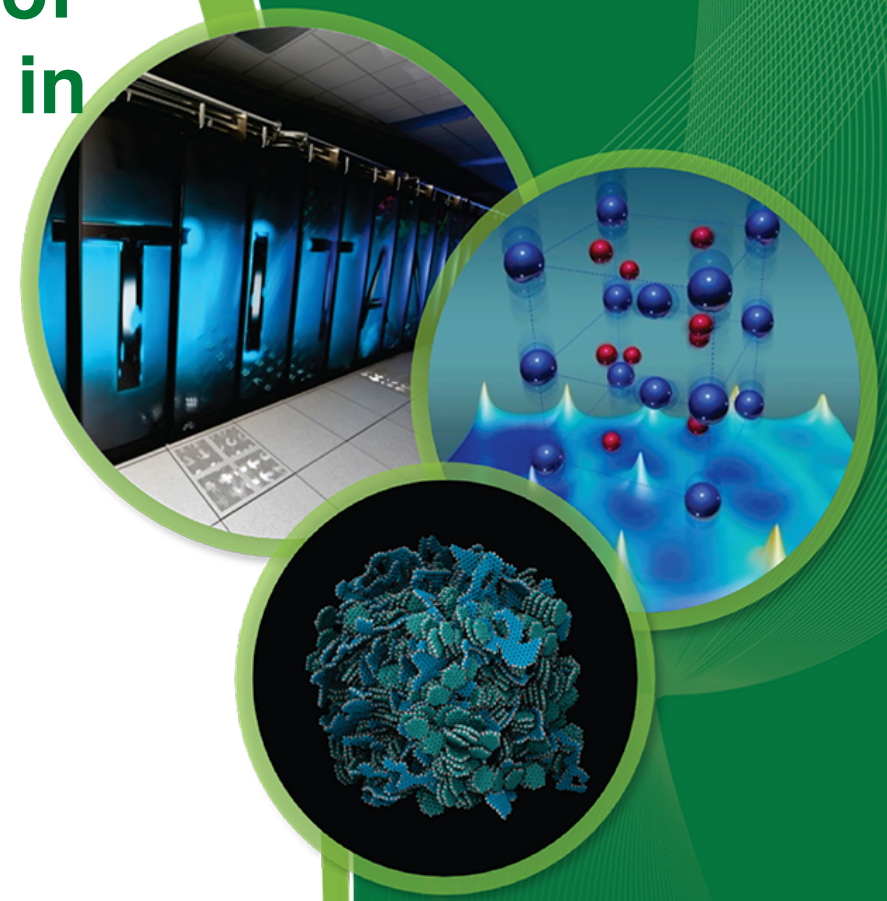
Cross Section Evaluation of ^{235}U, ^{16}O, and Dy Isotopes in the Resolved Resonance Neutron Region



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Outline

- **^{235}U (and ^{239}Pu)**
  - Summary of features of the newly evaluated resonance parameters
- **^{16}O**
  - Advanced evaluation methodology in SAMMY
    - Use of the $B_\ell = -\ell$ boundary condition
    - Inclusion of closed-channel effects
    - Treatment of the capture channel as particle channel
- **Dy isotopes**
  - Analysis of available experimental data (transmission and capture)
  - Resolved resonance evaluation (RRR)
- **Future work**
- **Acknowledgments**

Timeline

- **FY16/17**
  - Evaluation work on ^{235}U and ^{16}O
  - Preliminary work on Dy isotope evaluations
  - Presentation of the results at the Nuclear Data Week (CSEWG)
- **FY17**
  - Completion of ^{235}U evaluation (ENDF/B-VIII.0)
  - Evaluation work on ^{16}O and ^{156,158,160,161,162,163,164}Dy
  - Some work on ^{239}Pu (ENDF/B-VIII.0)
  - Development work on neutron multiplicities $\bar{\nu}_p$ (NDAG presentation)
  - Publication work (ND2016 proceedings and Nuclear Data Sheets)
- **FY17/18**
  - Completion of ^{16}O evaluation
  - Completion of ^{156,158,160,161,162,163,164}Dy evaluations

^{235}U (RRR evaluation) and ^{239}Pu

No.	Nucleus (I^{π})	E_{max}	Method	J_{3^-}	J_{4^-}
1	^{235}U $(7/2^-)$	2.25 keV	RM	1433	1731

