ANS Winter Meeting & Expo

2018 Joining Forces to Advance Nuclear

ENDF/B-VIII.0: the 8th major release of the ENDF/B library

D.A. Brown

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ENDF/B-VIII.0 was released on 2 Feb. 2018 by the Cross Section Evaluation Working Group (CSEWG)

ENDF
B-VIII.0

Integrates contributions for many sources

- **Neutron Data Standards** *IAEA, NIST*
- **CIELO Pilot Project** *BNL led Fe, LANL led ^{16}O and ^{239}Pu, IAEA led ^{235,238}U*
- **Many new and improved neutron evaluations** *(DP, Crit. Safety, NE, USNDP)*
- **New thermal scattering libraries** *(Crit. Safety, Naval Reactors)*
- **Decay data** *USNDP (BNL)*
- **Charged particles** *USNDP (LLNL)*
- **New atomic data** *(LLNL)*
- **Success rests on EXFOR & ENSDF libraries**
  USNDP (BNL) compiles EXFOR reaction data for US & Canada
  USNDP develops the ENSDF library

Happy 50th Anniversary!*

* ENDF/B-I was released in June 1968

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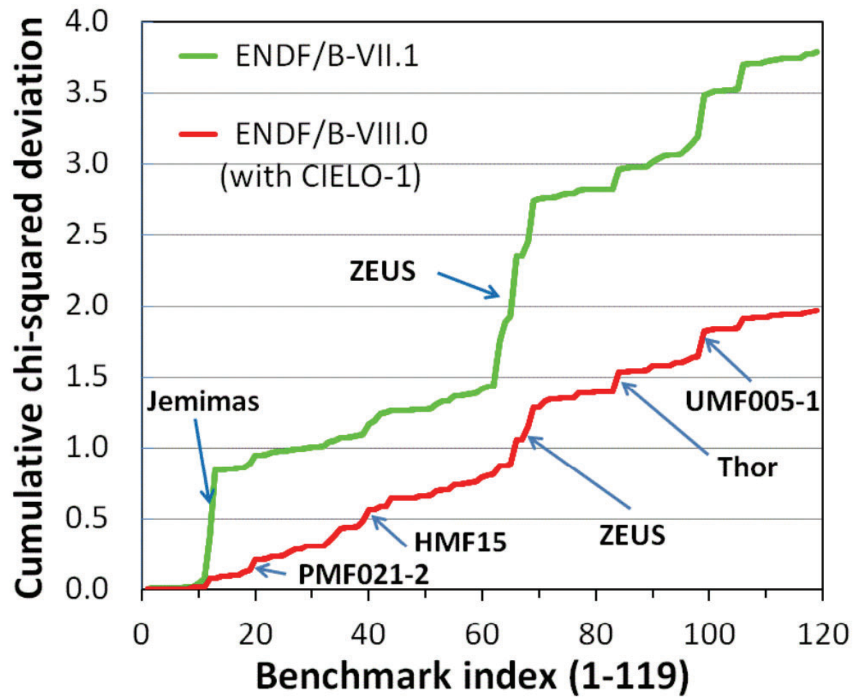
ENDF/B-VIII.0 is our best performing and highest quality library yet

- **Validate by simulating well characterized systems**
  - Thousands of critical assembly benchmarks
  - 14 MeV & ^{252}Cf(sf) source transmission
  - Many other tests
- **Quality also assured by**
  - ADVANCE continuous integration system at BNL
  - Annual Hackathons



M.B. Chadwick et al, Nuclear Data Sheets 148, 189 (2018)

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Library and evaluations detailed in Nuclear Data Sheets vol. 148 (2018)

- **ENDF/B-VIII.0**: D. Brown *et al.*, Nuclear Data Sheets 148, 1 (2018)
- **Neutron Data Standards**: A. Carlson *et al.*, Nuclear Data Sheets 148, 143 (2018)
- **CIELO Overview**: M.B. Chadwick, *et al.*, Nuclear Data Sheets 148, 189 (2018)
- **CIELO Iron**: M. Herman, *et al.*, Nuclear Data Sheets 148, 214 (2018)
- **CIELO Uranium**: R. Capote, *et al.*, Nuclear Data Sheets 148, 254 (2018)
- **PFNS evaluation**: D. Neudecker, *et al.*, Nuclear Data Sheets 148, 293 (2018)
- **^{239}Pu(n,g) measurement**: S. Mosby, *et al.*, Nuclear Data Sheets 148, 312 (2018)
- **^{235}U PFNS measurement**: M. Devlin, *et al.*, Nuclear Data Sheets 148, 322 (2018)


Volume 148, February 2018
ISSN 0090-3752
ELSEVIER

Nuclear Data Sheets

A Journal Devoted to Compilations and Evaluations of Experimental and Theoretical Results in Nuclear Physics

E. A. McCutchan, Editor
National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA
www.nndc.bnl.gov

Special Issue on Nuclear Reaction Data

Special Issue Editor: Pavel Obložinský
Special Issue Assistant Editor: Boris Pritychenko

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Outline for remainder of talk

- **We didn't "change anyone's answers"**
- **Big changes that "didn't change anyone's answers":** *^{235,238}U and ^{239}Pu*
- **Other potentially dramatic changes:** *New TSL evaluations for H2O and graphite*
- **Other big things that changed:** *^{16}O, ^{56}Fe*

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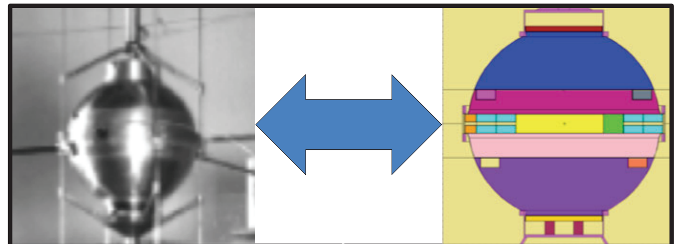
There are many ways to "get the right answer"

- E. Bauge, et al. (CEA-DAM)
- Swap portions of one evaluation for other until completely swapped
- Elastic & inelastic scattering provided biggest swing



BRC09 (CEA)	ENDF-VII.1
$k_{eff}=1.00082(11)$	$k_{eff}=1.00060(12)$

How does k_{eff} change when a BRC09 value is replaced by one from ENDF-VII.1?

Quantity	Δk_{eff} (1000th's of %)
Fission	-138
Capture	+269
Elastic Scattering	**-638**
Inelastic Scattering	**+522**

The end result is a lack of confidence in modeling systems that significantly differ from the integral benchmark

Figure from L. Bernstein

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Situation “unchanged” in VIII.0

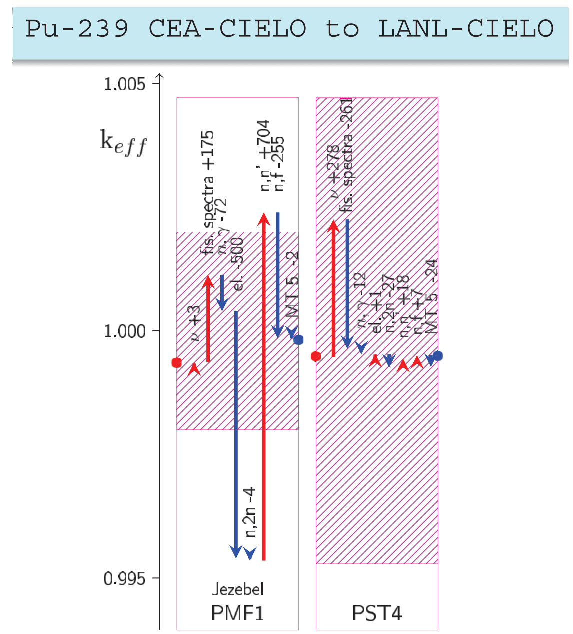

FIG. 28. (Color online) Simulations of criticality k-eff for ^{239}Pu for two critical assemblies: a fast assembly (Jezebel, PMF-1), and a thermal assembly (PST-4). This figure shows that both LANL CIELO-1 (ENDF/B-VIII.0) and CEA CIELO-2 (JEFF-3.3) predict similar k-eff values, but do so for very different reasons. The changes in criticality are evident when individual cross section channels are substituted between the two evaluations.

