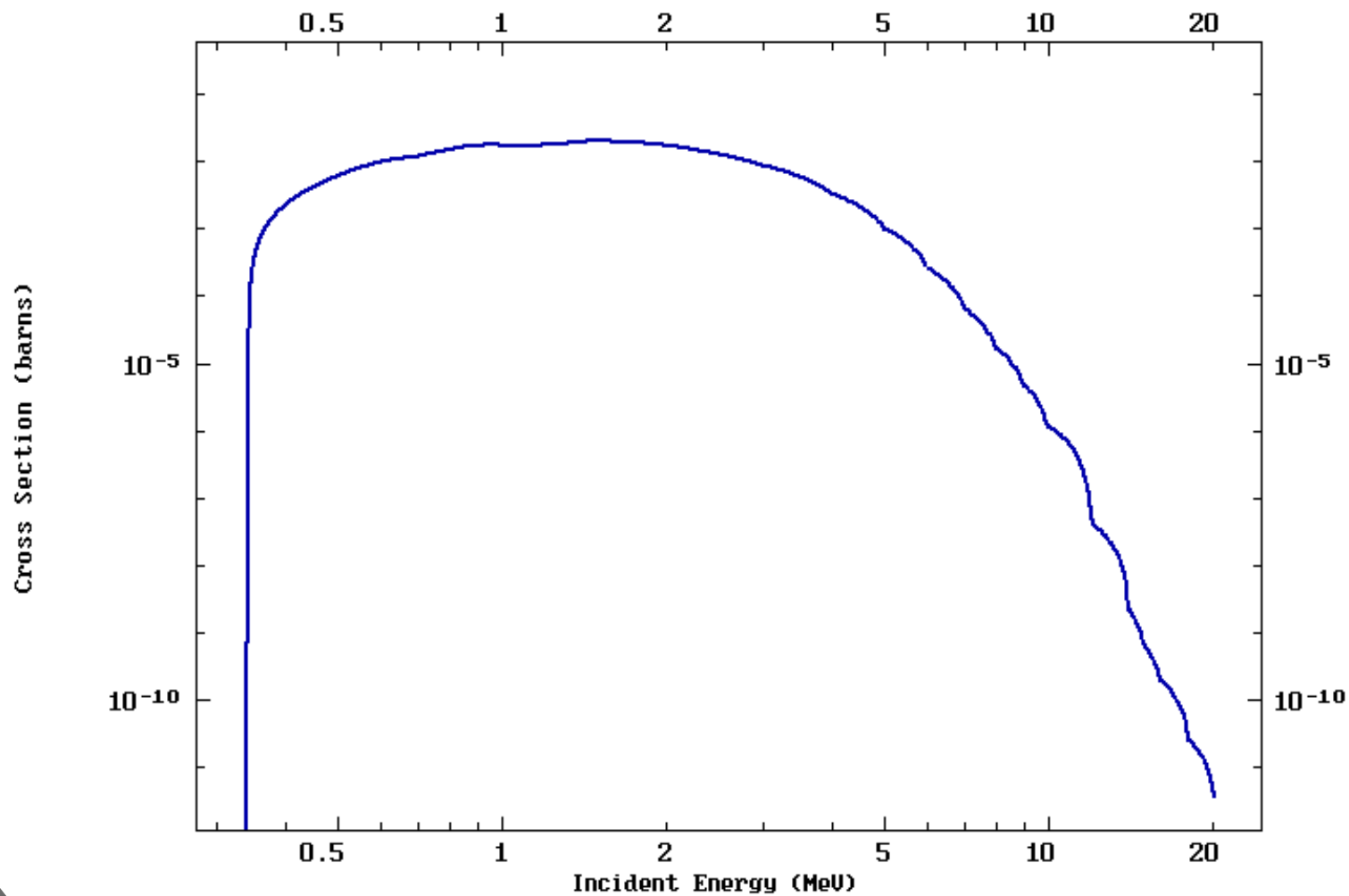
ENDF Request 6063, 2023-Sep-20,17:16:57



Energy-dependent cross section of the reaction:



