International Atomic Energy Agency

Simultaneous Evaluation of Fission Cross Sections Based on EXFOR Library

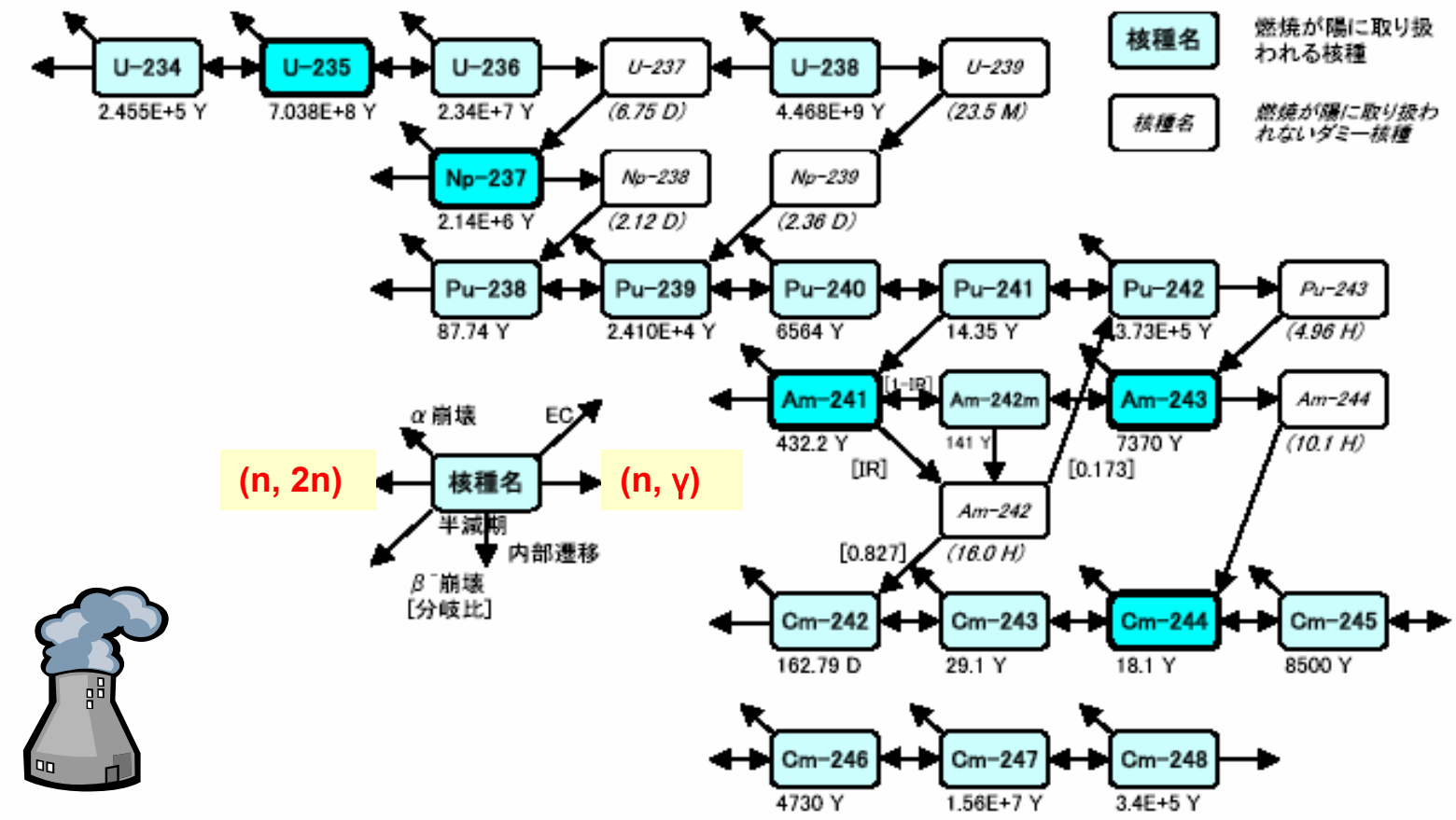
N. Otsuka

IAEA Nuclear Data Section

O. Iwamoto, T. Nakagawa

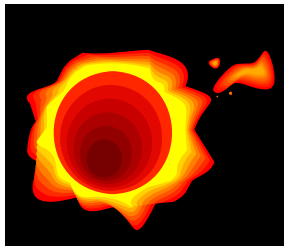
JAEA Nuclear Data Centre

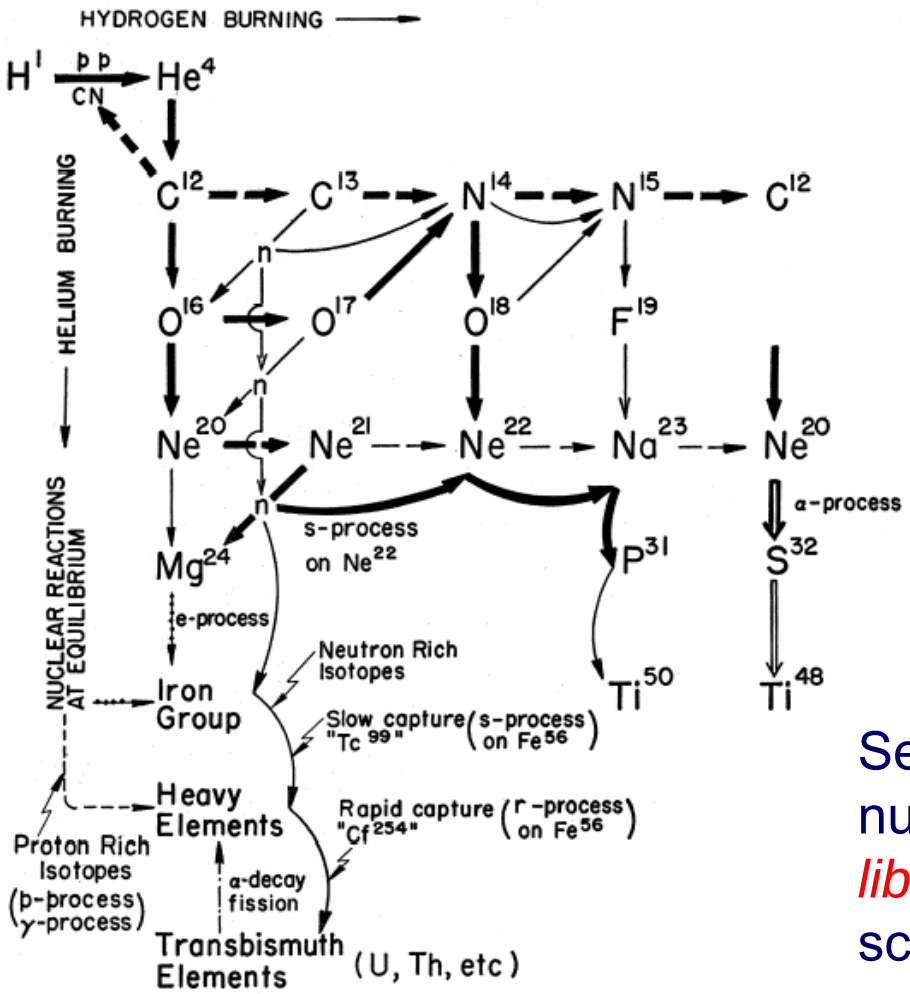
Nuclear Reaction Chain Problem (Reactor)



Burning chain in fast breeder reactor *JOYO* - Sugino (2007), private communication

Nuclear Reaction Chain Problem (Stellar)





Set of comprehensive nuclear data (*Nuclear data library*) for reaction chains in science and technology.

