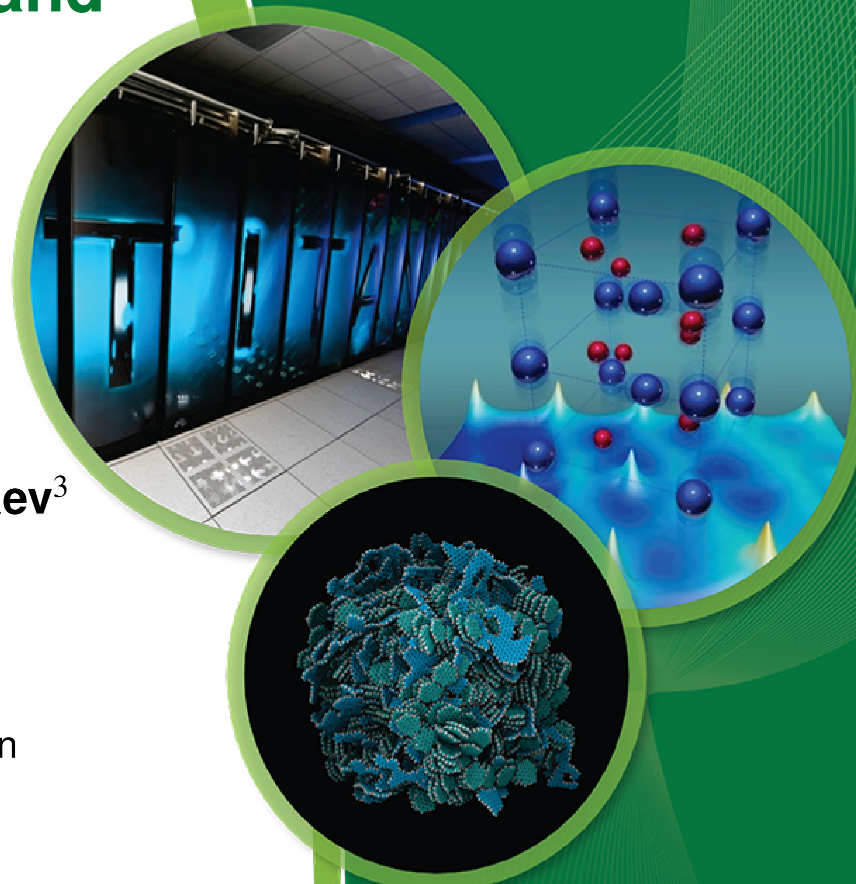
$n+{}^{235}$U Resonance Parameters and Neutrons Multiplicities in the Energy Region below 100 eV



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Outline

- Introduction : motivation and background
- Nuclear data evaluation overview for ^{235}U
- Brief description of the evaluation procedure with SAMMY
  - Evaluation procedure (SAMMY algorithm)
  - Experimental data (energy-depedent cross sections, angular distributions,. . .)
  - Link to benchmarks (integral data)
- Work on n+^{235}U cross sections (results)
- Summary and conclusions
- Acknowledgments

Introduction

Motivation

- For nuclear critcality applications and many others, the existing evaluated data perform well in transport simulations partly owing to *compensating errors* in the nuclear data libraries
- CIELO collaboration provides a framework for nuclear data evaluation aimed to establish the highest fidelity general purpose nuclear database
- ^{235}U among ^{1}H,^{16}O,^{56}Fe,^{238}U, ^{239}Pu is one of the highest priority isotopes

Background

- Current status of ^{235}U evaluation in ENDF/B-VII.1 library (2011)
  - Resonance parameters are the same as ENDF/B-VI.8 release (ORNL/TM-13516)[1]
  - Description of the ^{235}U resonance evaluation can be found in NEA/WPEC-18
- ^{235}U ORNL resonance evaluation(=CIELOb18=**o23**) is part of the ENDF/B-VIII.0β2 release (2016)

[1]See also L. C. Leal, H. Derrien, N. M. Larson, R. Q. Wright, *Nucl. Sci. Eng.*, **131** 230 (1999).