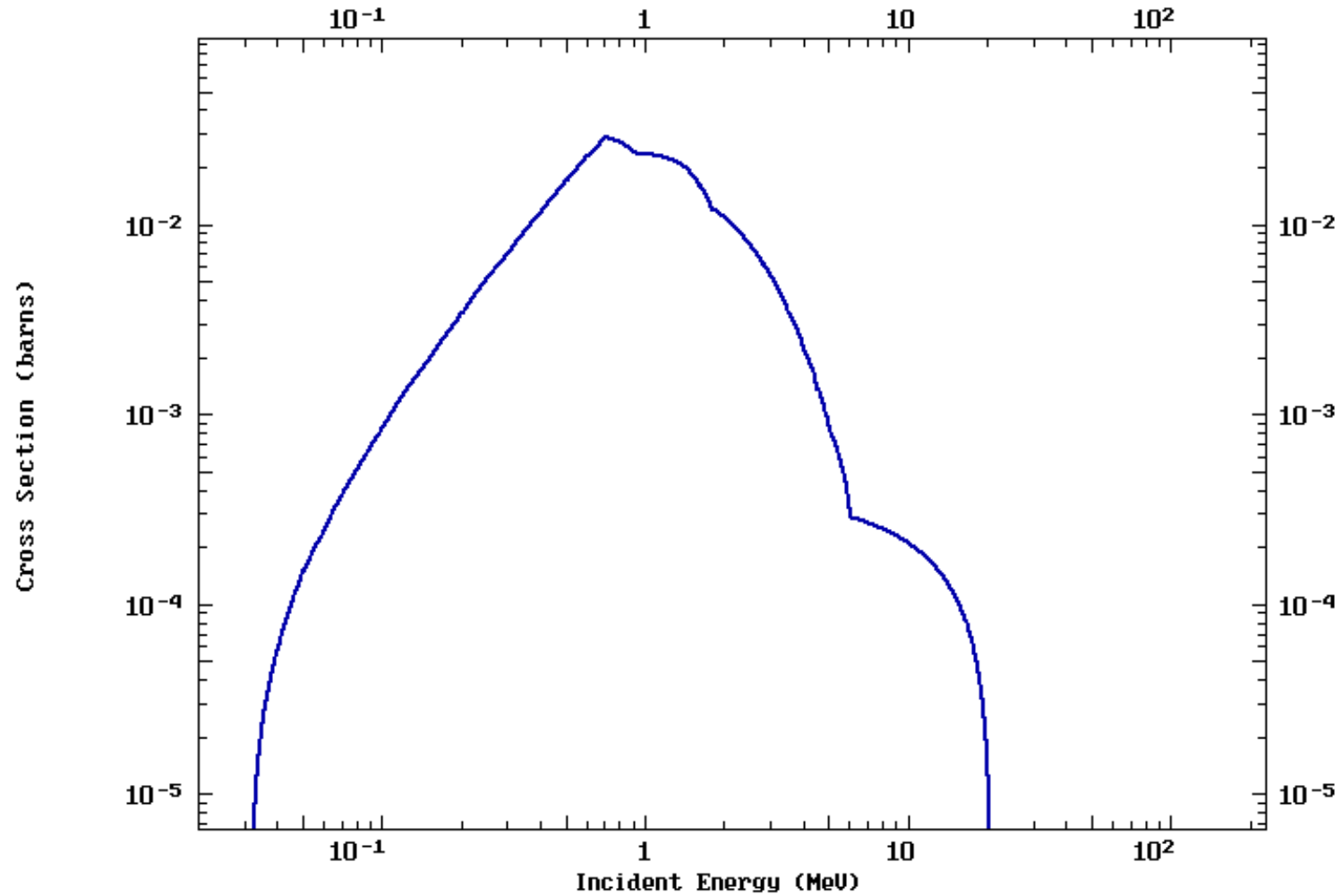
ENDF Request 6069, 2023-Sep-20,18:13:31



Energy-dependent cross section of the reaction:



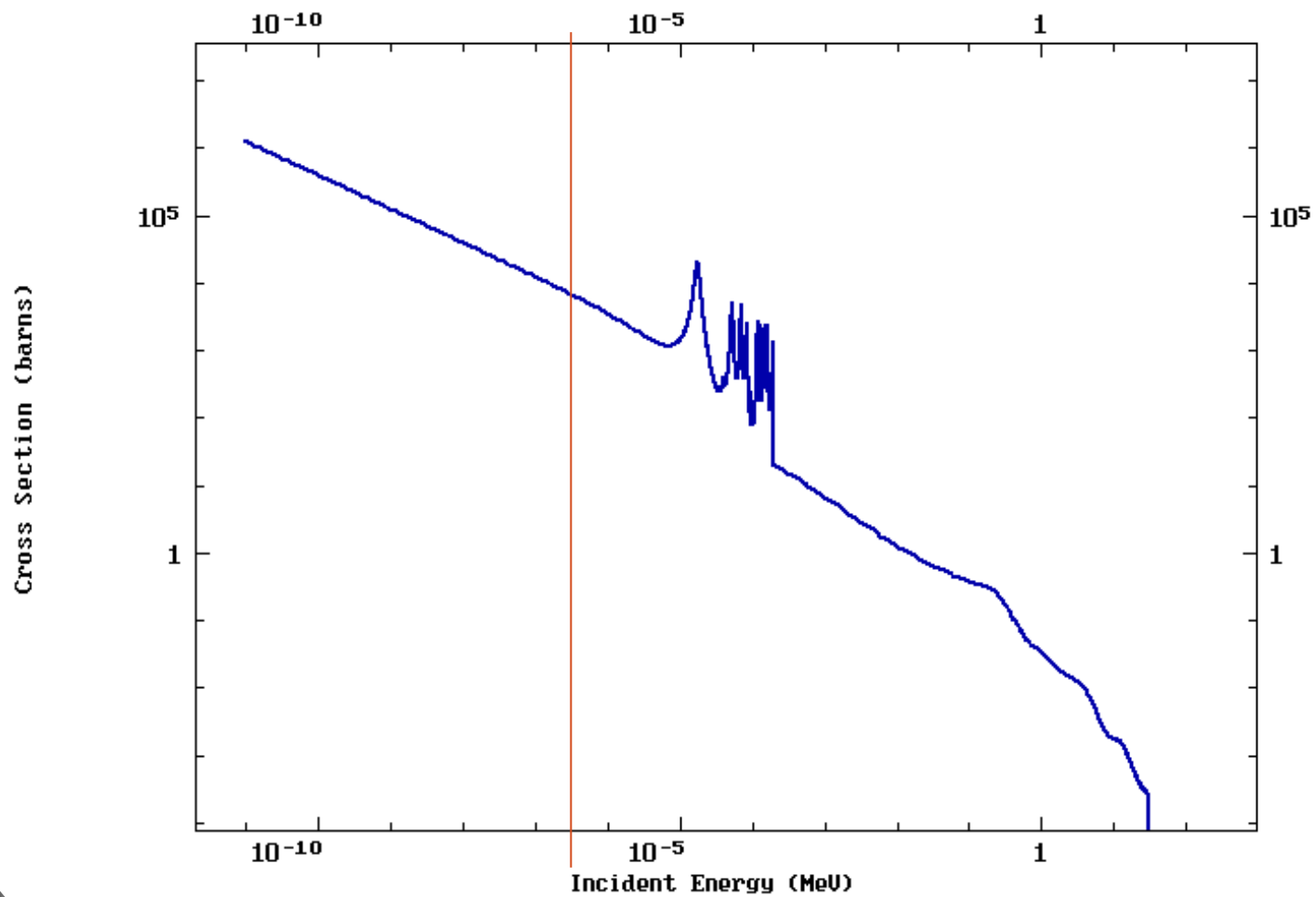
ENDF Request 6071, 2023-Sep-20,18:41:31



Energy-dependent cross section of the reaction:

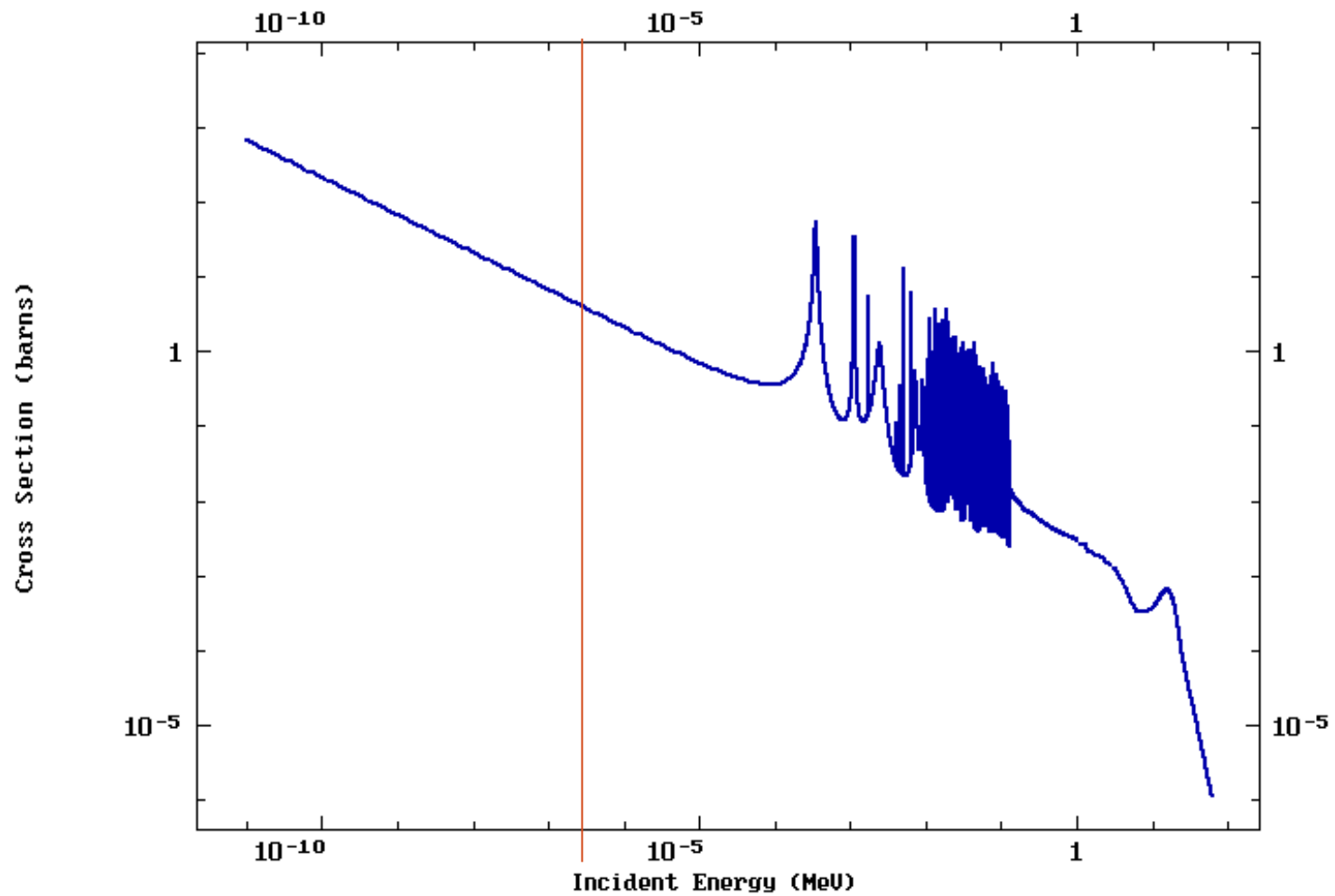


ENDF Request 6062, 2023-Sep-20,17:04:29



Energy-dependent cross section of the reaction: $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$