E. M. Burbidge et al., (B^2FH) Rev.Mod.Phys.29(1957)

IAEA Nuclear Data Services

http://www-nds.iaea.org/

(free of charge, no registration)

IAEA Neutron Cross-Section Standards

NEUTRON CROSS-SECTION STANDARDS, 2006

An IAEA Nuclear Data Section Initiative

http://www-nds.iaea.org/standards/

DATA

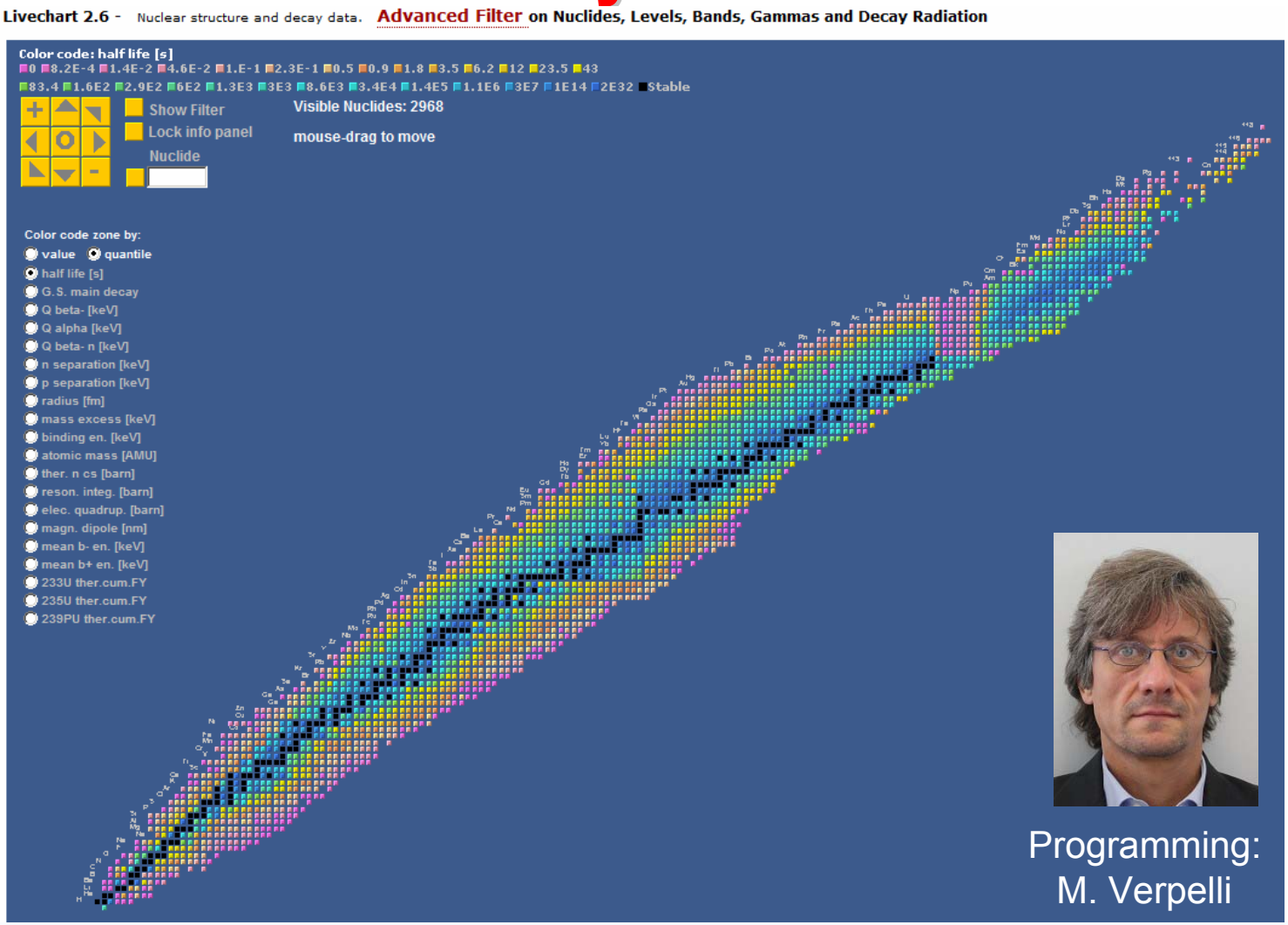
This is a collection of data for standards cross sections and related quantities. The data are provided in different formats readly usable. Some information on the evaluation procedures are found in the reference [1]. Additional information is provided in reference [2] and in the other sections of this website (see Documents and Reports pages).

Neutron Cross-section Standards

Reaction	Neutron Energy Range			
	1987	2002-2005/06		
			ENDF-6 Format	Free text Format
H(n,n)	1 keV to 20 MeV	1 keV to 20 MeV	std-001_H_001.endf	not available
^{3}He(n,p)	0.0253 eV to 50 keV	0.0253 eV to 50 keV (1987 adopted)	std-002_He_003.endf	not available
^{6}Li(n,t)	0.0253 eV to 1 MeV	0.0253 eV to 1 MeV	std-003_Li_006.endf	standards-6Li_xs-data.txt
^{10}B(n,α)	0.0253 eV to 250 keV	0.0253 eV to 1 MeV	std-005_B_010.endf	standards-10B_na-xs-data.txt
^{10}B(n,α$_1$γ)	0.0253 eV to 250 keV	0.0253 eV to 1 MeV	std-005_B_010.endf	standards-10B_na1-xs-data.txt
C(n,n)	up to 1.8 MeV	up to 1.8 MeV (1987 adopted)	std-006_C_000.endf	not available
Au(n,γ)	0.0253 eV, and 0.2 to 2.5 MeV	0.0253 eV, and 0.2 to 2.5 MeV	std-079_Au_197.endf	standards-197Au_xs-data.txt
^{235}U(n,f)	0.0253 eV, and 0.15 to 20 MeV	0.0253 eV, and 0.15 to 200 MeV	std-092_U_235.endf	standards-235U_xs-data.txt
^{238}U(n,f)	threshold to 20 MeV	2 to 200 MeV	std-092_U_238.endf	standards-238U_xs-data.txt

^{3}He(n,p)	1 keV – 20 MeV
^{6}Li(n,t)	0.0253 eV – 50 keV
^{10}B(n,α)	0.0253 eV to 1 MeV
^{10}B(n, α$_1$γ)	0.0253 eV to 1 MeV
^{nat}C(n,n)	10^{-5} eV to 1.8 MeV
^{197}Au(n, γ)	0.0253 eV, 0.2-2.5 MeV
^{235}U(n,f)	0.0253 eV, 0.15 – 200 MeV
^{238}U(n,f)	2 to 200 MeV

LiveChart of Nuclides
(Web Tool for Decay and Structure Data)



Experiment, Evaluation and Applications

Experimental cannot be directly used for applications.

EXFOR

Experimental data

ENDF
JENDL
…

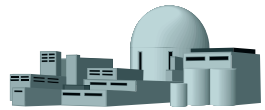
Evaluated data

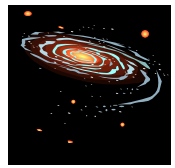
Reactor constant etc.

Processing

Transport calculation (MCNP) etc.