Nuclear Data ORNL Evaluation Overview

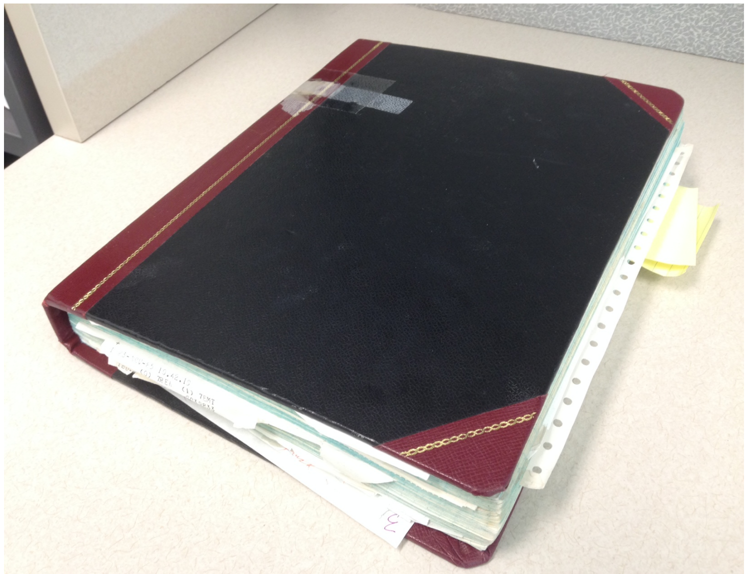
Resolved Resonance Region (RRR) Cross Section Evaluations

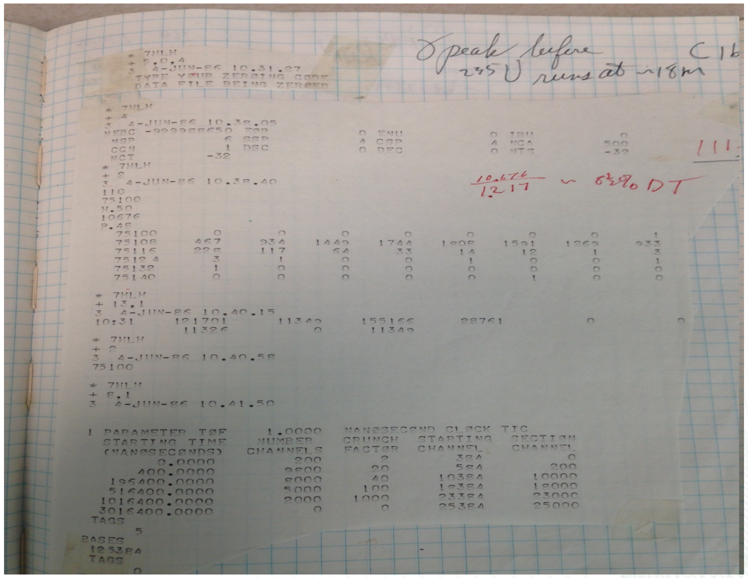
No.	Nucleus (I^π)	E_{min}– E_{max}	Method	No. Levels	J_{3^-}	J_{4^-}	Evaluator
1	^{235}U $(7/2^-)$	10^{-5} eV– 2.25 keV	Reich-Moore	3164	1433	1731	Pigni

- The current ORNL resonance evaluation **o23** (ORNLv23) is an intermediate step of the evaluation process within CIELO
- The current **o23** resonance evaluation started from a set of resonance parameters (**o17**)
  - **o17** was documented in the ORNL presentation at the mini-CSEWG meeting (LANL, April 2016) and released in May 2016 as part of the ENDF/VIII.0β1 release.
- Particular emphasis in producing **o23** was devoted to
  - *Sub-thermal and thermal* : Thermal Constants (Pronyaev, micro. data)
  - *Fission integrals (7.8-11 eV)*
  - Neutron incident energies up to 20 eV for *measurements of* $\alpha = \sigma_\gamma/\sigma_f$ *(or* η*)*

Nuclear Data ORNL Evaluation Overview

- The current ORNL resonance evaluation **o23** is generated by the SAMMY code using the *Reich-Moore approximation*
  - All SAMMY inputs included in the current evaluation procedure are written using the most recent key-word for particle-pair definitions.
  - Isotopic impurities included
  - Parameters for the resolution functions (crunch data, γ-peak) of transmission experimental data (J. A. Harvey) retrieved from ORELA logbook (special thanks to K. Guber).
- Residuals and chi-squared of all experimental data