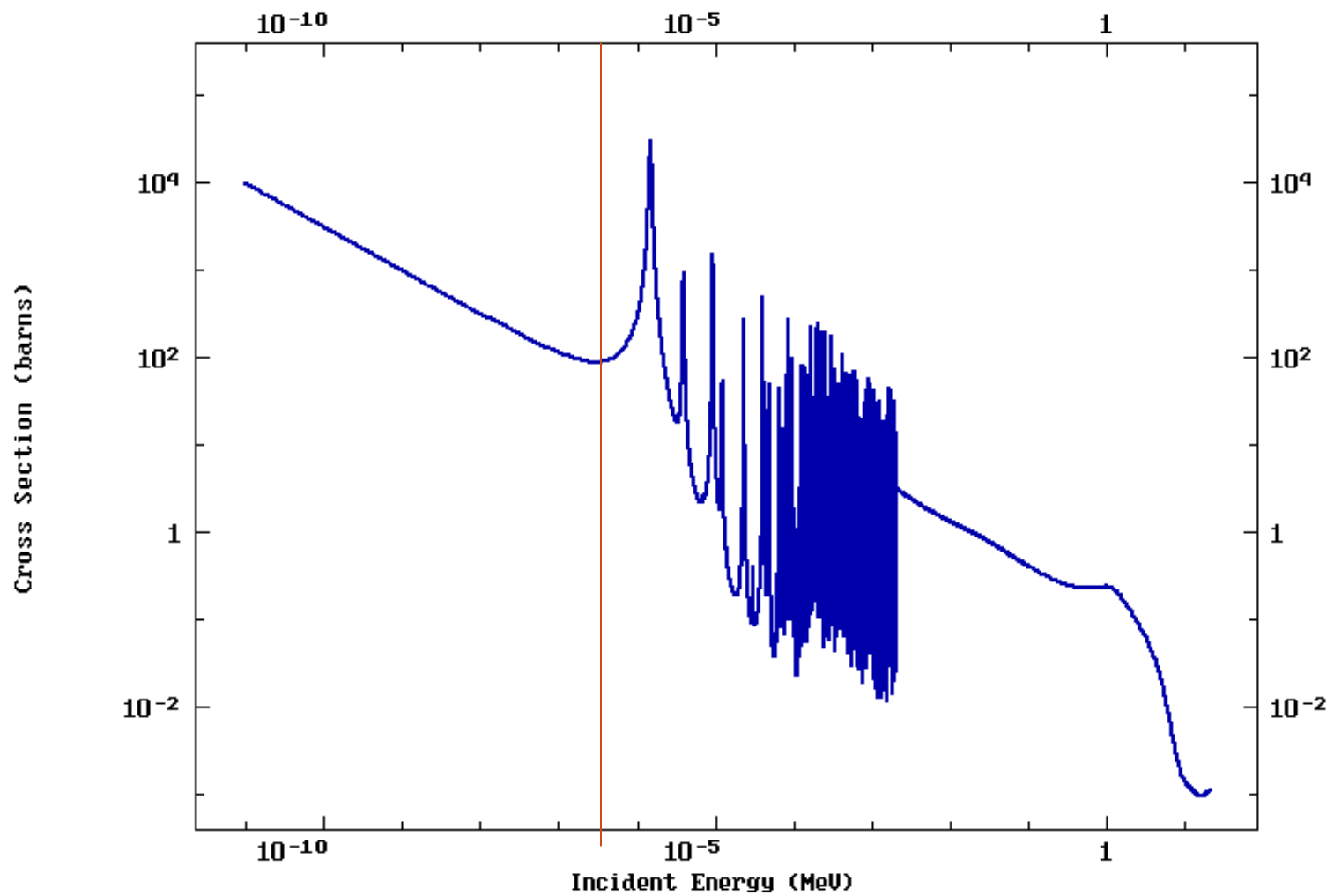
ENDF Request 5956, 2023-Sep-20, 18:07:26



Energy-dependent cross section of the reaction:

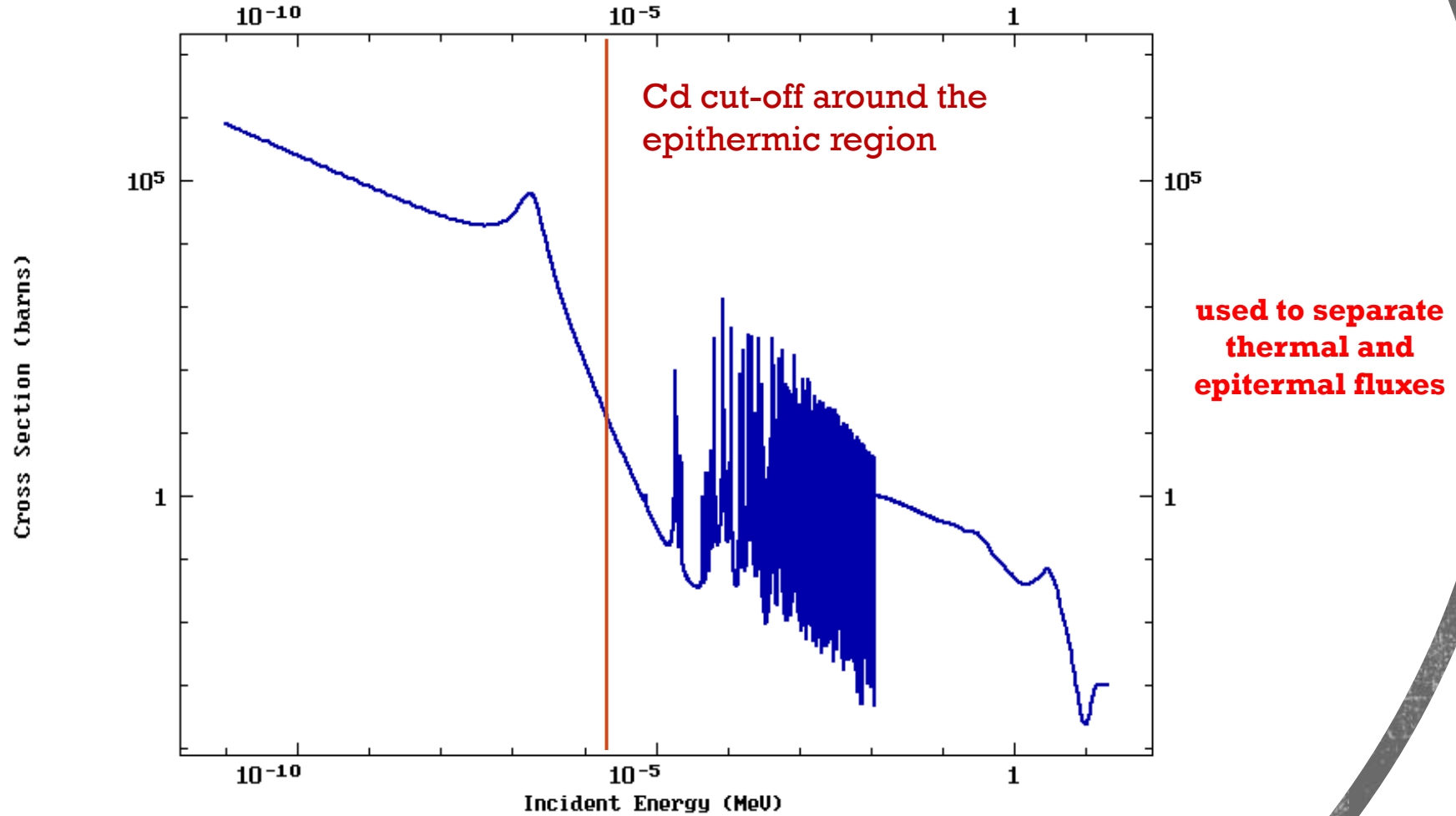


ENDF Request 6950, 2023-Sep-23,13:18:11



Energy-dependent cross section of the reaction: $^{113}\text{Cd}(n,\gamma)^{114}\text{Cd}$