M. Chadwick *et al.,* Nuclear Data Sheets 418, 189 (2018)

We focused on thermal & fast applications

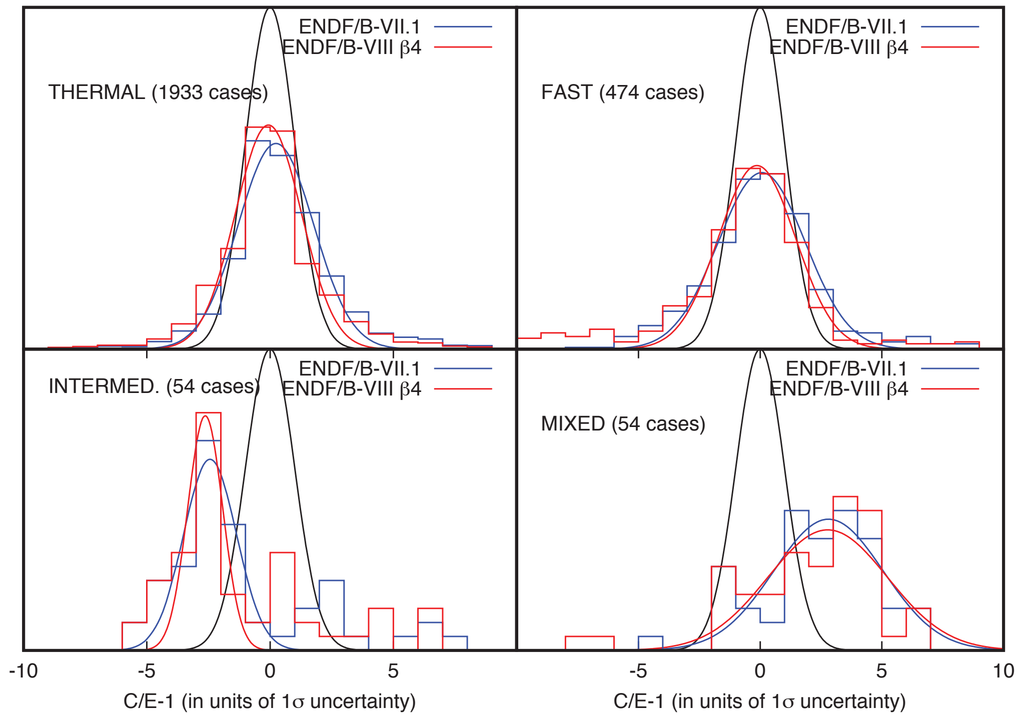

FIG. 29. (Color online) The distribution of C/E, in units of the combined benchmark and statistical uncertainty. The normal distribution (in black) would be the perfect situation.

M. Chadwick *et al.*, Nuclear Data Sheets 418, 189 (2018)

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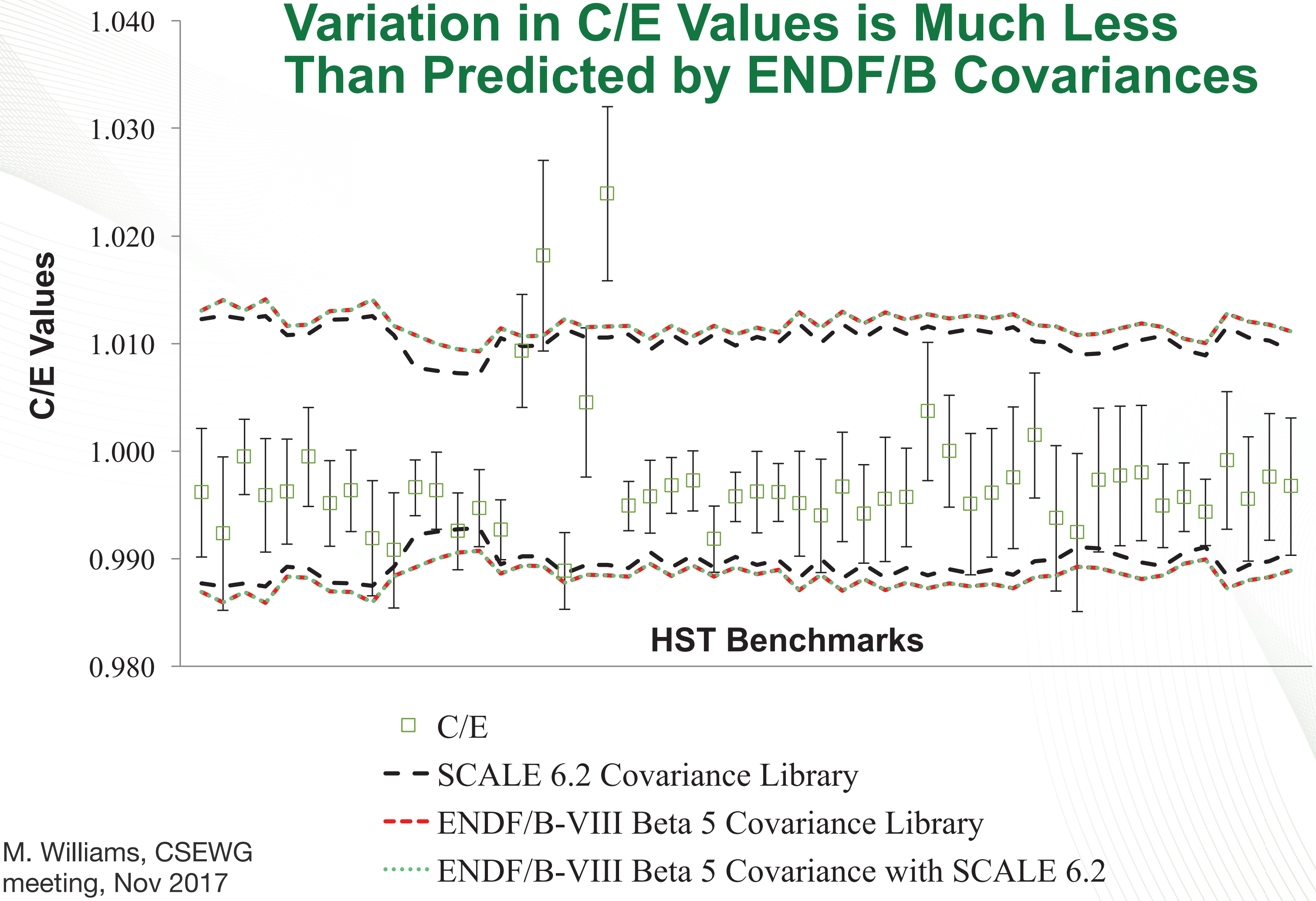
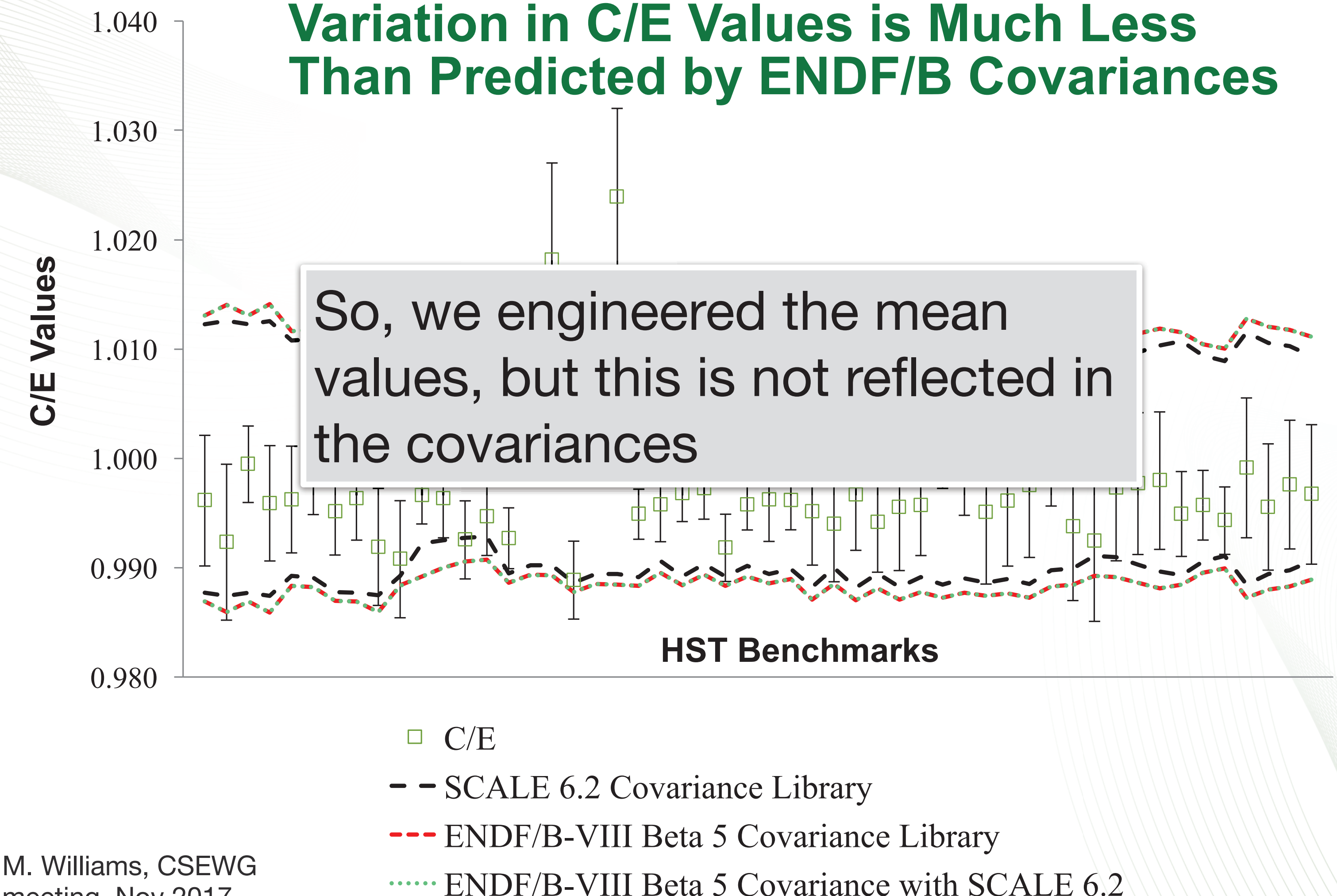
Variation in C/E Values is Much Less Than Predicted by ENDF/B Covariances