SAMMY Algorithm

The various reaction cross sections $\sigma_{cc'}$ for an incoming channel c and outgoing channel c' can be written in terms of the matrix

$$X_{cc'} = \sqrt{P_c} L_c^{-1} \sum_{c''} [(L^{-1} - R)^{-1}]_{cc''} R_{c''c'} \sqrt{P_{c'}} \delta_{JJ'} , \qquad (1)$$

where, in the eliminated-channel approximation, the matrix R (or R-matrix) for the channel spin group defined by the total spin J^π is

$$R_{cc'} = \left[\sum_{\lambda=1}^{n} \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_\lambda - E - \imath \bar{\Gamma}_{\lambda\gamma}/2} + R_c^{\text{ext}} \delta_{cc'} \right] \delta_{JJ'} \qquad (2)$$

SAMMY derives from the best fit of experimental data the reduced-width amplitude $\gamma_{\lambda c}$ related to the channel width using

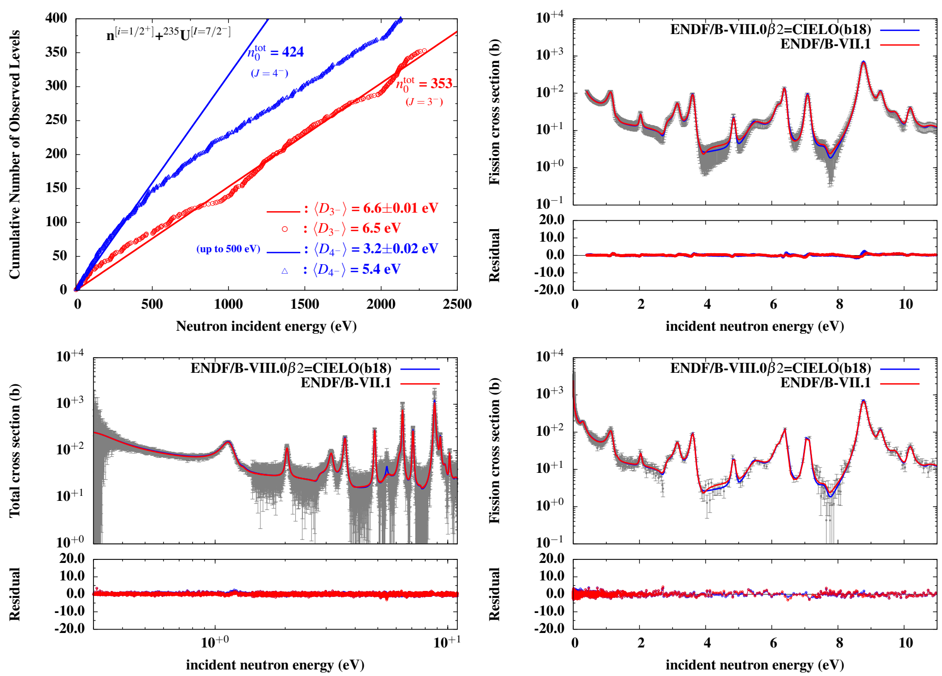
$$\Gamma_{\lambda c} = 2\gamma_{\lambda c}^2 P_c(E) , \qquad (3)$$

where the penetrability factors depend on the Coulomb functions F_ℓ, G_ℓ as $P_c(E) = ka/[F_\ell^2(ka,\eta) + G_\ell^2(ka,\eta)]$.

Differential and Integral Data

Differential data

- Application of the R-matrix SAMMY method (Reich-Moore) to determine a consistent set of neutron resonance parameters (RP) based on the fit of available experimental data (transmission, capture, angular distribution, . . .)
- Statistical properties of RP such as average spacing $\langle D_\ell \rangle$ and strength function S_ℓ