- In the ORNL resonance evaluation in the ENDF/B-VIII.0 library, particular emphasis was devoted to
  - STD-2017 thermal cross sections and the fission integral between 7.8–11 eV
  - Neutron incident energies up to 20 eV for *measurements of* $\alpha = \sigma_\gamma/\sigma_f$ *(or* η*)*
  - New thermal prompt fission neutron spectra (PFNS) evaluated by the IAEA (Capote/Trkov)
  - Newly evaluated STD-2017 fission average cross sections up 1 keV
- In the covariance analysis, the large number of resonance parameters (about 15,500) led to a related covariance matrix of 1.7 Gb when formatted in an ENDF-compatible file (MT=32 with LCOMP=1)
- Upon request from the IAEA, the resonance covariance file (MT=32) was processed to generate a set of covariance matrices formatted as MT=33
- The covariance file MT=33 is part of the ENDF/B-VIII.0, library but the resonance covariance file (MT=32) should also be stored
- Resonance covariance file MT=32 for ^{239}Pu was adopted from JEFF-3.2 (SG34) because it is coupled to the resonance parameter evaluation MT=2 submitted in September 2012 to the ENDF repository
- Minor corrections were made (last digits) to the resonance parameter in file 32 to match those in file 2

Motivation (n+^{16}O RRR evaluation)

- Neutron scattering on oxygen is important in criticality safety applications where oxides are present in significant abundance
- Longstanding issues from measured cross sections on ^{13}C(α,n)^{16}O[1] due to the discrepancies between Bair (1973) and Harissopulos (2005) data sets
- The aim of this work is to provide a set of *resonance parameters* (RP)s as an alternative to the extant point-wise evaluation of oxygen in the ENDF/B-VIII.0 library
- RPs are important in nuclear data evaluation analyses in which measurements were performed on oxide samples or liquid samples that have been dissolved or diluted with solutions containing light nuclei

[1] Due to the lack of direct experimental data, the ^{16}O(n,α) cross sections are usually obtained by inverse kinematics from measured data on ^{13}C(α,n)^{16}O on the basis of the reciprocity theorem.

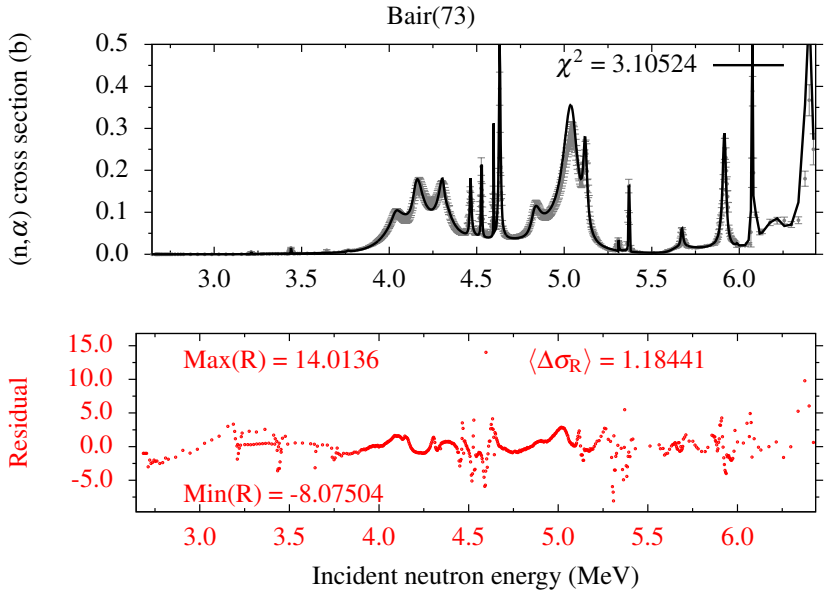
Evaluation methodology

- The R-matrix SAMMY code was used to generate a set of resonance parameters for n+^{16}O reactions in the energy range of thermal up to about 6 MeV
- Three advanced major features of the present evaluation are as follows
  - **(a)** The use of the $\boldsymbol{B_c = -\ell}$ **boundary condition** commonly used in the formal R-matrix theory but rarely used in SAMMY evaluation work. The default option is the energy-dependent boundary condition $B_c = S_c$
  - **(b)** In order to preserve the **unitary** of the S-matrix, the **capture channel** was treated as particle channels whose penetrability factor is set to be unitary in SAMMY input file
  - **(c)** **Closed-channel effects**[2] were included for the (n,α) reaction channel
- The evaluation work builds on a comprehensive resonance analysis that was initiated in FY16 **(a)**,**(b)**[3] and updated through FY17 **(c)**[4]