Application

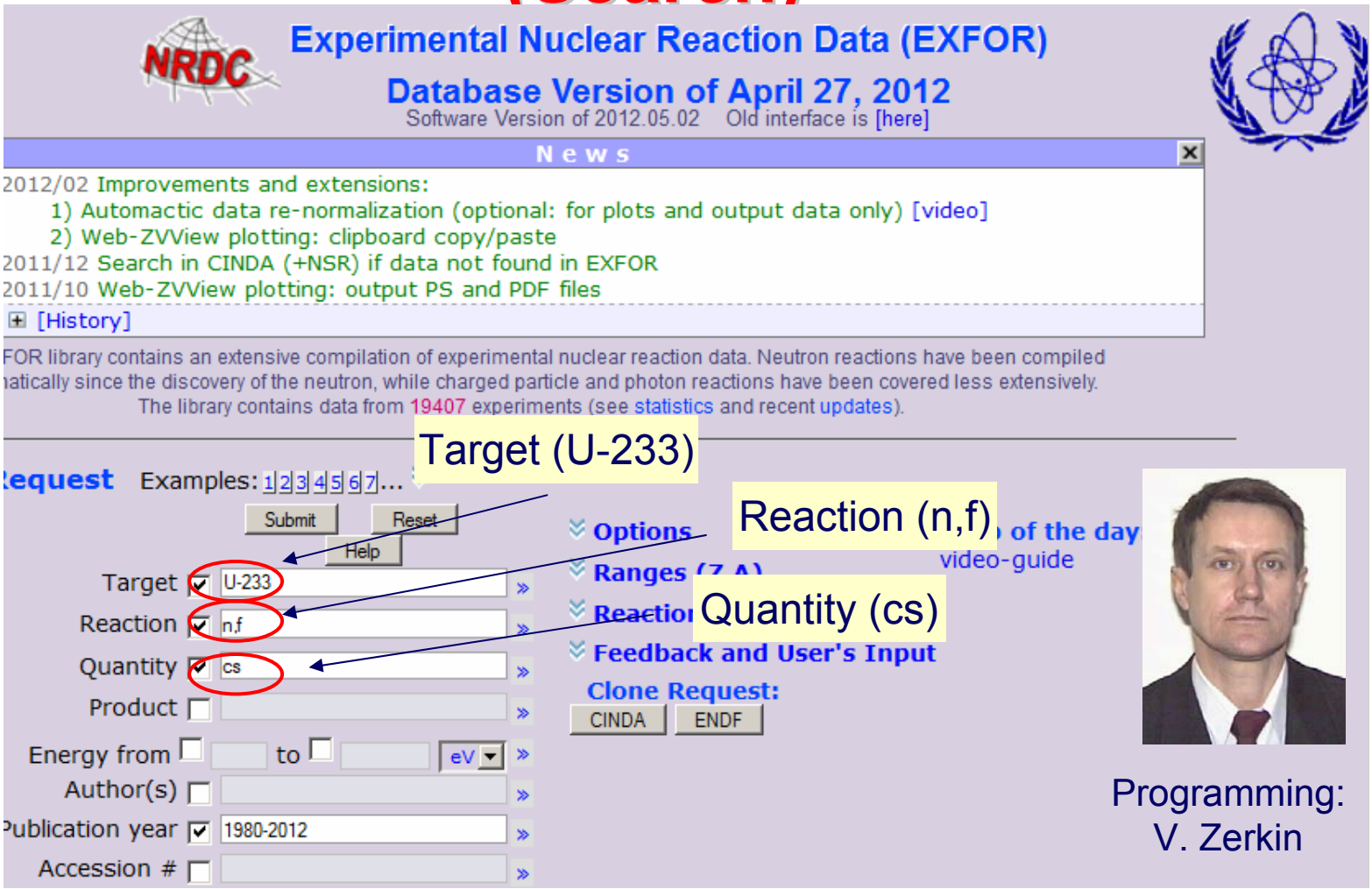




Theory

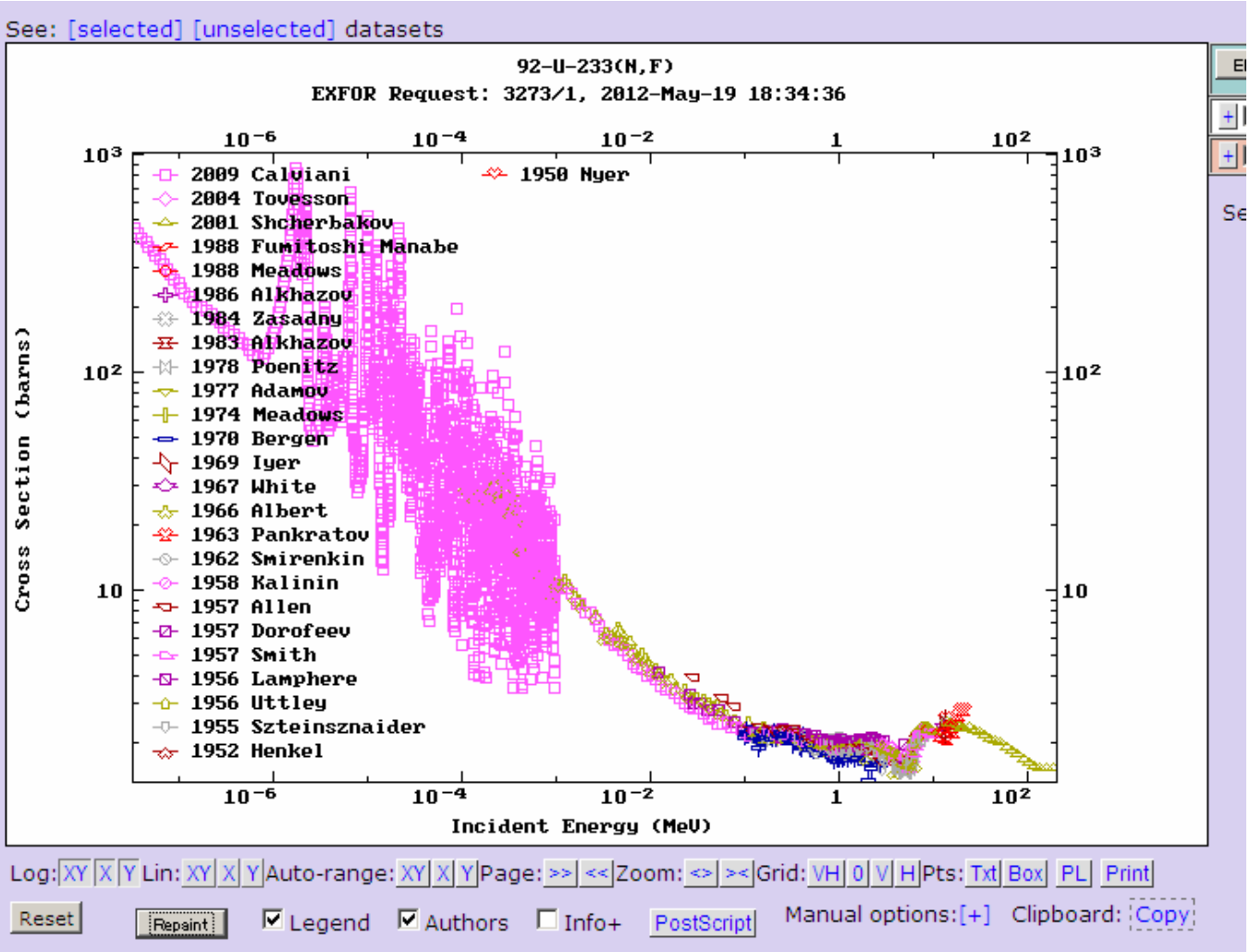
Optical model
Statistical model
etc.

EXFOR - Experimental Data Library (Search)



http://www-nds.iaea.org/exfor/

EXFOR - Experimental Data Library (Result)



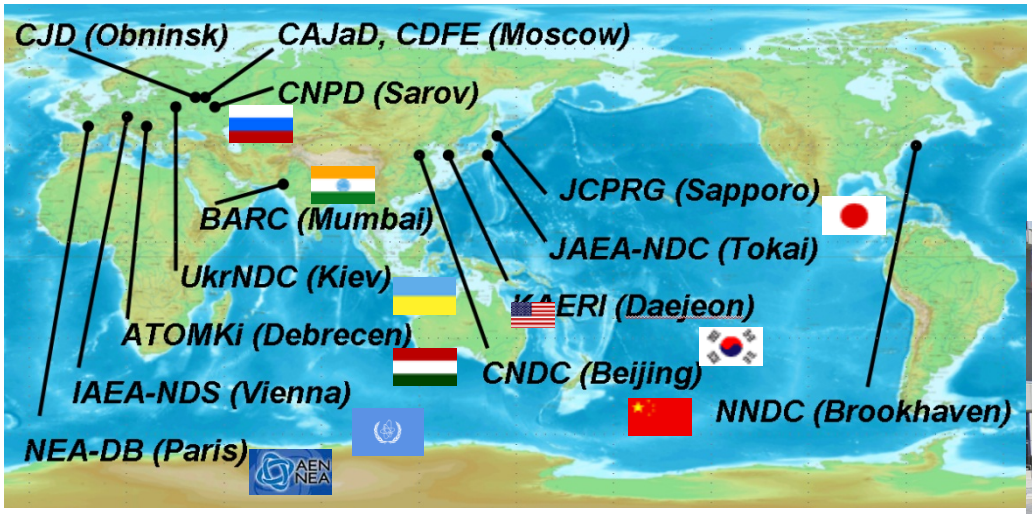
http://www-nds.iaea.org/exfor/

Contents of EXFOR Library

- "All" (1932~) neutron beam data (9,800 experiments)
- Selected charged-particle beam data (e.g., 3,800 exps for proton)
- Cross section, differential cross section, fission yield etc.
- More than 60 journals regularly canned by IAEA for new inputs.
- M nf. Proc. (150 experiments) .

ISINN Conf. Proc. could be more valuable if all articles are available on the ISINN web page!