ENDF Request 6075, 2023-Sep-20,19:28:01

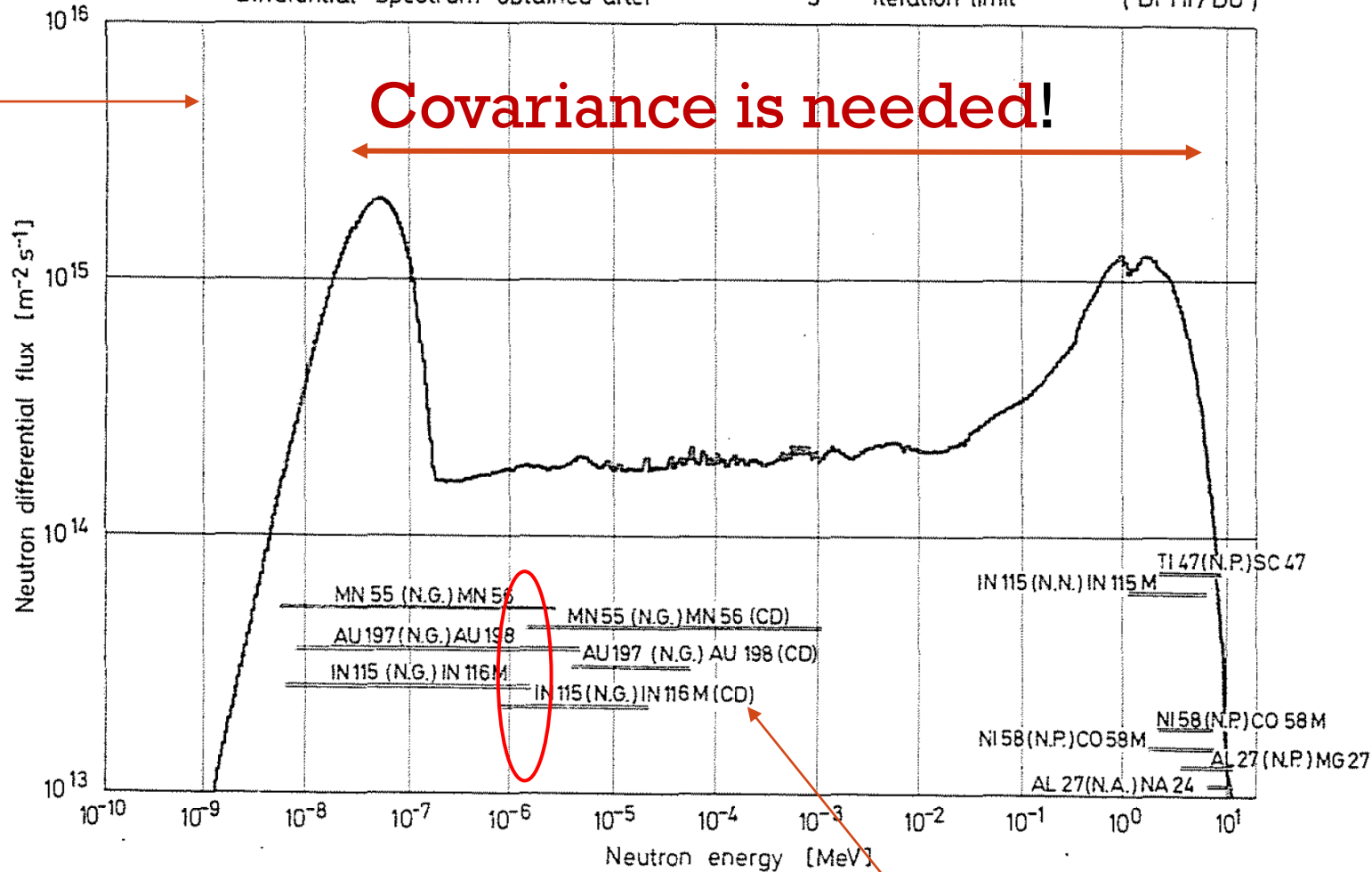


Neutron spectrum of a light-water reactor [3]

Differential spectrum obtained after 3 iteration limit (DPHI/DU)

We measure continuous spectra

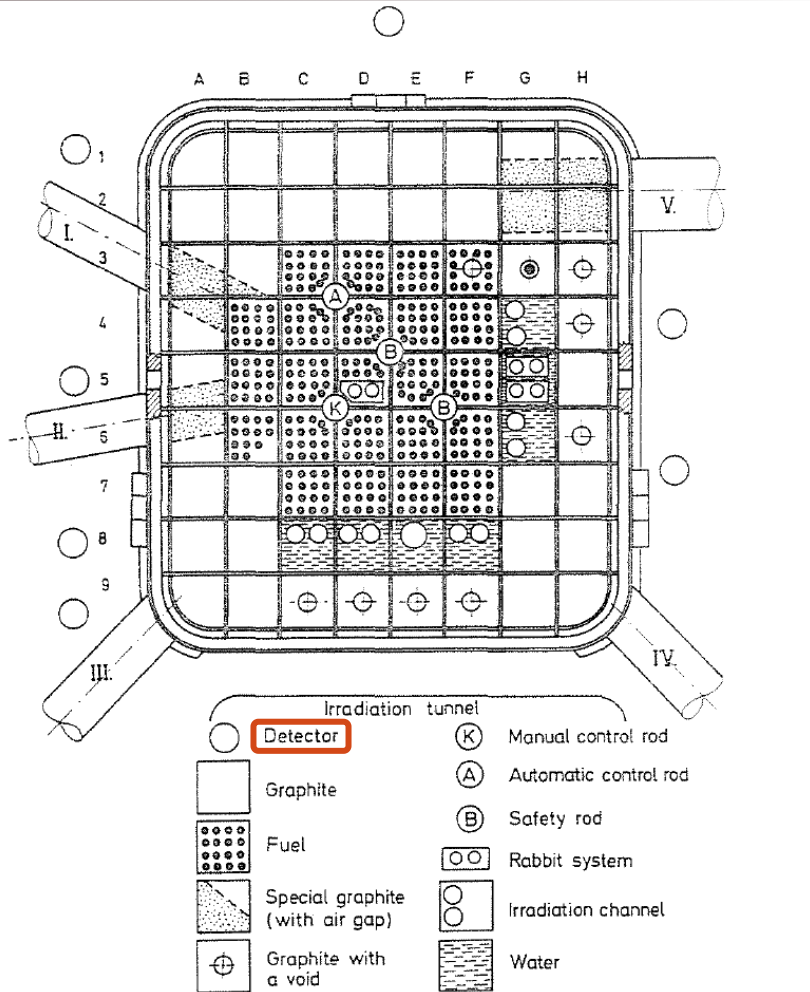
Covariance is needed!