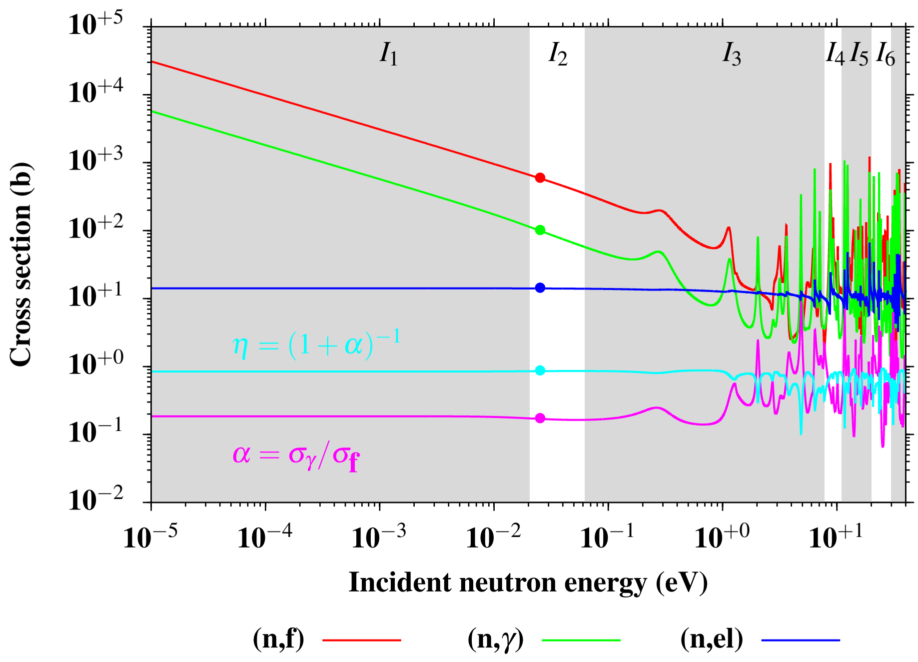
Integral data

- Resonance parameter and covariance are converted into the ENDF/B format - file 2 (parameter) and 32 (covariance matrix)
- Process ENDF/B file with processing codes as NJOY or AMPX in order to generate cross section in point-wise and/or group representation
- Test evaluations against integral benchmarks (e.g. reaction rate) sensitive to a specific energy range (RRR)

$$R = \int_{\mathrm{RRR}} \sigma(E)\phi(E)dE \qquad (4)$$

Thermal Cross Sections and Integrals

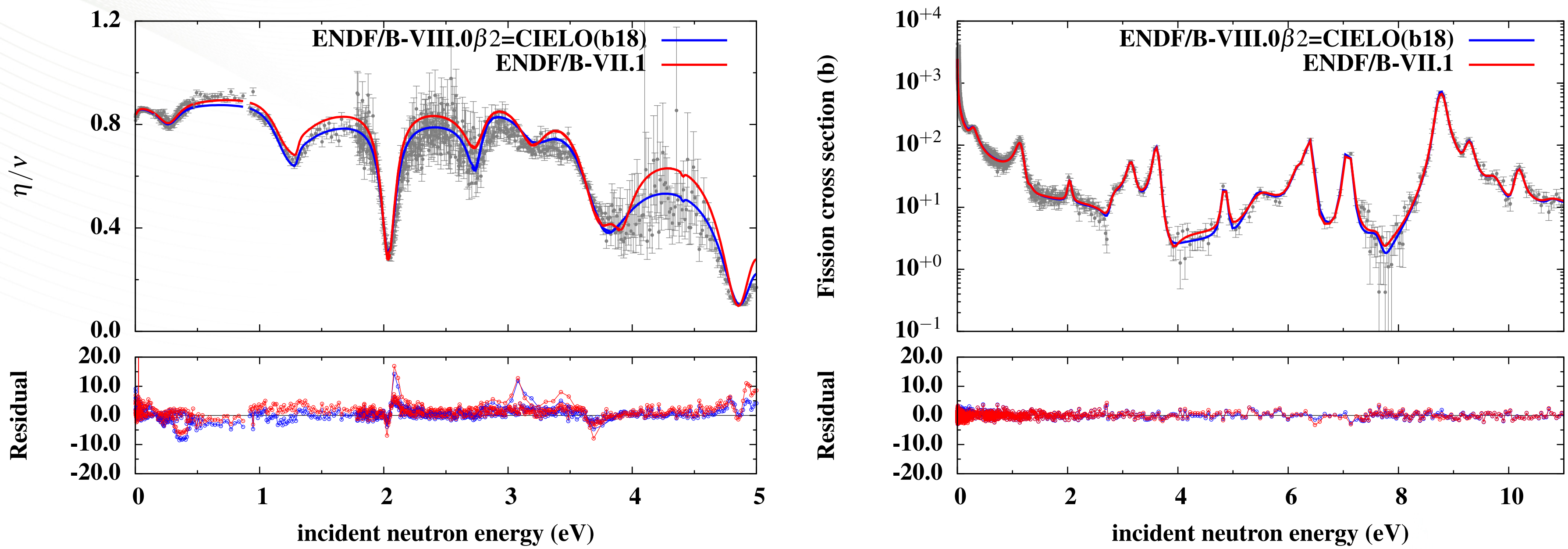
- **o23** values for fission and capture thermal cross sections are based on ^{235}U(n,f) thermal constants obtained on the basis of microscopic data (i.e., only considering Wallner thermal capture measurements)
- Fission integral (I_4 in the Figure below) between 7.8 and 11 eV based on recommendation of Neutron Standards