M. Williams, CSEWG meeting, Nov 2017

Variation in C/E Values is Much Less Than Predicted by ENDF/B Covariances



So, we engineered the mean values, but this is not reflected in the covariances

M. Williams, CSEWG meeting, Nov 2017

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ENDF B-VIII.0

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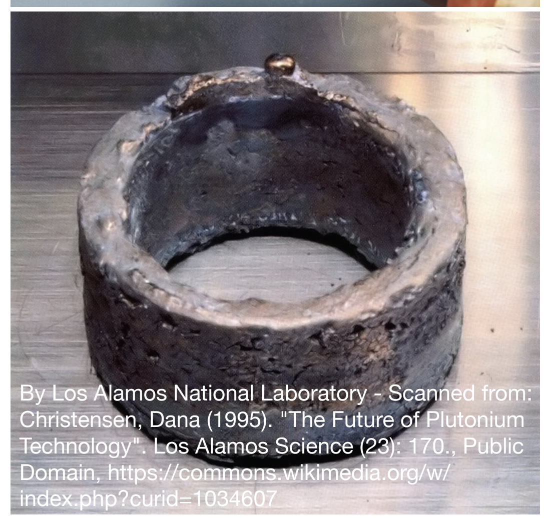
Large overlap in evaluations of Big 3

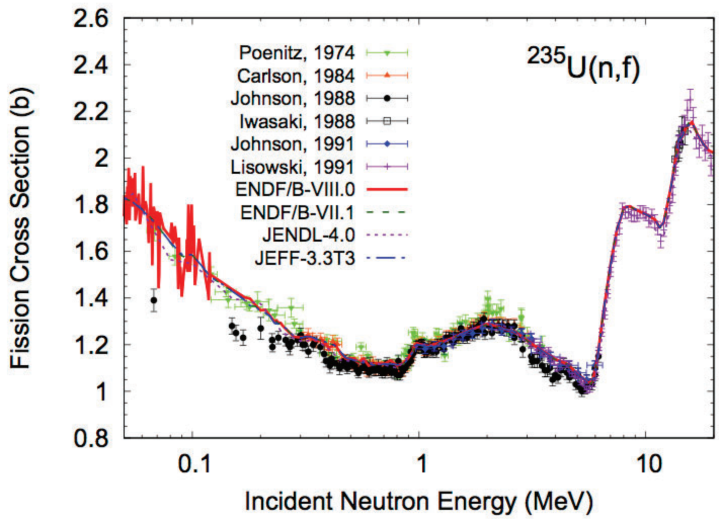
- **Neutron Data Standards**: (n,f) cross section
- **P(nu) for neutrons and gammas** (Talou)
- **Fission energy release** (Lestone)
- **PFNS & associated cov.** (Neudecker)
- **PFGS new**, resolves long standing problem with fission gammas (Stetcu)
- **Feedback from benchmarks**
- **Main differences**: treatments of RR & Fast parts of evaluation

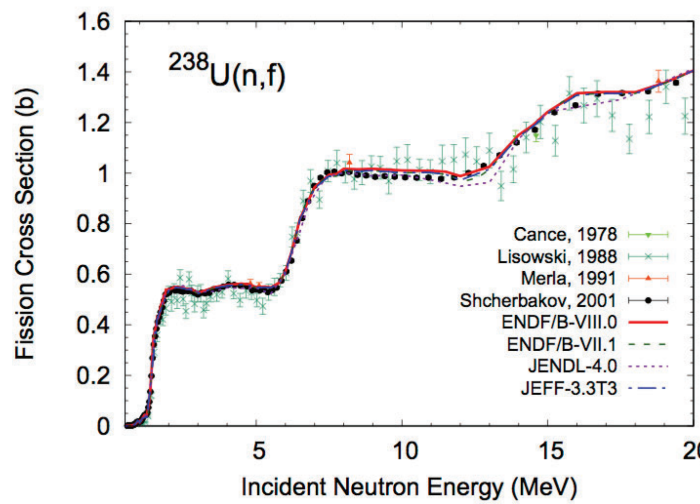


Each major ENDF release is built off the newest release of the Neutron Data Standards

TABLE XXXII. Neutron Data Standards.