Cadmium cover -> epithermic spectrum

- Reactor core, reactor operating at 10 kW [3]

ABOUT THE MEASUREMENT



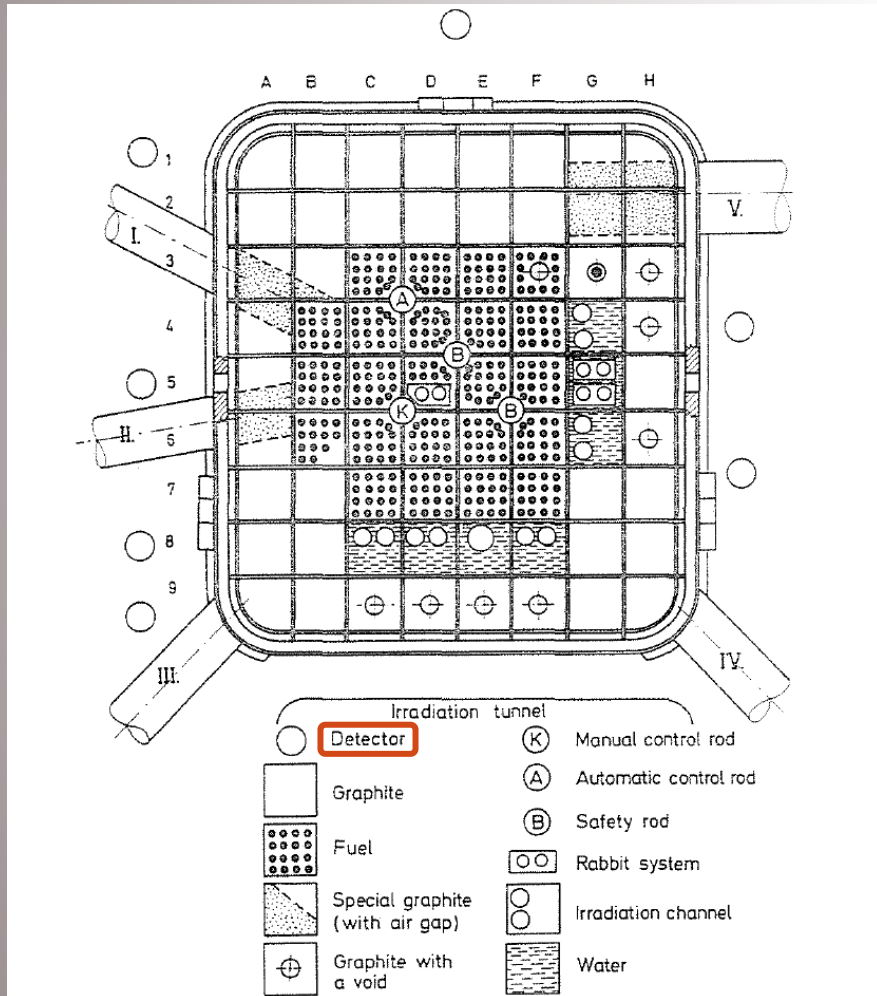
Reaction	Half-life
$^{164}\text{Dy}(n, \gamma)^{165}\text{Dy}^*$	139.2 min
$^{164}\text{Dy}(n, \gamma)^{165}\text{Dy}^*$	139.2 min
$^{27}\text{Al}(n, p)^{27}\text{Mg}$	9.46 min
$^{27}\text{Al}(n, \alpha)^{24}\text{Na}$	15.03 h
$^{45}\text{Sc}(n, \gamma)^{46}\text{Sc}^*$	84.0 d
$^{56}\text{Fe}(n, p)^{56}\text{Mn}^*$	2.587 h
$^{58}\text{Ni}(n, p)^{58}\text{Co}$	71.3 d
$^{58}\text{Ni}(n, p)^{58}\text{Co}$	71.3 d
$^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$	53.34 min
$^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$	53.34 min
$^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$	155.2 min
$^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$	155.2 min
$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	2.695 d
$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	2.695 d
$^{115}\text{In}(n, n')^{115\text{m}}\text{In}$	4.5 h
$^{47}\text{Ti}(n, p)^{47}\text{Sc}$	80.4 h
$^{48}\text{Ti}(n, p)^{48}\text{Sc}$	44.1 h

↑
Typical monitor substances

↑
The reaction products are β -decaying or γ -decaying isotopes

- HPGe semi-conductor detectors
- Sets of irradiated thin foils covered by Al or Cd (**neutron monitors**)
- Detecting γ -lines

- Reactor core, reactor operating at 10 kW [3]