EXFOR Compilers in the World (Nuclear Reaction Data Centres - NRDC)



EXFOR Compilation Workshop
(May 2011, Vienna)

14 centres from 8 countries and 2 international organisations
(China, Hungary, India, Japan, Korea, Russia, Ukraine, USA, NEA, IAEA)

Coordinated by IAEA Nuclear Data Section

Frank's IBR-2 Data (1988) in EXFOR Library

Nuclear Data for Science and Technology (1988 MITO), 395- 398. Copyright © 1988 JAERI.

FAST PULSED REACTORS FOR NEUTRON PHYSICS EXPERIMENTS

I.M.Frank, V.I.Luschikov and E.I.Sharapov

Laboratory of Neutron Physics, Joint Institute for Nuclear Research, Dubna, Head Post Office Box 79, 101000 Moscow, USSR

Abstract: Fast pulsed reactors IBR-2 and IBR-30 are in routine use in the Labo tory of Neutron Physics, JINR, Dubna. Their today characteristics and performa are reported. The IBR-2 in use for condensed matter research is mentioned. Som results of nuclear physics experiments conducted during the recent years at th IBR-30 reactor working with a linear accelerator as an injector are reviewed. The fields of research under discussion are : p-wave neutron resonance spectros and parity nonconservation; differential scattering cross sections and p-wave tron strength functions; cascade γ-transitions and peculiarities of the nuclea structure; prompt γ-ray yields and characteristics of the U-235 fission induc by resonance neutrons.

(neutron sources, pulsed reactors, polarized neutrons, parity violation, neutr scattering, strength functions, gamma-ray spectrum, nuclear structure, fission gamma-rays, fission fragments)

```
SUBENT        41008001     900426
BIB                 10         10
TITLE       FAST PULSED REACTOR FOR NEUTRON PHYSICS EXPERIMENTS
AUTHOR      (I.M.FRANK,V.I.LUSHCHIKOV,E.I.SHARAPOV)
INSTITUTE   (4ZZZDUB)
REFERENCE   (C,88MITO,,395,8805) DATA TABLE IS GIVEN
FACILITY    (REAC) REACTOR IBR-2
METHOD      (TOF)
...
ENDBIB              10
NOCOMMON             0          0
ENDSUBENT           13
SUBENT        41008002     900426
BIB                  1          3
REACTION   1(50-SN-117(N,0),,EN)
           2(50-SN-117(N,EL),,WID,,G)
           3(50-SN-117(N,TOT),,WID)
ENDBIB               3
...
DATA                 5          1
DATA       1DATA      2DATA-ERR  2DATA      3DATA-ERR  3
EV          EV         EV         EV         EV
   1.33       1.66E-07    3.0E-08   1.80E-01    1.8E-02
ENDDATA              3
ENDSUBENT           15
```

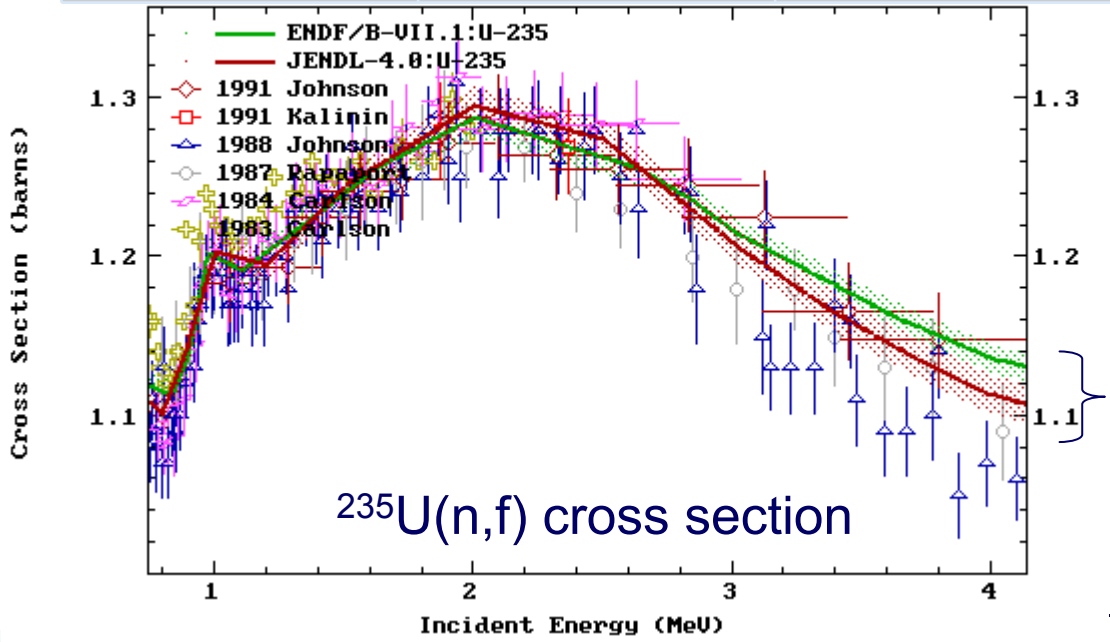
^{117}Sn+n resonance parameters at 1.33 eV measured at IBR-2.

gΓn = 0.166 (30) micro-eV

(0.138 micro-eV is a current recommended value.)

Major Evaluated Neutron Reaction Data Libraries

Library	Country	Release	# of nuclide	# of covariance
JEFF-3.1.2	Europe	2012	381	29+x
ENDF-B/VII.1	USA	2011	423	190
JENDL-4.0	Japan	2010	406	95
CENDL-3.1	China	2009	240	5+x
BROND-2.2	Russia	1993	121	2+x



^{235}U(n,f) cross section

Evaluated cross sections and their uncertainties

http://www-nds.iaea.org/endf/

"Target Accuracy" for Energy Application

Report from OECD NEA (WPEC SG36)

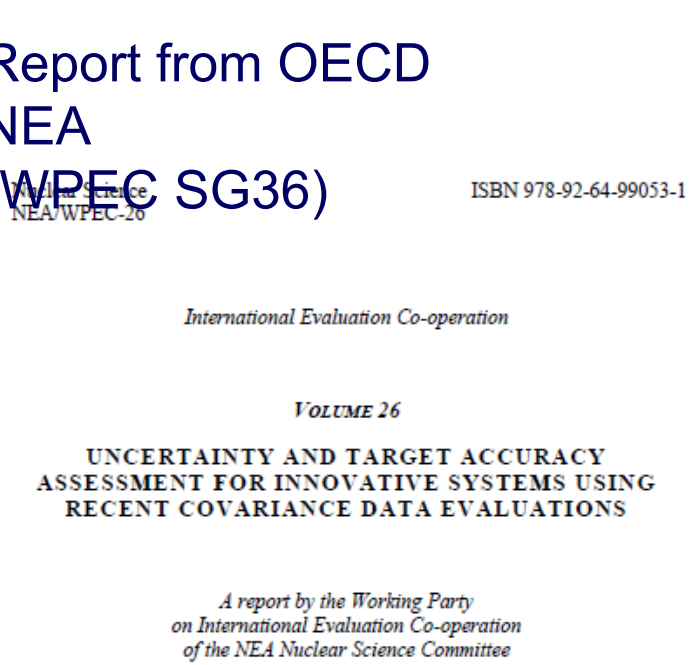


Table 30. ADMAB: uncertainty reduction requirements needed to meet integral parameter target accuracies