Reaction	Standards Energy Range
H(n,n)	1 keV to 20 MeV
^{3}He(n,p)	0.0253 eV to 50 keV
^{6}Li(n,t)	0.0253 eV to 1.0 MeV
^{10}B(n,α)	0.0253 eV to 1 MeV
^{10}B(n,$\alpha_1\gamma$)	0.0253 eV to 1 MeV
C(n,n)	10 eV to 1.8 MeV
Au(n,γ)	0.0253 eV, 0.2 to 2.5 MeV, 30 keV MACS
^{235}U(n,f)	0.0253 eV, 7.8-11 eV, 0.15 MeV to 200 MeV
^{238}U(n,f)	2 MeV to 200 MeV
^{252}Cf(sf)	Prompt fission neutron spectra





A. Carlson *et al.,* Nuclear Data Sheets 418, 143 (2018)
D. Brown *et al.*, Nuclear Data Sheets 418, 1 (2018)

Unrecognized systematic uncertainty estimated and included

TABLE IX. Unrecognized systematic uncertainties from the analyses of the (weighted) standard deviations of the distributions for cross sections and $\overline{\nu}_{tot}$ for ^{252}Cf(sf). The $\overline{\nu}_{tot}$ for ^{252}Cf(sf) unrecognized systematic uncertainty was determined to be 0.4 %. All thermal neutron-induced $\overline{\nu}_{tot}$ unrecognized systematic uncertainties are also assumed to be 0.4 %.

Cross section	Unrecognized systematic uncertainty (%)
H(n,n) total	0.34
^{6}Li(n,t)	0.5
^{10}B(n,$\alpha_1\gamma$)	0.8
^{10}B(n,α)	0.8
C(n,n) total	0.65
Au(n,γ)	1.7
^{235}U(n,f)	1.2
^{238}U(n,f)	1.2
^{238}U(n,γ)	1.7 below 1 MeV
^{238}U(n,γ)	2.4 for 1 MeV and above
^{239}Pu(n,f)	1.2

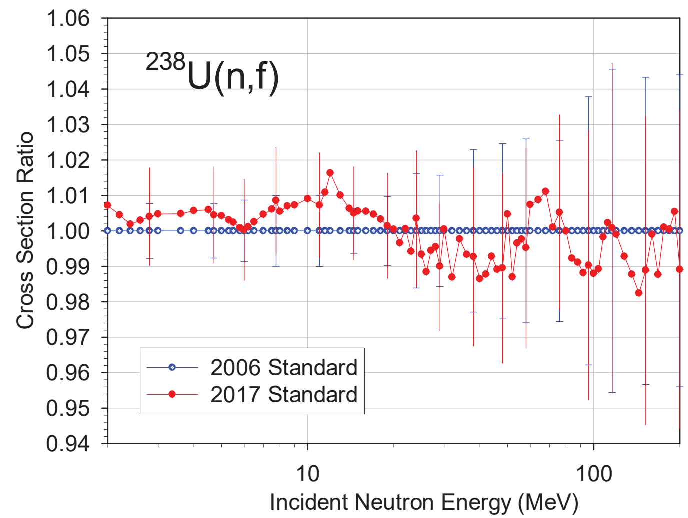
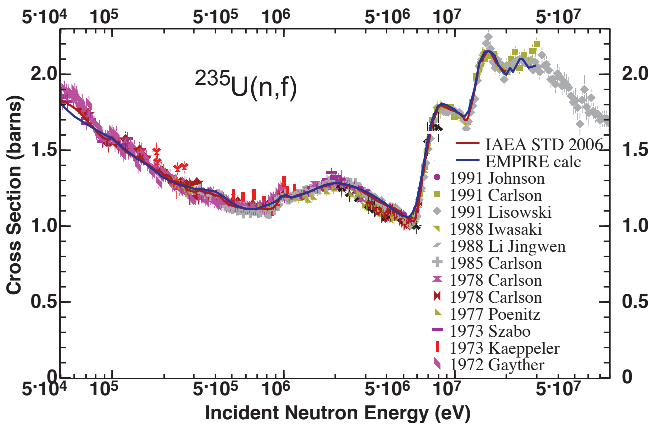
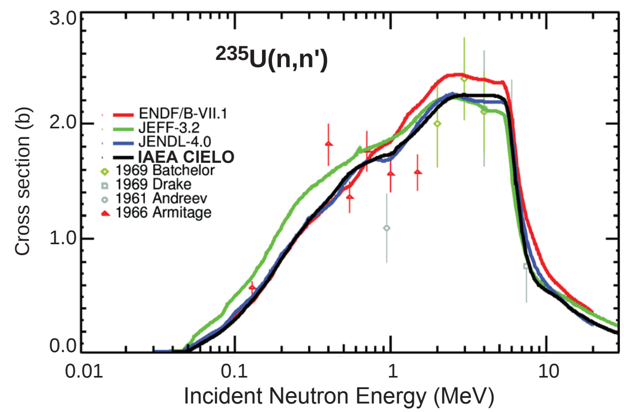


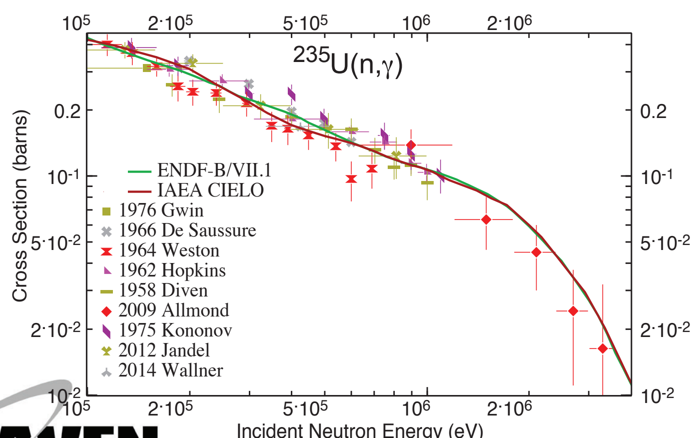
FIG. 14. (Color online) Comparison of the ^{238}U(n,f) cross section from the 2017 evaluation with the 2006 standards evaluation. The unrecognized systematic uncertainty of 1.2 % has been included in the 2017 data. The baseline at 1.00 is the 2006 standards evaluation.

A. Carlson *et al.*, Nuclear Data Sheets 418, 143 (2018)

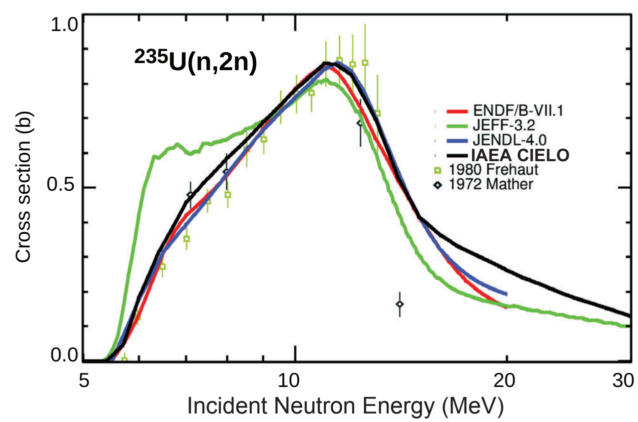
Other cross sections adjusted to match fission







(b) Fast neutron range above 100 keV.