Reaction	Half-life	$A_{sat}/\text{target atom}$ [Bq]
$^{164}\text{Dy}(n, \gamma)^{165}\text{Dy}^*$	139.2 min	6.35 E-10
$^{164}\text{Dy}(n, \gamma)^{165}\text{Dy}^*$	139.2 min	6.32 E-12
$^{27}\text{Al}(n, p)^{27}\text{Mg}$	9.46 min	9.01 E-16
$^{27}\text{Al}(n, \alpha)^{24}\text{Na}$	15.03 h	1.60 E-16
$^{45}\text{Sc}(n, \gamma)^{46}\text{Sc}^*$	84.0 d	3.45 E-12
$^{56}\text{Fe}(n, p)^{56}\text{Mn}^*$	2.587 h	1.35 E-17
$^{58}\text{Ni}(n, p)^{58}\text{mCo}$	71.3 d	2.47 E-14
$^{58}\text{Ni}(n, p)^{58}\text{Co}$	71.3 d	2.48 E-14
$^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$	53.34 min	1.75 E-11
$^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$	53.34 min	1.22 E-11
$^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$	155.2 min	5.73 E-12
$^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$	155.2 min	2.79 E-13
$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	2.695 d	5.86 E-11
$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	2.695 d	3.22 E-11
$^{115}\text{In}(n, n')^{115\text{m}}\text{In}$	4.5 h	4.56 E-14
$^{47}\text{Ti}(n, p)^{47}\text{Sc}$	80.4 h	4.29 E-15
$^{48}\text{Ti}(n, p)^{48}\text{Sc}$	44.1 h	3.92 E-17

Typical monitor substances (also Cu, Ag, Co)

ABOUT THE MEASUREMENT

- HPGe semi-conductor detectors
- Sets of irradiated thin foils covered by Al or Cd (neutron monitors)
- Measure the activity values of the foil detectors
- The use of Cd enables us to extract the epithermic spectrum information

Spectrum unfolding with SAND II or SANDBP

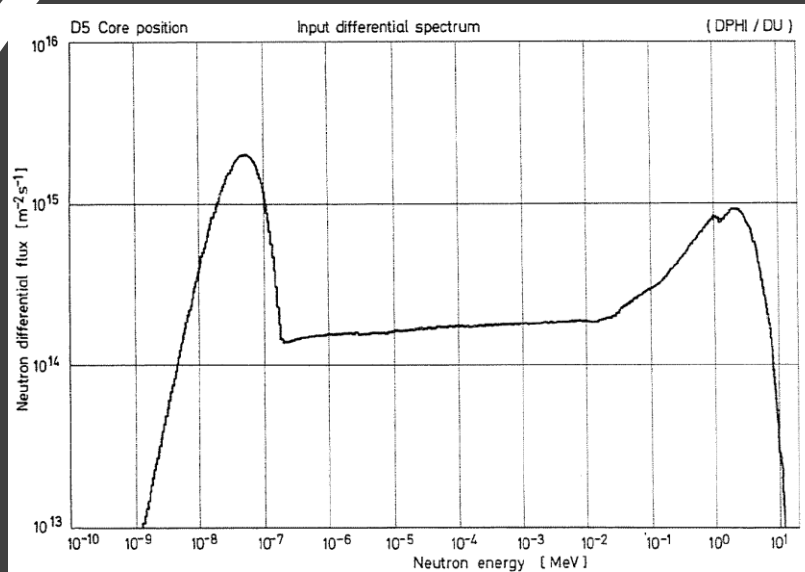
- Input
 - **Measure the activity** of the neutron monitors (per target atom)
 - **Use** the relevant **cross section** information from the IRDFF library
 - **Select** an initial approximation (**input**) **spectrum** (guess)
 - Estimate **relative errors** for the activities and cross sections (weighting with errors ->faster convergence)
- **Iterative adjustments** of the **input spectrum** in 640 energy intervals by fitting the calculated activities to the measured ones (with a given error limit, calculating DEV)
- Output
 - **Best-fit neutron flux density spectrum + covariance and correlation matrices (with Monte Carlo runs)**

DETERMINATION OF THE NEUTRON SPECTRUM

$$A_i = \int_0^{\infty} \sigma_i(E) \Phi(E) dE \quad i=1(1)n$$

saturation activity of the ith foil detector

The spectrum unfolding method

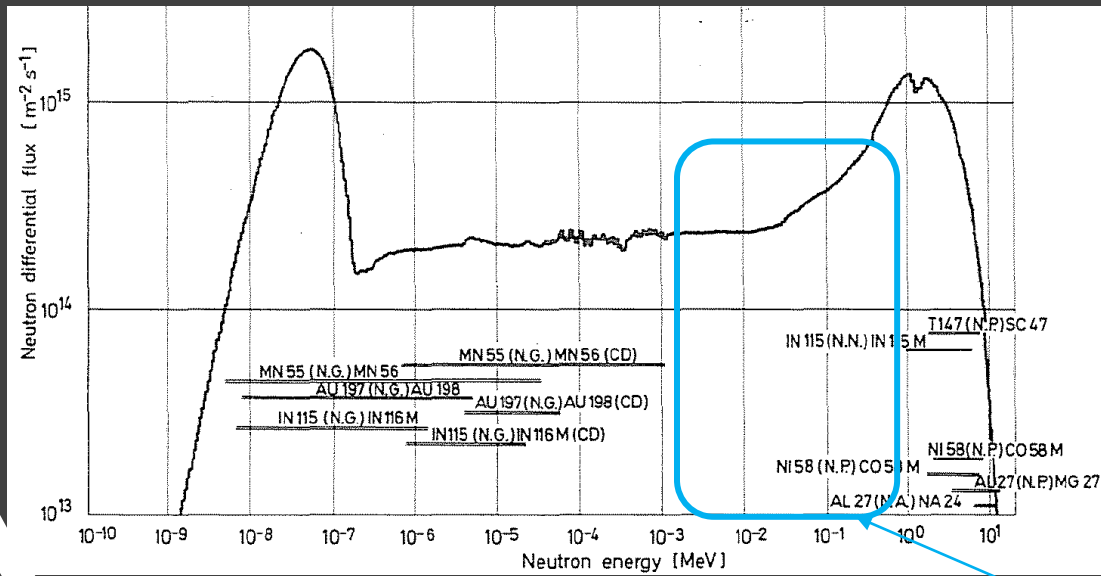


The **input spectrum** extrapolated to 640 energy intervals (j) [3]