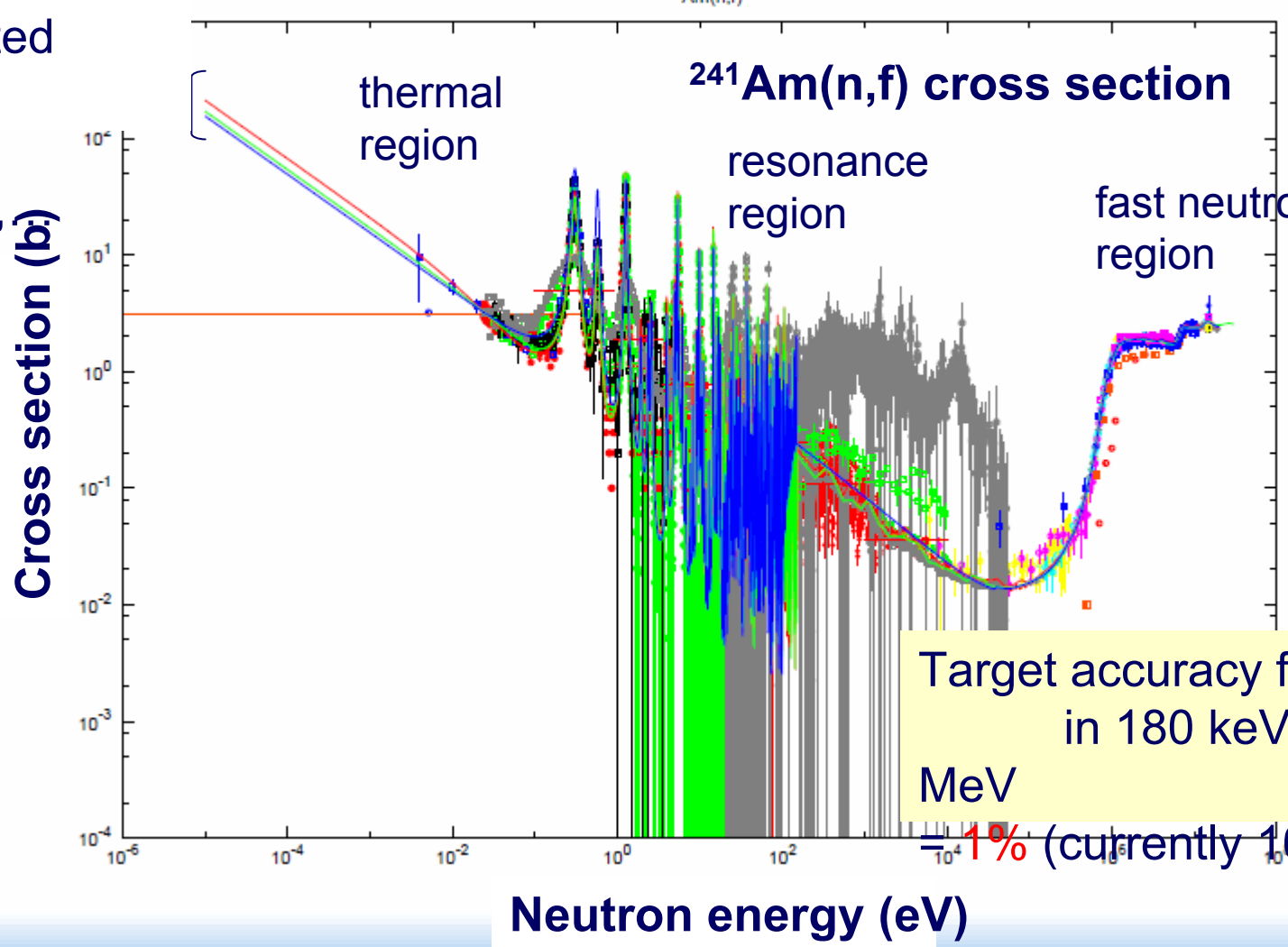
Isotope	Cross-Section	Energy range	Uncertainty (%)		
			Initial	Required	
				$\lambda=1$	$\lambda\neq1$ [a]
Pu238	σ_{fiss}	6.07 - 0.498 MeV	20	3	3
	ν	1.35 - 0. 183 MeV	7	3	3
Pu239	σ_{capt}	498 - 2.03 keV	12	4	3
	σ_{inel}	6.07 - 0.498 MeV	25	5	6
Pu240	σ_{capt}	183 - 67.4 keV	14	6	6
	σ_{fiss}	2.23 - 0.498 MeV	6	2	2
	ν	1.35 - 0.498 MeV	4	2	2
Pu241	σ_{capt}	1.35 - 0. 183 MeV	20	7	7
	σ_{fiss}	6.07 MeV-22.6 eV	15	2	2
Pu242	σ_{capt}	24.8 - 9.12 keV	35	10	10
	σ_{fiss}	6.07 - 0.498 MeV	20	4	4
Np237	σ_{capt}	498 - 0.454 keV	6	3	3
	σ_{fiss}	6.07 - 0.183 MeV	8	2	2
	σ_{inel}	2.23 – 0.183 MeV	25	5	6
Am241	σ_{capt}	1.35 MeV- 0.454 keV	8	2	2
	σ_{fiss}	6.07 – 0.183 MeV	10	1	1
	ν	6.07 - 1.35 MeV	2	1	1
	σ_{inel}	6.07 – 0.183 MeV	25	4	5

ADMAB: Accelerator driven minor actinide burner

Evaluated data must be provided with their uncertainty information - variance (standard deviation) and covariance.

Fission Cross Section Experimental and Evaluated Data Library

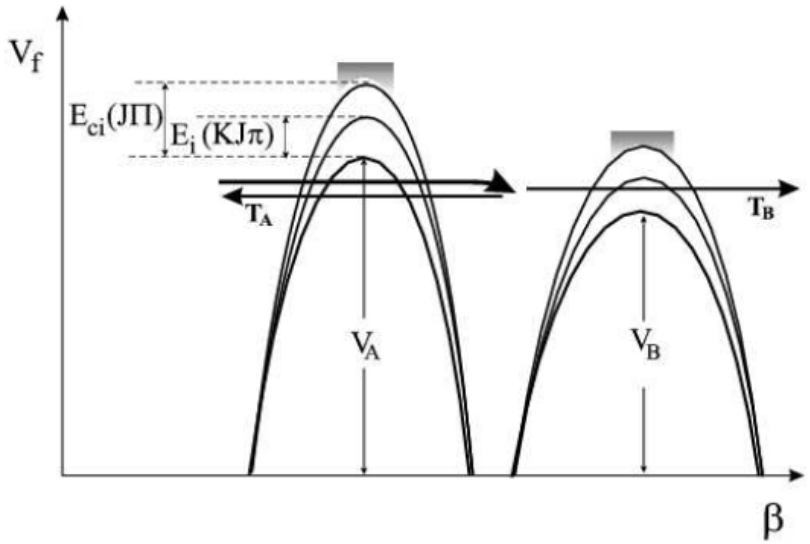
Evaluated data: ENDF, JENDL,



Target accuracy for ADS in 180 keV to 6 MeV
=1% (currently 10%)