Scattering data carefully re-evaluated for ^{238}U

ENDF B-VIII.0

- Dispersive OMP tuned to major actinides
- Proper treatment of (in)elastic mixing though E-W transform
- Proper compound angular distributions
- (n,n'g) data WAS NOT used

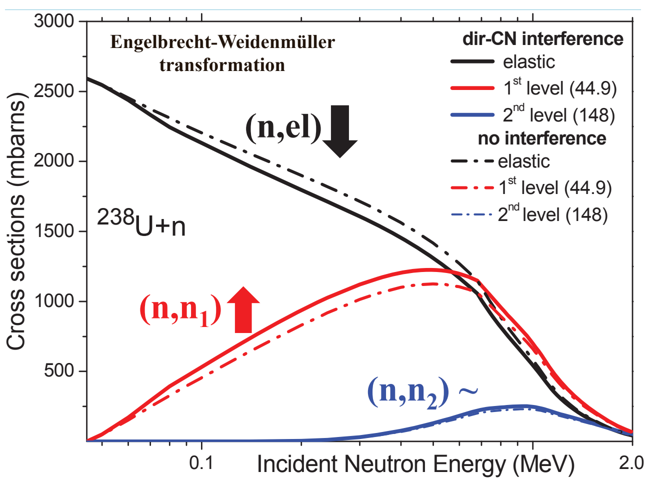


FIG. 17. (Color online) Neutron-induced reaction cross sections on ^{238}U (top) and effect of the Engelbrecht-Weidenmüller transformation [179] on elastic and inelastic scattering on the first two excited levels of ^{238}U (bottom). Experimental data in the top panel have been taken from EXFOR [91].

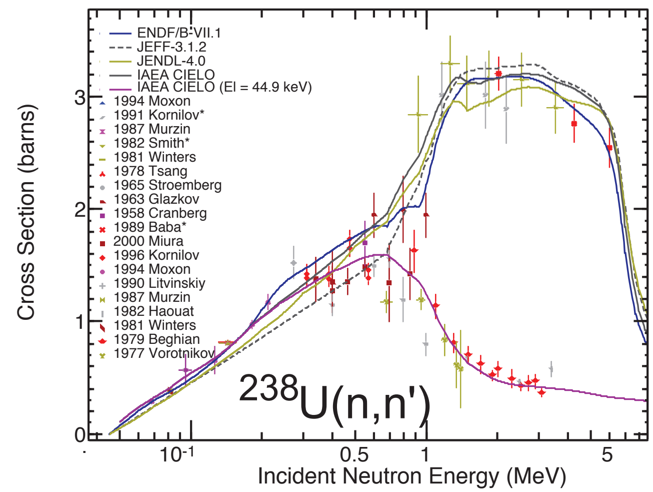


FIG. 18. (Color online) Calculated total and partial inelastic ^{238}U(n,n') cross sections on 45 keV level compared with experimental and evaluated data files. Experimental data have been taken from EXFOR [91].

R. Capote *et al.*, Nuclear Data Sheets 418, 254 (2018)

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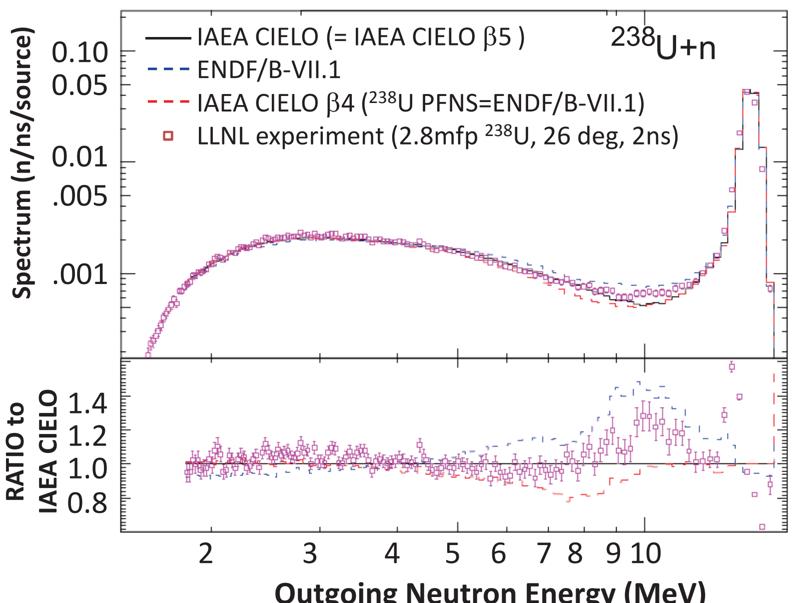
Scattering data carefully re-evaluated for ^{238}U

Excellent performance in Pulsed Sphere test



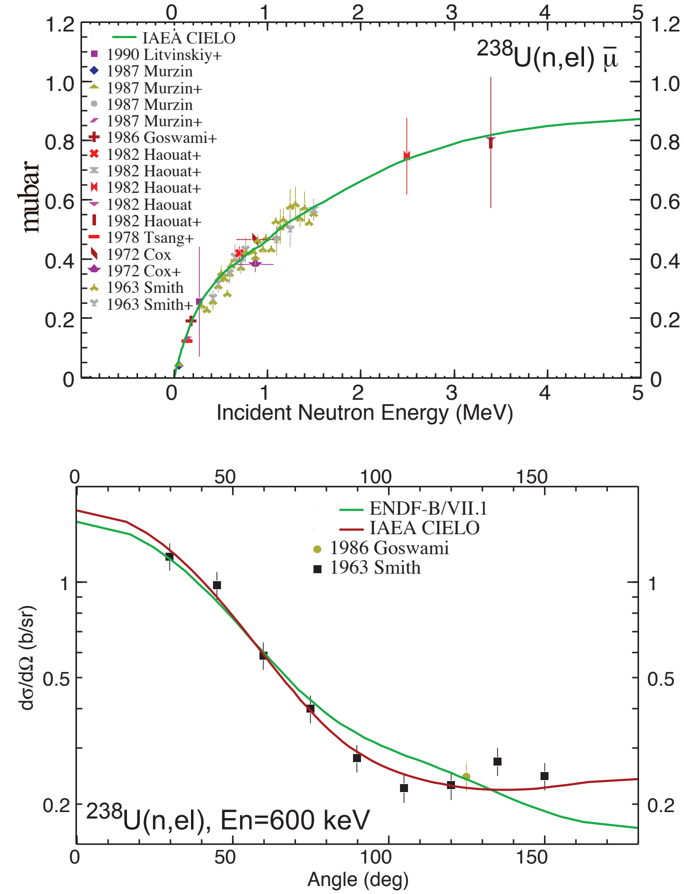


FIG. 19. (Color online) Average cosine of neutron elastic scattering $\overline{\mu}$ on ^{238}U (top). Angular distribution of neutron elastic scattering at 650 keV incident energy (bottom) on ^{238}U. Experimental data have been taken from EXFOR [91].