[2]For threshold reaction channels as ^{16}O(n,α), the RPs are sensitive to the cross sections also for incident energies below the energy threshold.
[3]Notes on the consistency of ^{16}O(n,α) cross sections
[4]ORNL contribution to ENDF/B-VIII.0 and progress on light nuclei evaluations

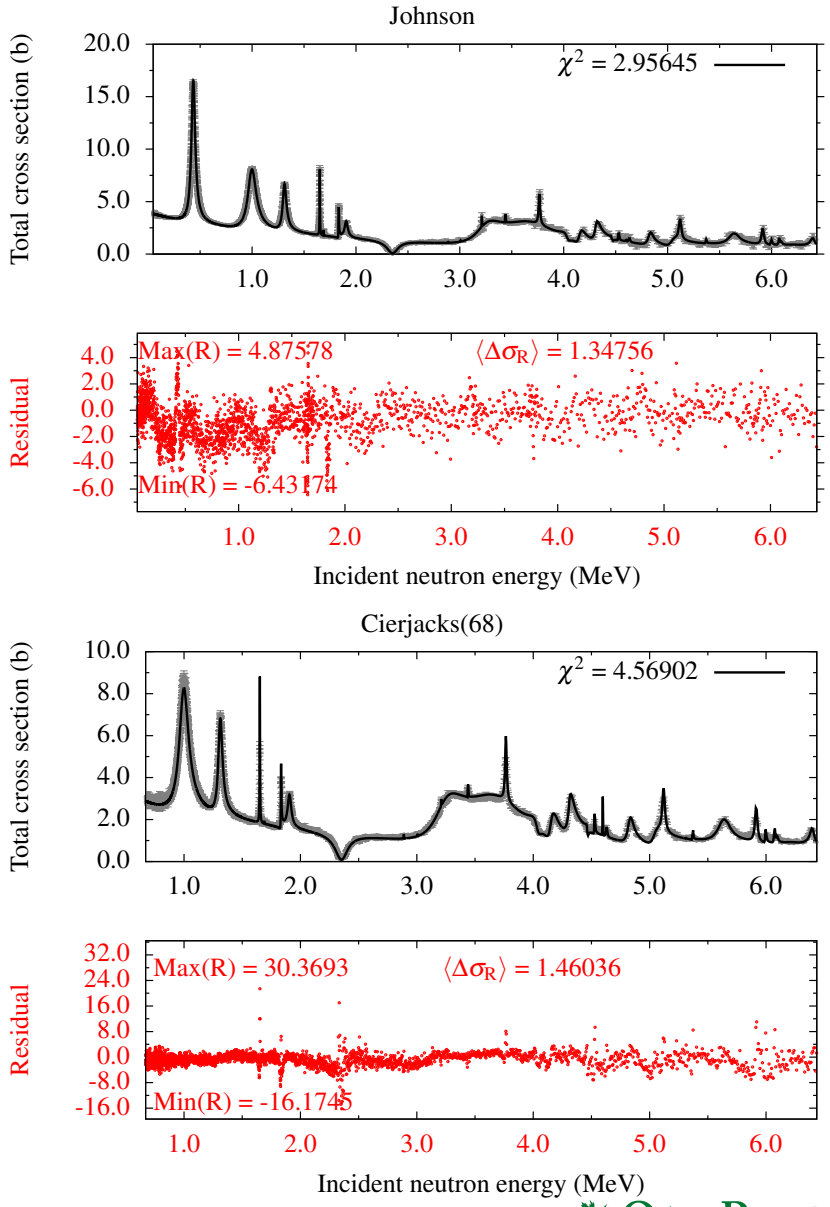
Results

(n,α) cross sections



- **Normalization to shown theoretical data**
  - Bair (73) : 1.248
  - Cierjacks (68) : 1.0293
  - Johnson : 1.000
- **Correlation of experimental data estimated at 20%**
- **Average residual $\langle \Delta\sigma_R \rangle < 2$ sigmas**