Model for Evaluation of Fission Cross Section

Theoretical description adopted in evaluation for JENDL-4.0 library

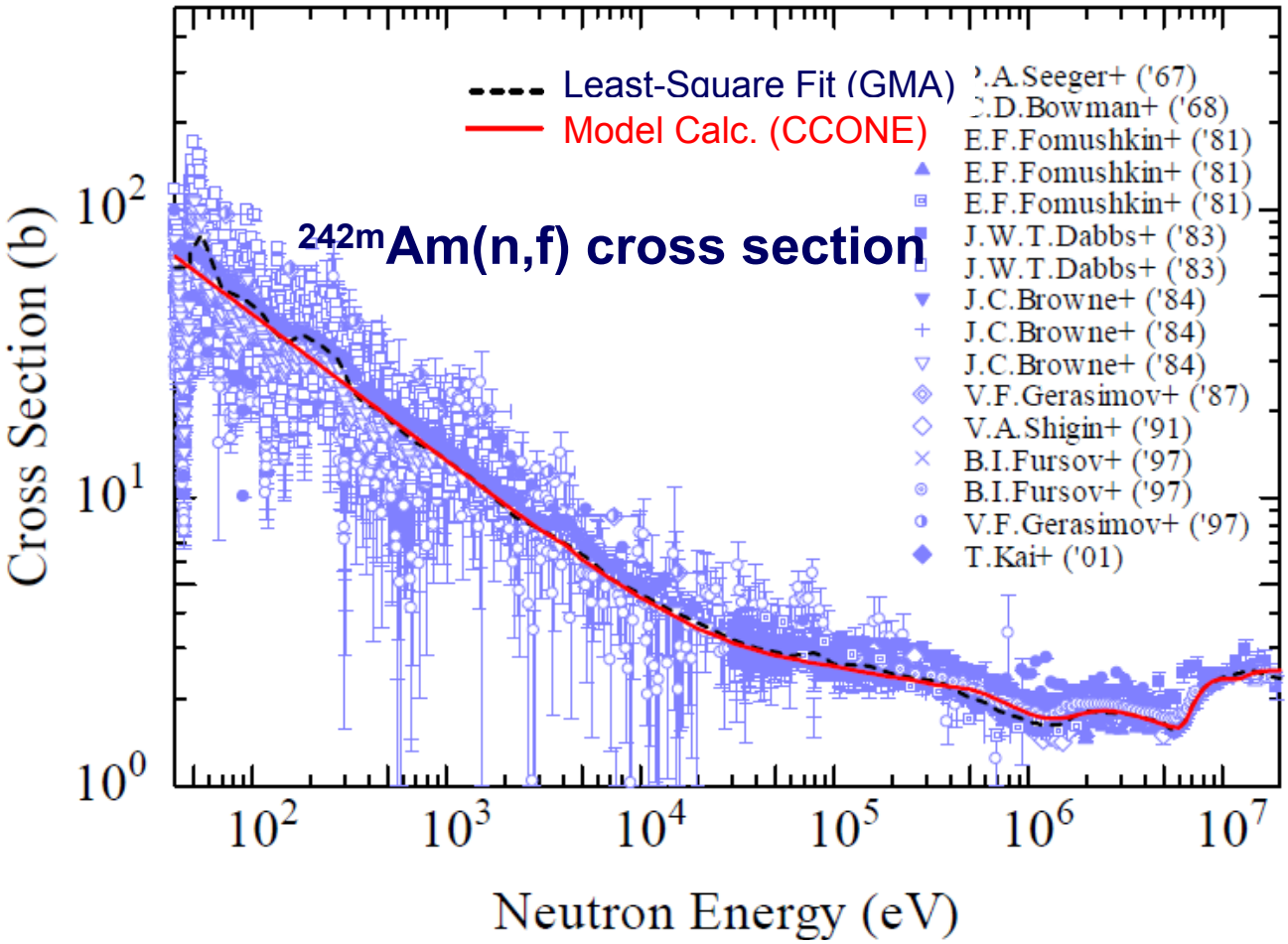


Transition to a state
above the fission barrier (Hill-Wheeler)

$$T=(E_x,J^\pi)=\int_0^\infty \mathrm{d}\varepsilon \frac{\rho(\varepsilon,J^\pi)}{1+\exp\left(-2\pi\frac{E_x-V-\varepsilon}{\hbar\omega}\right)}$$

$V,\hbar\omega$: fitting parameter

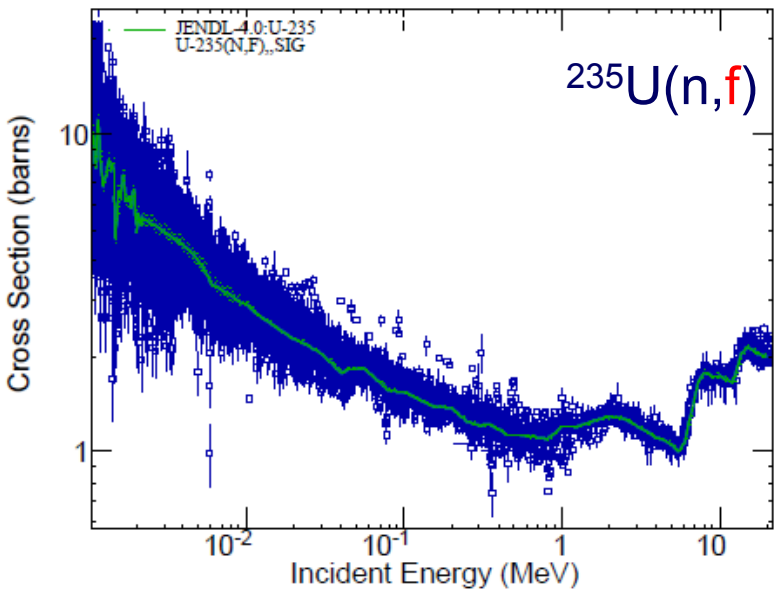
Model Calculation v.s. Least-Squares Fit

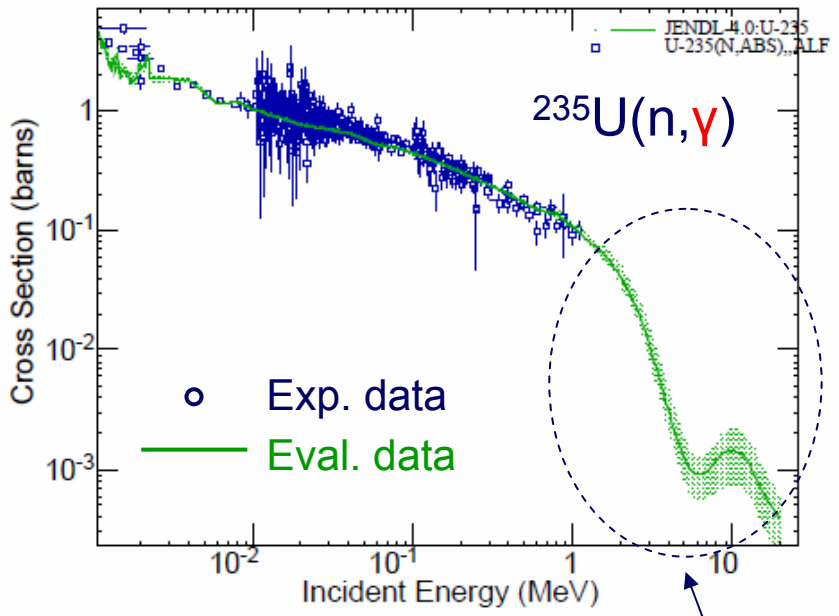


In JENDL-4.0 evaluation, least-squares analysis was adopted when enough number of experimental data are available.

O. Iwamoto et al., PHYSOR 2008 Conf. Proc.

Availability of Experimental Data for Fission





Fission:

Many data in experimental data library (EXFOR),
(even for minor actinides – Np, Am, Cm.)
Suitable for least-squares analysis.

(c.f. few experimental data for capture, scattering etc.)

Evaluated by model calculation (no exp. data)

(Conventional) Least-Squares Method

Existing evaluated cross section (before experiment, *prior*)

- Existing evaluated cross section $\sigma_{old} \pm \Delta\sigma_{old}$
- Probability to find the true value as σ $P_{old}(\sigma) = \exp [- (\sigma - \sigma_{old})^2 / (\Delta\sigma_{old})^2]$

New experimental data for a quantity y

- New experimental data for quantity $y_{exp} \pm \Delta y_{exp}$
- Relation between y and σ (model) $y = f(\sigma)$ (y = σ is also possible.)
- Likelihood to have y_{exp} under σ $P(y_{exp}|\sigma)= \exp[-(y_{exp}– f(\sigma))^2 /(\Delta y_{exp})^2]$

Probability distribution P_{new} updated by Bayes' theorem (*posterior*)

$$P_{new}(\sigma) = C \cdot P(y_{exp}|\sigma) \cdot P_{old}(\sigma) = \exp \{-[(y_{exp}- f(\sigma))^2 / (\Delta y_{exp})^2 + (\sigma - \sigma_{old})^2 / (\Delta\sigma_{old})^2]\}$$

Generalized Least-Squares Method

Chi-square to be minimized:

$$\chi^2 = [(y_{exp} - f(\sigma))^2 / (\Delta y_{exp})^2 + (\sigma - \sigma_{old})^2 / (\Delta\sigma_{old})^2]$$

when the uncertainties are **uncorrelated** between exp. data points.

Example: Counting statistics

But Correlated sources also exists:

Example: Sample mass weight (constant of one exp. data set)

Generalized least-squares method

Covariance matrices instead of variances to consider correlations:

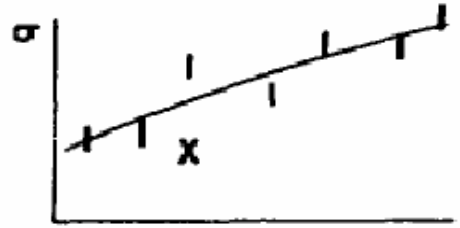
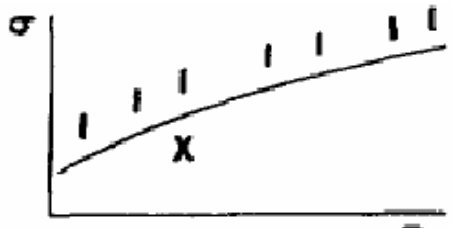
$$(\Delta\sigma_{old})^2 \rightarrow V_{old} \text{ and } (\Delta y_{exp})^2 \rightarrow U_{exp}$$

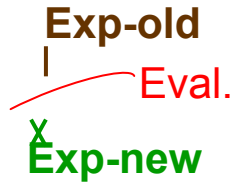
Impact of Covariance (Correlation) on Evaluation

$$C = [\,\Delta\sigma_{cor}(E_1)\cdot\Delta\sigma_{cor}(E_2)\,] / [\,\Delta\sigma_{tot}(E_1)\cdot\Delta\sigma_{tot}(E_2)\,] < 1$$

covariance

C~0: *weakly* correlated, C~1: *strongly* correlated

DOMINATING ERROR	CORRELATION MATRIX	MEASUREMENTS / EVALUATION
STATISTICAL (Uncorrelated source dominant)	1 .1 1 .1 .1 1 .1 .1 .1 1 .1 .1 .1 .1 1	
NORMALIZATION (Correlated source dominant)	1 .9 1 .9 .9 1 .9 .9 .9 1 .9 .9 .9 .9 1	



W.P. Poenitz, INDC(USA)-85, p249 (1981)

Separation to *uncorrelated* (~statistical) and *correlated* (~systematic) uncertainties by experimentalists is essential for evaluation.