Thermal values

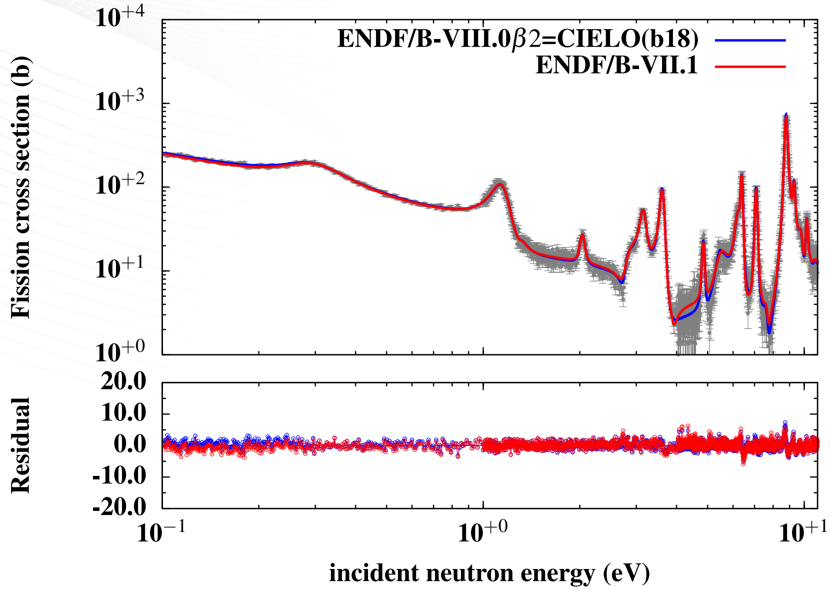
Standards	o23 (T=0° K)	
587.15±1.36	586.6	(n,f)
99.26±2.03	99.4	(n,γ)
14.09±0.21	14.08	(n,el)
0.855	0.855	η
0.1690	0.1694	α