Total cross sections



Motivation (DY isotopes evaluation)

- *Historical note*: the name is derived from the Greek “dysprositos” that means hard to get
- Dysprosium is produced in a reactor as a fission product and acts as a neutron absorber in a nuclear fuel or in a reactor control rod
- For its absorbing features, it can be used as a burnable poison to control a reactor
- Having large capture cross sections, Dy isotopes (mainly the ^{164}Dy isotope) can continuously and effectively absorb neutron for a long time
- Favorable thermophysical properties of dysprosium
- The set of resonance parameters in the ENDF/B-VIII.0 nuclear data library was evaluated by the unfavorable multilevel Breit-Wigner approximation[5]

[5]The level matrix is diagonal and the interference effects are neglected.

Status of Dy evaluations

- Current status of Dy evaluations in ENDF/B-VII.1 library

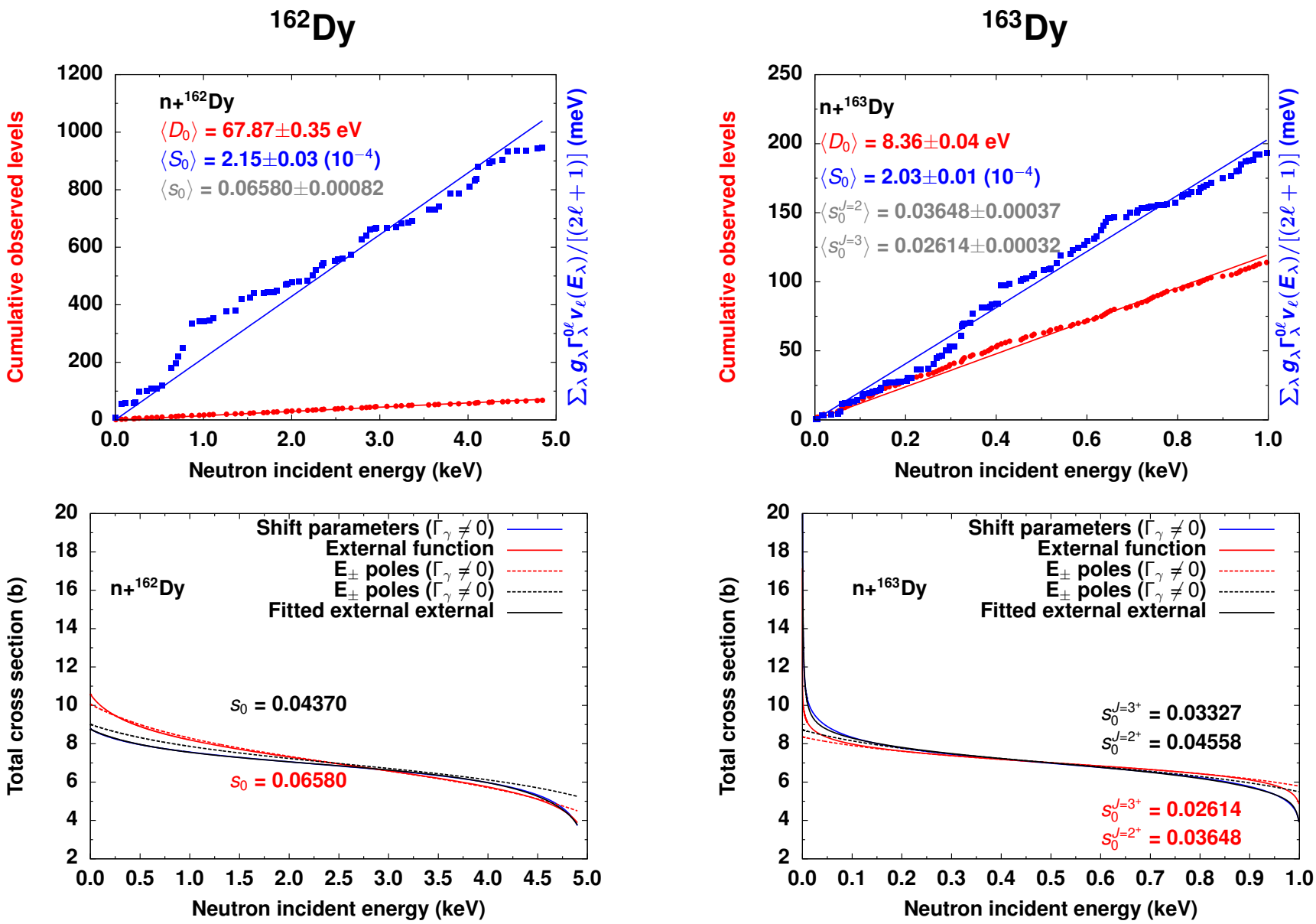
Isotope	Nat. Abnd. (%)	E_{max} (eV)	ℓ_{max}	Levels**	Transmission	(n,γ)
^{156}Dy	0.056	100	s	19		
^{158}Dy	0.095	90	s	3		
^{160}Dy	2.329	2000	p	65	X	
^{161}Dy*	18.889	1000	s	253	X	X
^{162}Dy*	25.475	5000	p	75	X	X
^{163}Dy*	24.896	1000	s	114	X	X
^{164}Dy*	28.260	7000	p	69	X	X
^{nat}Dy*	100.00	N/A	s,p	all	X	X