Correlation between Target Isotopes

Ratio measurement with ^{235}U fission cross section:

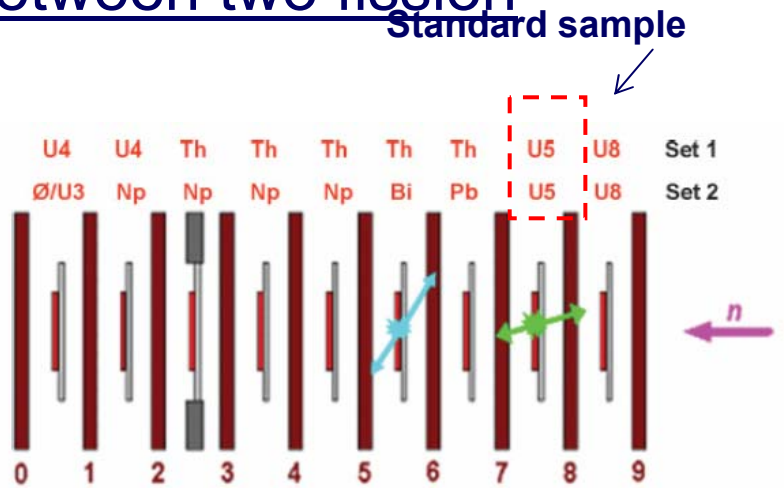
$$\sigma = [N/N_{U235}] \cdot [n_{U235}/n] \cdot \sigma_{U235}$$

N: count, n: sample atom number, σ_{U235}: $^{235}U(n,f)$ standard cross section (known)

This procedure makes correlation between two fission reactions.

Note:
The standard value may be updated.
(e.g., IAEA standard 1987, 2006.)

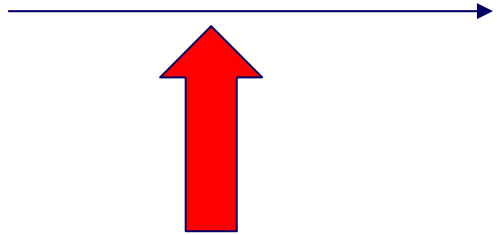
But ratio is free from standard update, more suitable for evaluation.



n_TOF PPAC fission measurement
C. Paradela et al., Phys. Rev. C82(2010)034601

Least-Squares Analysis (Summary)

Cross sections and covariances *before update*
σ_{old}, V_{old}



Cross sections and covariances *after update*
σ_{new}, V_{new}

New experimental data and covariances
y_{exp}, U_{exp}

$$\sigma_{new} = \sigma_{old} + V_{new} C^t U_{exp}^{-1} (y_{exp} - C\sigma_{old})$$

$$V_{new} = (V_{old}^{-1} + C^t U_{exp}^{-1} C)^{-1}$$

$$C = \frac{\partial y}{\partial \sigma}$$

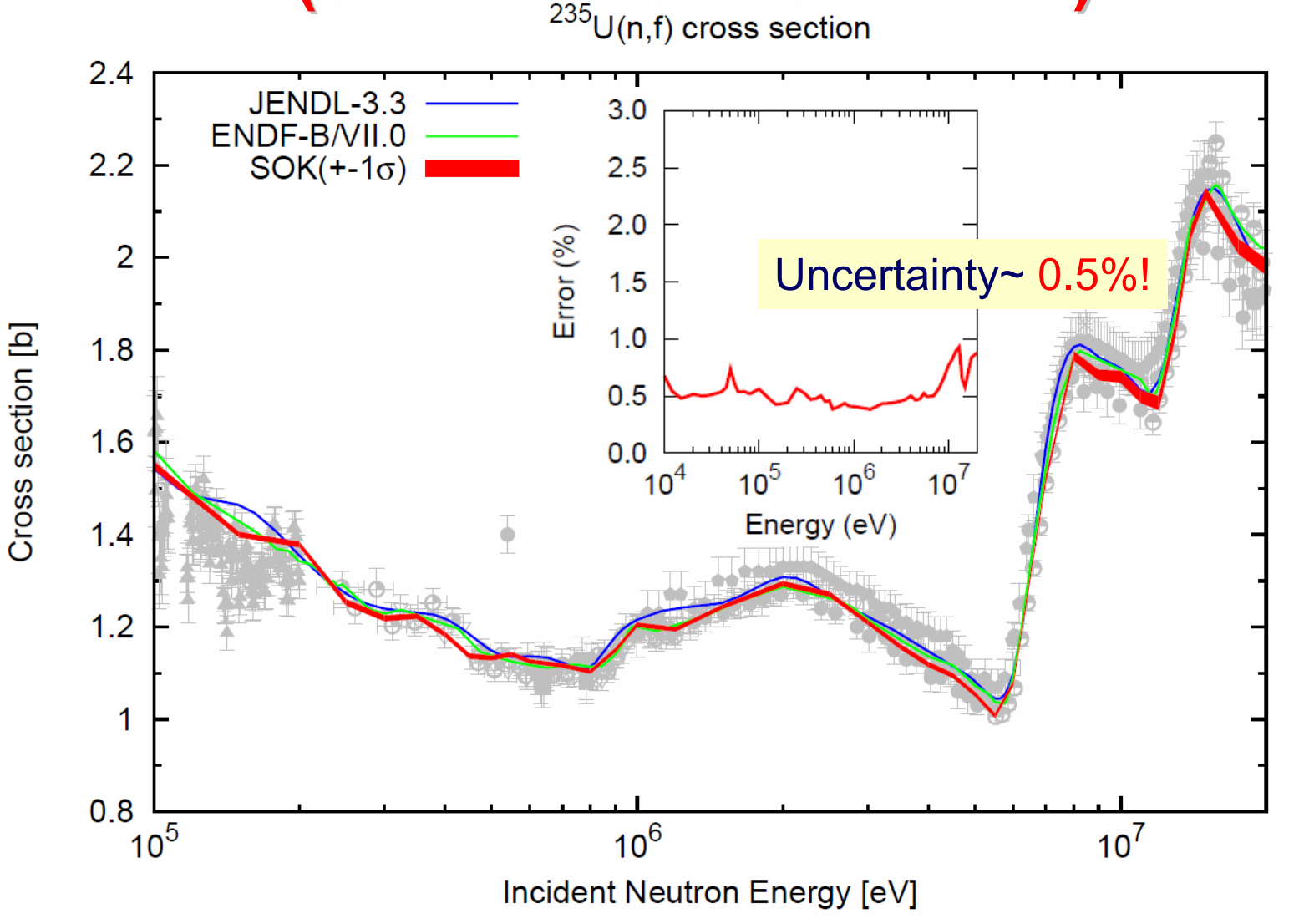
EXFOR Data for JENDL-4.0 Fission Evaluation

Fissile target	X4 data sets	Fissile target	X4 data sets
^{233}U	13	^{233}U/^{235}U	9
^{235}U	17	^{238}U/^{233}U	1
^{238}U	9	^{238}U/^{235}U	18
^{239}Pu	16	^{239}Pu/^{235}U	14
^{240}Pu	4	^{240}Pu/^{235}U	12
^{241}Pu	6	^{240}Pu/^{239}Pu	1
		^{241}Pu/^{235}U	4