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R. Capote *et al.*, Nuclear Data Sheets 418, 254 (2018)

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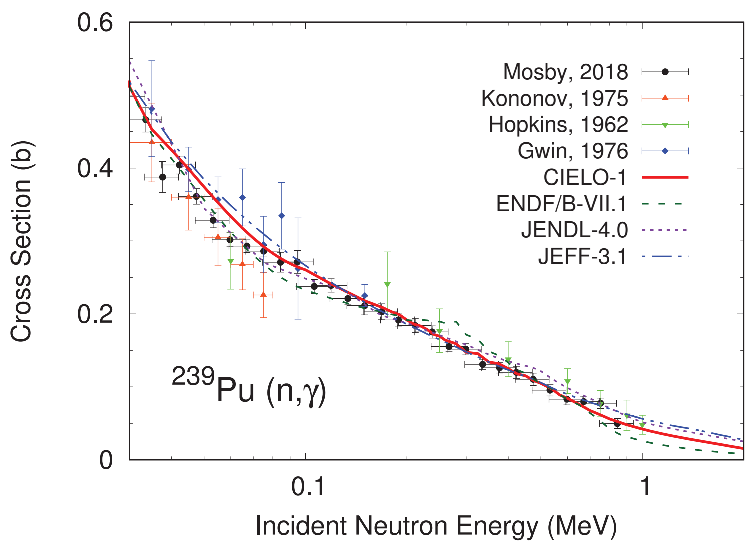
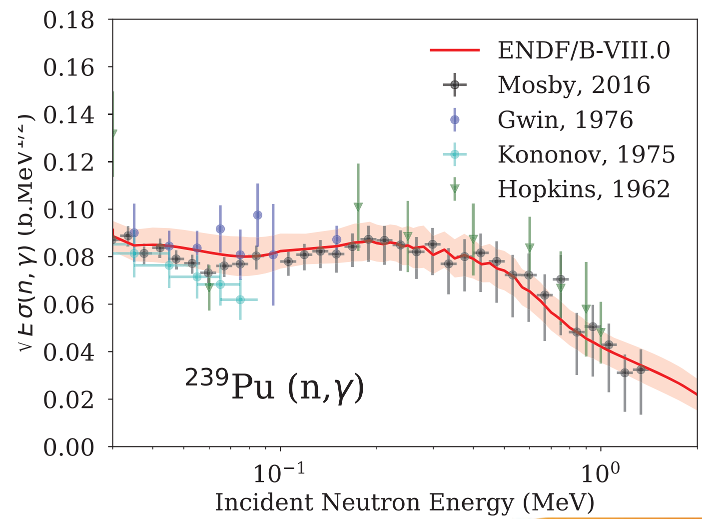
Main Updates from ENDF/B-VII.1

- Resonance region
  - Adoption of **WPEC SG-34** results up to 2.5 keV
  - New resonance parameters and nubar values
- Fast region: **not** a new full-blown evaluation!
  - Capture
    - Experimental data by Mosby et al. (DANCE, LANL)
    - Theoretical advances (Kawano)
  - Fission
    - Adoption of new IAEA standards result
  - Prompt Fission Neutron Spectrum
    - Chi-nu data (cf. Kelly's talk) still preliminary
    - New evaluation above 5 MeV incident neutron energy
  - **Updated covariances**

(n,γ) Cross Section

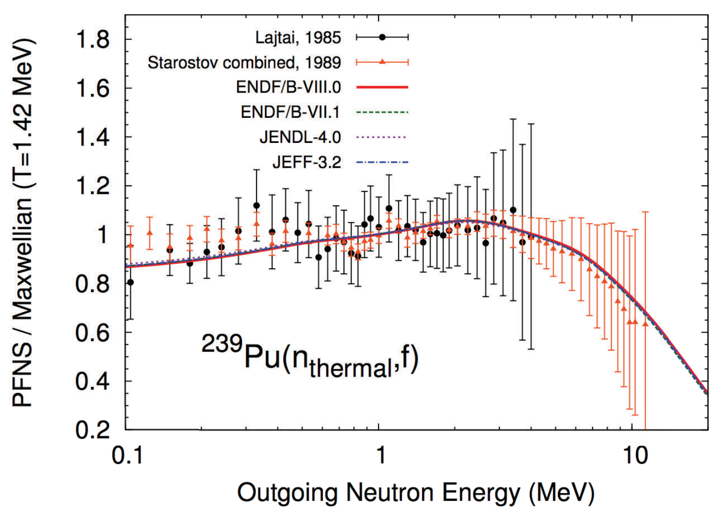
- New experimental results from DANCE measurement (**Mosby et al.**)
- New theoretical work (**Kawano**, CoH_3), including M1 "scissors" mode (also, **Ullmann et al.**)

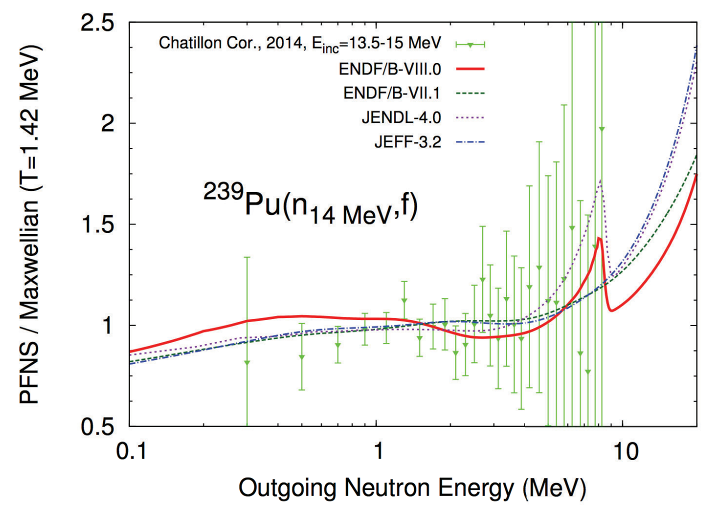




Prompt Fission Neutron Spectrum

- Small tweak for thermal PFNS to improve modeling of Plutonium thermal solution benchmarks
- Unchanged from B-VII.1 from 0.5 to 5 MeV
- New evaluation (**Neudecker et al.**) above 5 MeV
- Preliminary chi-nu data (**Kelly et al.**)





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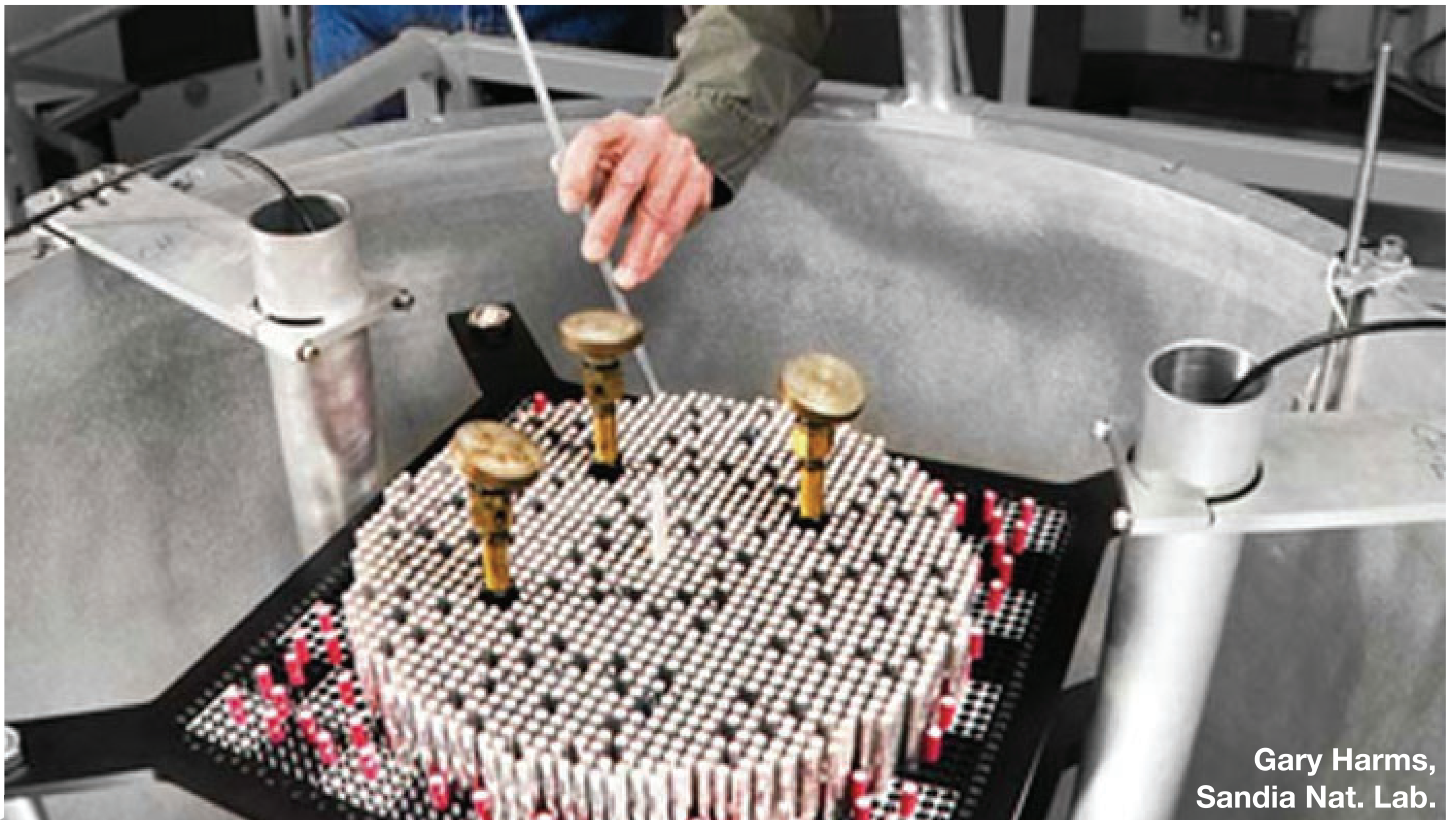
Light water used in LWR, PWR, many solution assemblies