$(*)$ Relevant to NCSP $(**)$ Without negative levels

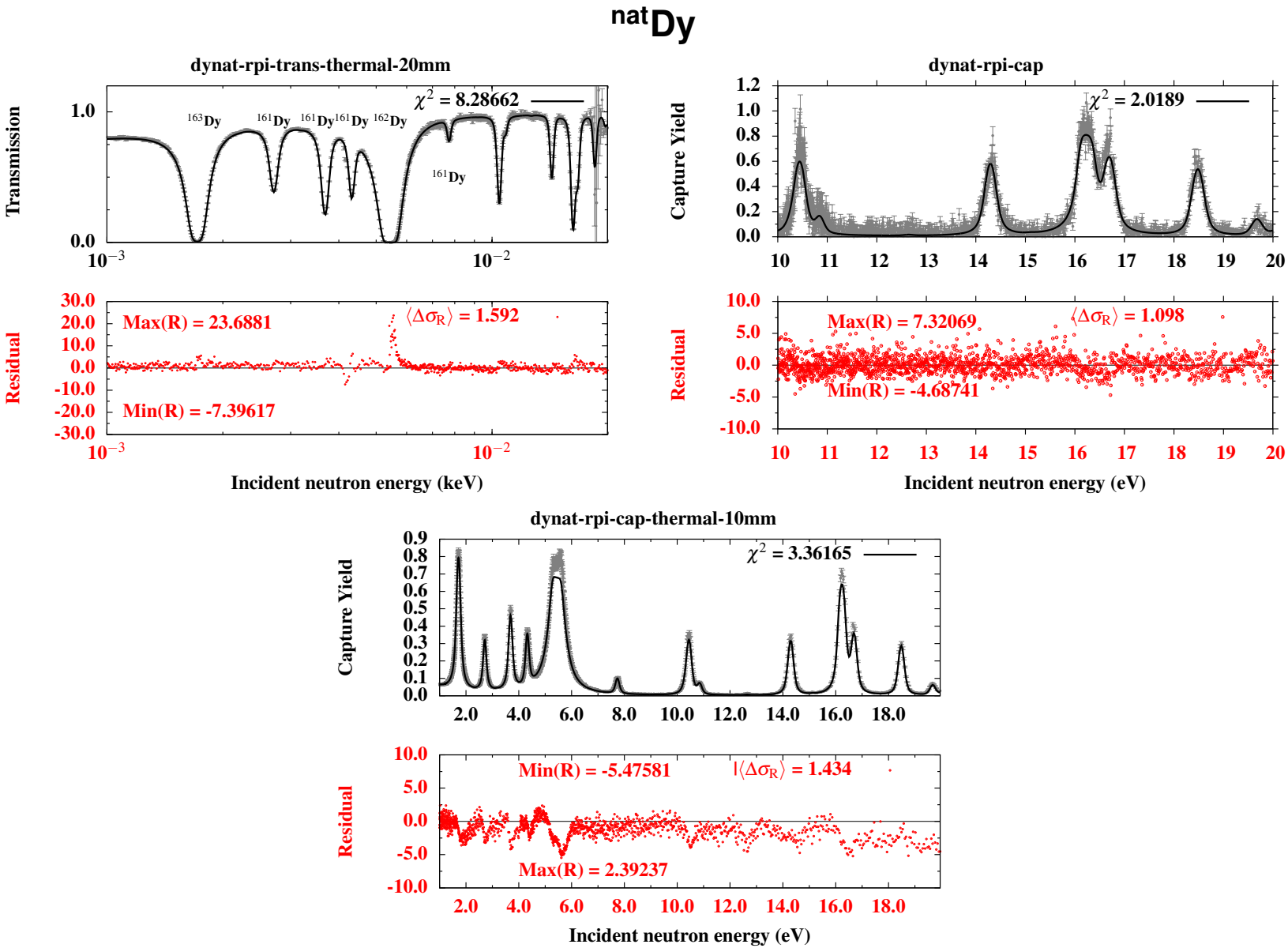
- Review of old existing Liou's transmission data sets showed several issues
  - The large number and magnitude of negative values found in the ^{160,163,164}Dy total cross sections imply an over correction of the background contribution
  - The measurements were performed on oxide samples (DY_2O_3), but the number of atoms/barn reported seems related to the specific enriched isotope. This affected our ability to correctly calculate the total number of atoms/barn of the sample
  - Several "black" resonances[6] were reported and no uncertainty analysis was reported