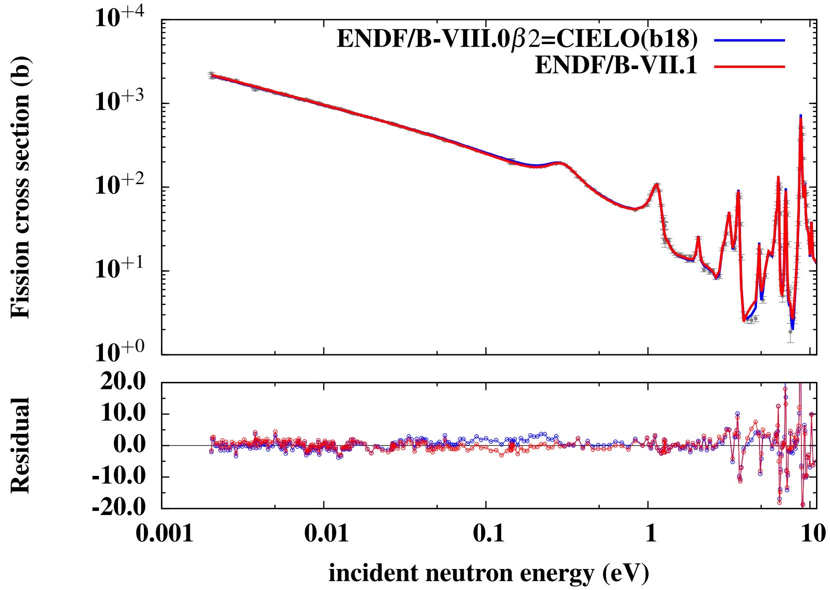
Results

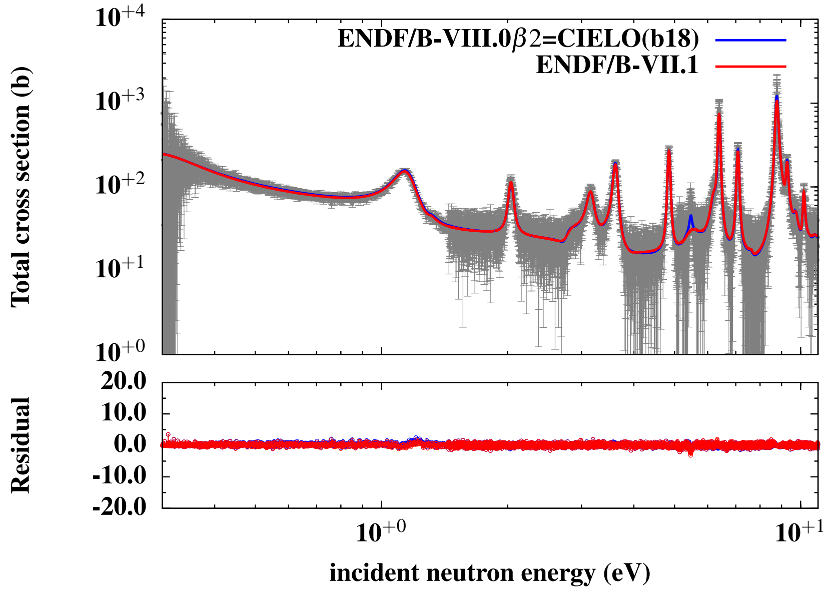


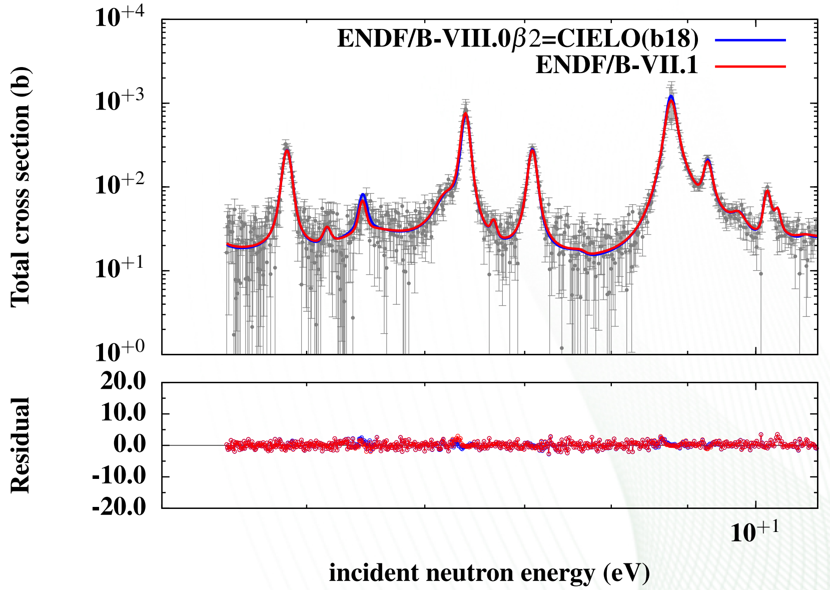
- n+^{235}U η measurements of Brooks, Wartena, and Weigmann (left) and Gwin's fission measured cross sections (right) compared to ENDF/B-VII.1 and ENDF/B-VIII.0β2 values.
- the CIELO η (decreased) values are, on average, in better agreement with the experimental data
  - achieved by increasing the capture cross sections, mostly in the valley of the resonances while keeping their peak values unchanged. The resonance at E_n=2 eV is clearly an example.
- The sensitivity of the resonance parameters to fission cross sections seems to be more relevant than to capture cross sections at neutron energies $\gtrsim 4$ eV (see fission cross sections shown in blue continuous line).

Other Results









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Summary and Conclusions

- We applied the R-matrix SAMMY method using the Reich-Moore approximation to determine a consistent set of neutron resonance parameters for ^{235}U
- The **o23**=CIELOb18 is currently part of the ENDF/B-VIII.0β2 (2016)
- Constraints applied on the **o23** resonance parameter evaluation are
  - Brooks'η experimental data
  - Standard thermal cross sections and the fission integral between 7.8–11 eV
  - New thermal Prompt Fission Neutron Spectra (PFNS)
- The present set of resonance parameters yields cross sections still in reasonable agreement with the suite of experimental data
- The validation analysis on the thermal benchmarks showed good agreement with the experimental response and that the **o23** resonance parameters are compatible with the current values of $\bar{\nu}$ (from thermal constants) and thermal PFNS (average energy 2.00$\pm$0.01)

Conclusion : new resonance analysis allowed to combine new evaluation of Thermal Neutron Constants, the recommended value of the fission resonance integral from 7.8-11 eV, new PFNS evaluation, and to describe Brooks data while keeping an excellent agreement with existing fission, capture and transmission measurements.

Future Work : Analysis of new experimental data (fission and capture) over the entire energy range up 2.25 keV.

Acknowledgments

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Thank you!