Light water re-evaluated by Centro Atomico Bariloche (Argentina)

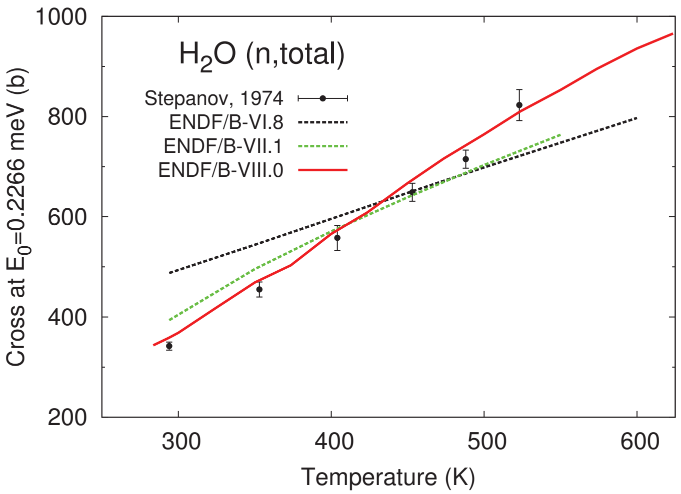


FIG. 126. (Color online) Evaluated ${}^{1}H_2O$(n,tot) total cross section at different temperatures, compared with data measured by Stepanov *et al.* [339, 340] at 0.2266 meV.

- CAB Light water model
- Molecular diffusion using a modified Egelstaff-Schofield diffusion model.
- A continuous spectrum derived from molecular dynamics simulations
- Alpha and beta grids were refined

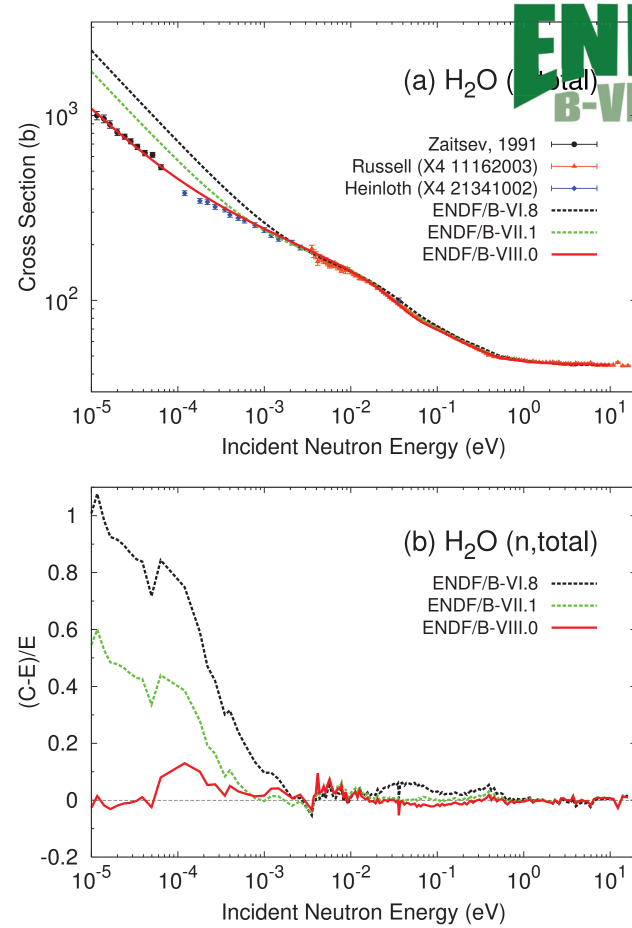


FIG. 125. (Color online) Evaluated ${}^{1}H_2O$(n,tot) total cross section at 293.6 K, compared with data retrieved from EXFOR and published by Zaitsev *et al.* [338].

D. Brown *et al.*, Nuclear Data Sheets 418, 1 (2018)

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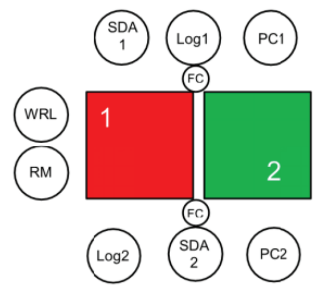
Neptune Experiment Used for Validation of ENDF/B-VIII.0(β5) H-H_2O TSL as a Function of Temperature

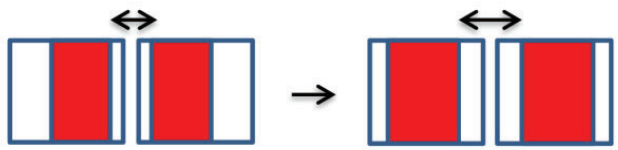
- Rolls-Royce conducted a series of critical experiments at the Neptune facility to validate the ability to predict criticality for water-isolated arrays as function of temperature [see Ref.].
- Configurations were neutronically similar to spent fuel storage racks without poison inserts in flux trap.
- Test was specifically designed to assess criticality safety issues for spent fuel rack configurations with water gaps.
- In this configuration, undermoderated fuel assemblies can have a positive temperature coefficient of reactivity.
- Water temperature varied from 20-60 °C