[6] Energy levels for which there is no transmission of neutrons or, vice versa, the neutron absorption is maximum.

External functions determination



Preliminary results on ^{nat}Dy



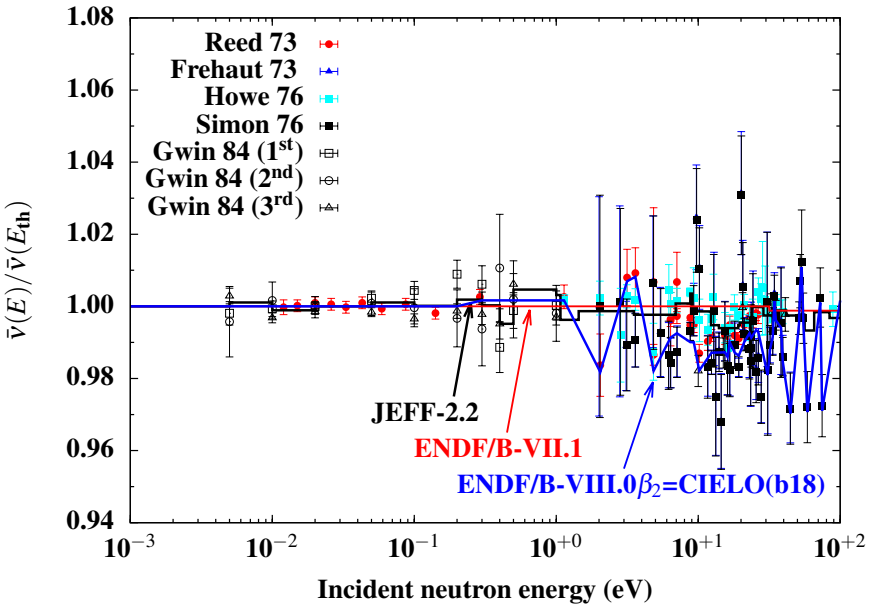
Neutron multiplicities $\bar{\nu}_p$ (NDAG)