$$\Phi_j^{k+1} = \Phi_j^k \exp(C_j^k)$$

$$C_j^k = \frac{\sum_{i=1}^n W_{ij}^k \ln(A_i/A_i^k)}{\sum_{i=1}^n W_{ij}^k}$$

$$W_{ij}^k = \frac{A_{ij}^k}{A_i^k} \left(\frac{1}{(\delta A_i)^u} \times \frac{1}{(\delta \sigma_{ij})^v} \right)$$

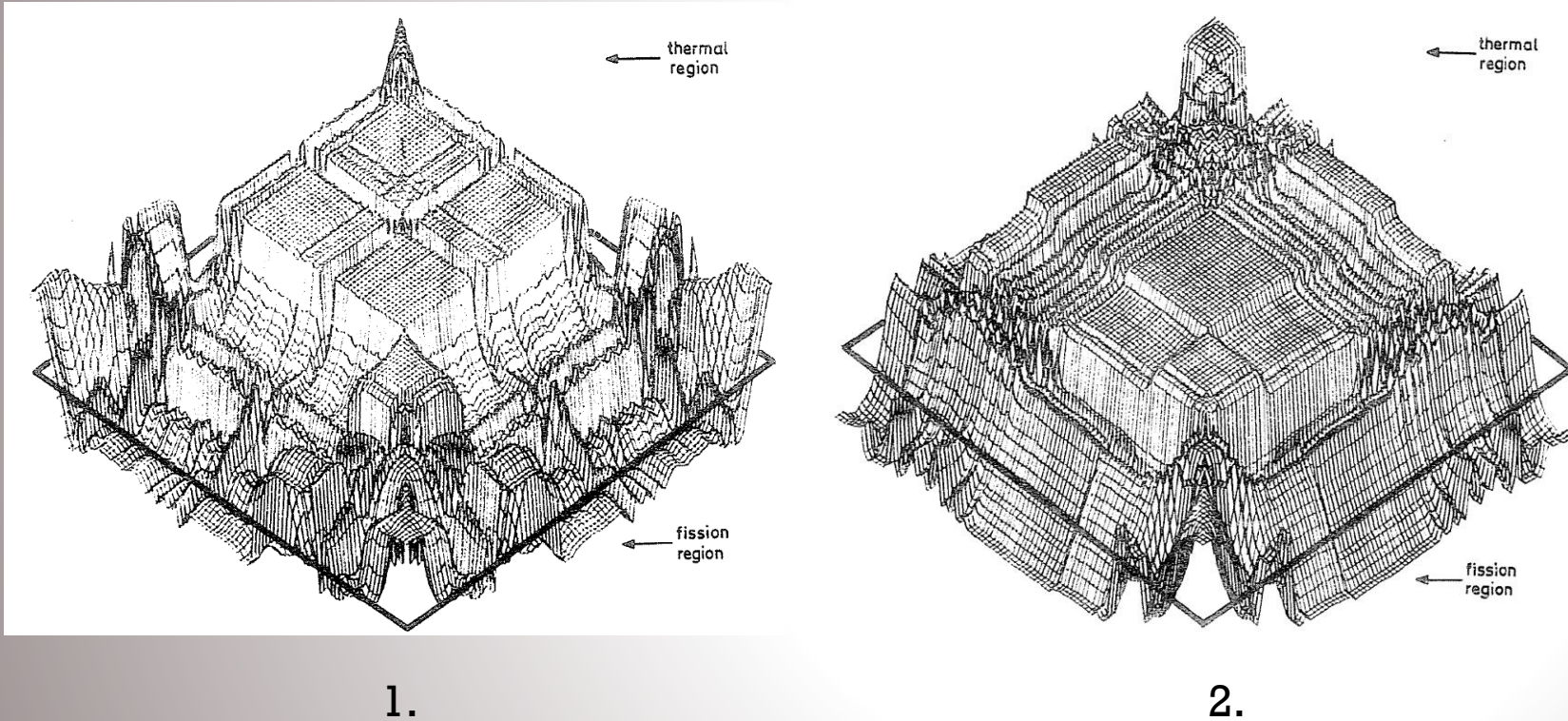


The **solution spectrum** obtained with

- error weighting (u,v)
- up to 3 iterations (k=3)
- 17 activation detectors (i) [3]

not covered by the response of the detector set!

- The correlation matrices for the flux density values in all the neutron energy regions [1]



strong correlation is observed
(most energy regions are highly covered by the responses)

DETERMINATION OF THE NEUTRON SPECTRUM

1. Correlation matrix without error weighting

1. Correlation matrix with higher error weighting

↓
smoother

References

- [1] Zsolnay Éva, Czifrus Szabolcs, Kis Dániel Péter: A PAKSI ATOMERM 2. SZÁMÚ REAKTORBLOKKJÁN A REAKTORTARTÁLY KÜLS FELÜLETÉNÉL A 28. REAKTORKAMPÁNY SORÁN BESUGÁRZOTT NEUTRONMONITOROK VÁLASZÁNAK KIÉRTÉKELÉSE (2013)
- [2] <https://www.nuclear-power.com/nuclear-power/reactor-physics/nuclear-engineering-fundamentals/neutron-nuclear-reactions/neutron-flux-spectra/>
- [3] É. M. Zsolnay and E. J. Szondi: *Neutron spectrum determination by multiple foil activation method* (1982)