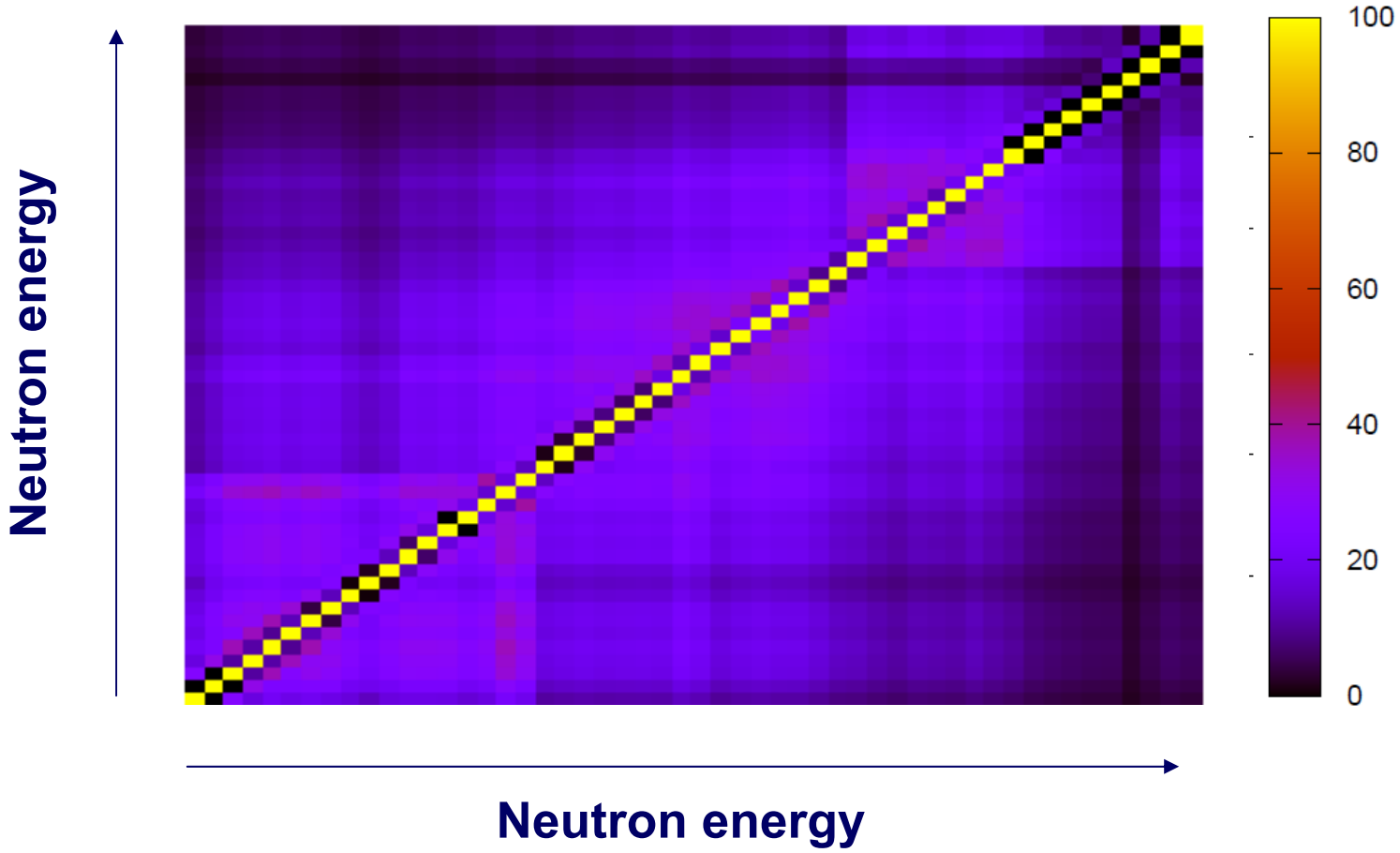
Six actinide fission cross sections and their ratio were simultaneously evaluated.

Least-squares analysis code **SOK** developed by T. Kawano (LANL) was used.

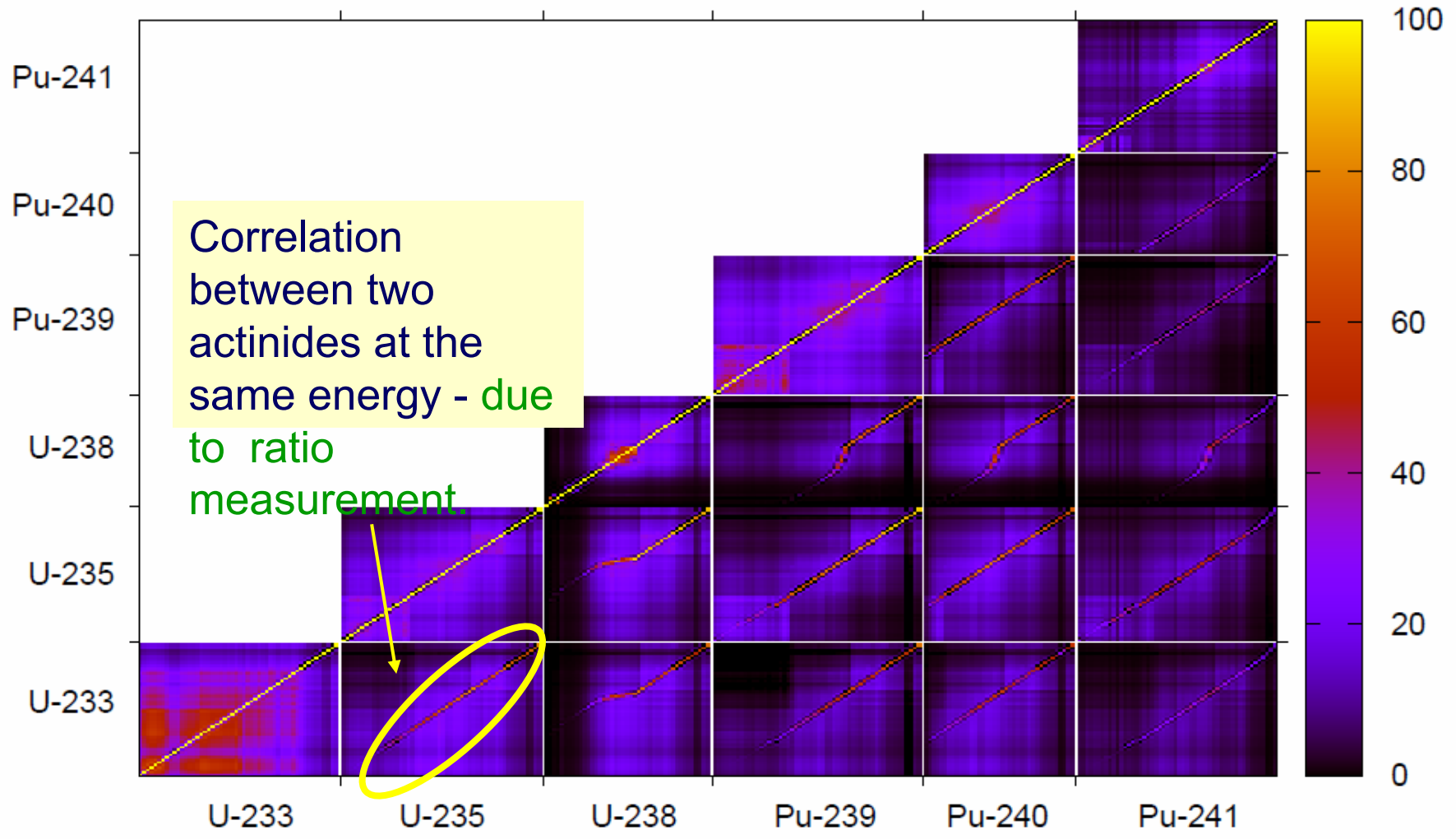
Example of Evaluated Cross Section (JENDL-4.0 ^{235}U fission)



Example of Evaluated Correlation Matrix (JENDL-4.0 ^{235}U fission)



Correlation Matrix (JENDL-4.0 6 actinides)



Summary

- **EXFOR**: Essential resource to perform neutron cross section evaluation (and many other nuclear reaction studies…).
- Simultaneous evaluation of major actinide (U, Pu) fission cross sections and covariances by least squares fitting for JENDL-4.0.
- Too small uncertainty (~0.5%)? Insufficient information on correlation? (cross-measurement correlation?) The current uncertainty may or may *not* be underestimated.
- More correlation information should be added to the EXFOR library in collaboration with experimentalists.

Example of Evaluated Cross Section Ratio (JENDL-4.0 ^{233}U fission/^{235}U fission)