Fort's formalism

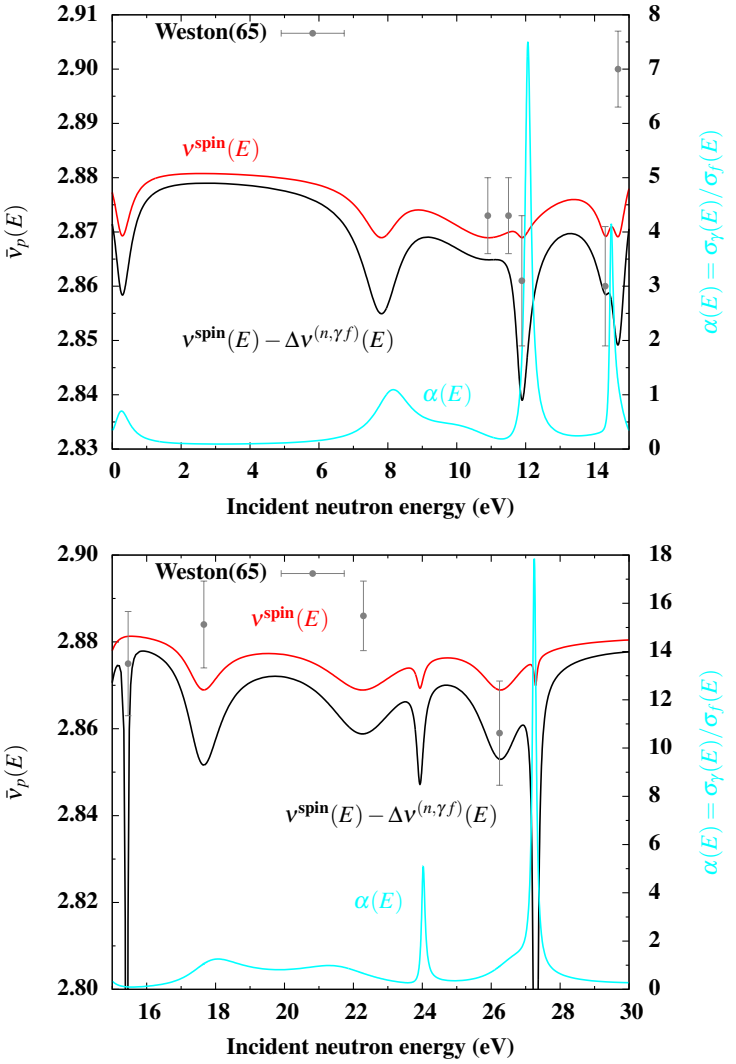
- One can define and compute the fluctuating behavior of prompt neutrons based on the competition of $(n,\gamma f)$ and direct fission (n,f) processes and spin effect,

$$\bar{\nu}_p(E) \quad = \quad \nu^{\text{spin}}(E) - \Delta\nu^{(n,\gamma f)}(E) \qquad (1)$$

- This work was motivated by the difficulties in ^{235}U evaluation to quantify the $\bar{\nu}_p$ fluctuations (see below)
- It is important to quantify the coupling between RRR and $\bar{\nu}_p$ evaluation to improve performance in the benchmarks and uncertainty quantification



Spin effect and (n,γf) reaction



The $\bar{\nu}_p$ of ^{239}Pu in the incident neutron energy up 30 eV plotted together with spin effect component. Calculations performed with SAMMY and based on Fort's formalism.

Publications related to NCSP

- ND2016 : "*Validation of W Cross Sections in the Neutron Energy Region up to 100 keV*" **146**, 06010 (2017)
- ND2016 : "*n+^{235}U Resonance Parameters and Neutrons Multiplicities in the Energy Region below 100 eV*" **146**, 02011 (2017)
- ND2016 : "*The CIELO collaboration: Progress in international evaluations of neutron reactions on Oxygen, Iron, Uranium and Plutonium*" **146**, 02001 (2017)
- ND2016 : "*Evaluation of the neutron induced reactions on ^{235}U from 2.25 keV up to 30 MeV* **146**, 02029 (2017)
- Nuclear Data Sheets (Special issue 2018) : "*The CIELO Collaboration Summary Results: International Evaluations of Neutron Reactions on Oxygen, Iron, Uranium and Plutonium*"
- Nuclear Data Sheets (Special issue 2018) : "*The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data*"
- Nuclear Data Sheets (Special issue 2018) : "*Evaluation of Neutron-induced Reactions on ^{235}U and ^{238}U targets up to 30 MeV*"

Conclusions and future work

- There have been major contributions to the ENDF/B-VIII.0 library focused on resolved resonance evaluations of ^{182,183,184,186}**W**, ^{235}**U** evaluations and one of ^{40}**Ca**. Other work related to NCSP was on the ^{63,65}**Cu**.
- Ongoing resonance work includes ^{16}**O** and the set of **Dy** isotopes (end of FY18). Other ongoing resonance work is on **Gd** isotopes.
- First attempt to couple resonance evaluation to fluctuations in the $\bar{\nu}_p$ was initiated (NDAG) and ORNL seed money proposal was drafted
- Future work on ^{239}**Pu** is planned to improve agreement with plutonium critical experiments (also connected to the work on $\bar{\nu}_p$)
- A report on dysprosium evaluation work is planned
- A journal paper on ^{16}**O** evaluation is planned for submission

Acknowledgments

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Thank you!