Schematic of Core and Detector Arrangement



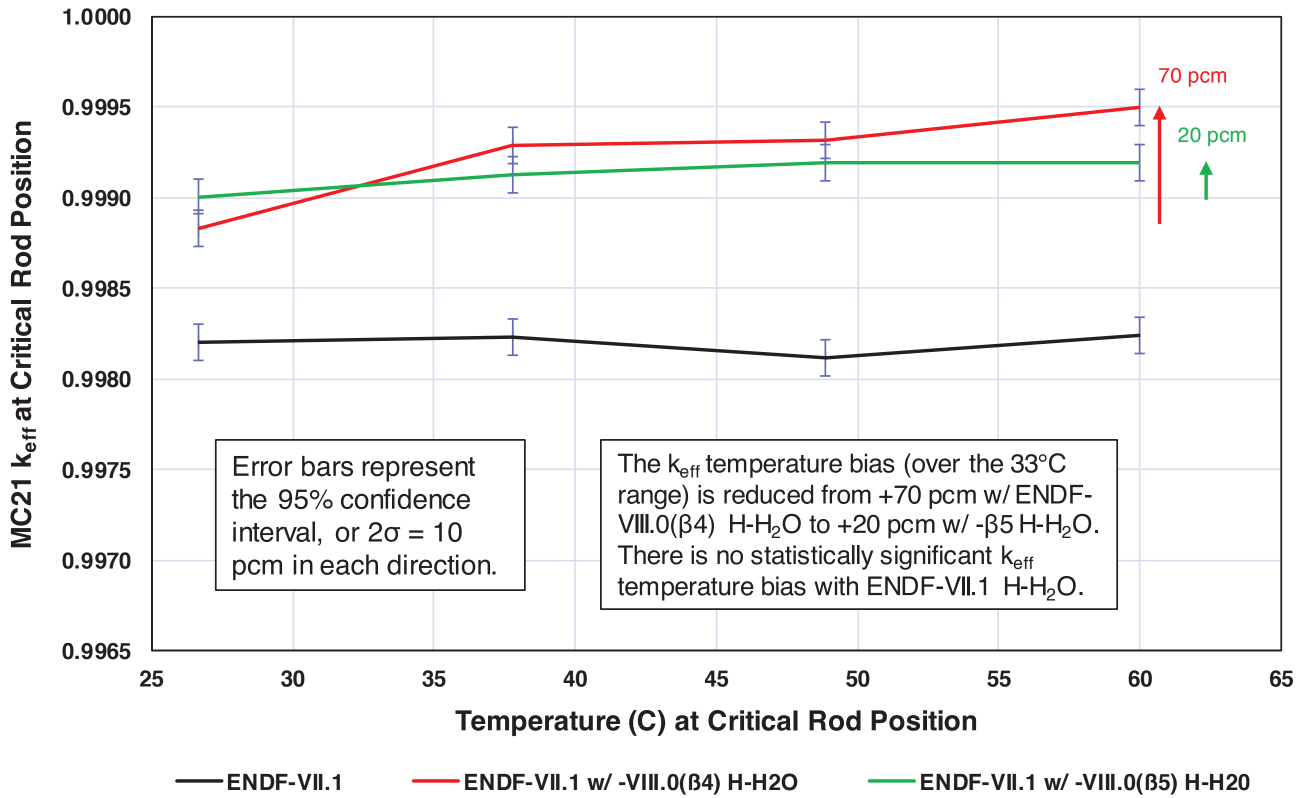
FC = Fission Chamber
SDA = ShutDown Amplifier
Log = Log Channel
PC = Pulse Channel
WRL = Wide Range Linear
RM = Reactivity Meter

Schematic of Fuel Arrangement Showing Increase in Effective Water Gap



Ref.: S. Walley et al., "Measurement of Positive Temperature Coefficients of Reactivity for Rack-like Arrangements of Reactor Fuel in the Neptune Zero Energy Facility," Proc. RRFM-2016, Berlin, March 13-17, 2016.

MC21 Calculated k_{eff} for Neptune Configuration C as a Function of Temperature Using ENDF/B-VII.1 Non-Moderator Libraries and Various $H-H_2O$ TSL Libraries



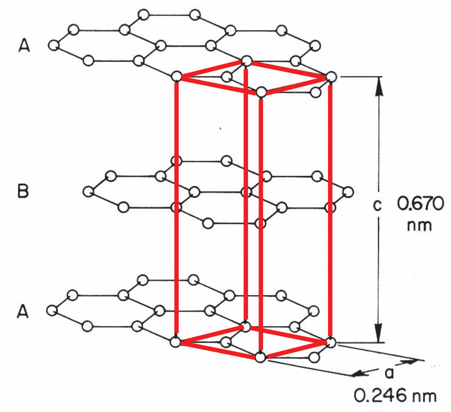
TREAT reactor@INL restarted Nov 14, 2017: need graphite

- Graphite moderated
- Materials testing
- Shut down in 1994
- After Fukushima, interest in restarting

TREAT Reactor (wikimedia commons)

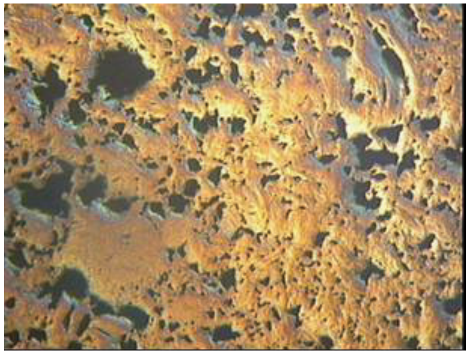
Graphite

Ideal "crystalline" graphite consists of planes (sheets) of carbon atoms arranged in a hexagonal lattice. Covalent bonding exits between intraplaner atoms, while the interplaner bonding is of the weak Van der Waals type. The planes are stacked in an "abab" sequence.



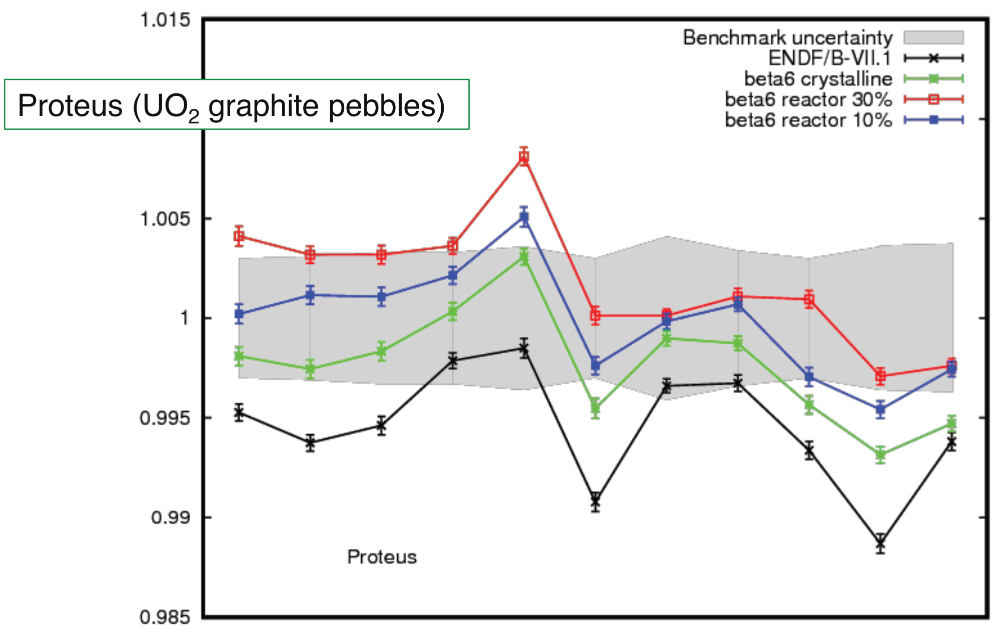
- Hexagonal Structure
- 4 atoms per unit cell
- a = b = 2.46 Å
- c = 6.7 Å
- Density = 2.25 g/cm^3

Reactor graphite consists of ideal graphite crystallites (randomly oriented) in a carbon binder. It is highly porous structure with porosity level ranging between 10% and 30%.



Nuclear Graphite (SEM at NCSU)
Density = 1.5 – 1.8 g/cm^3

PROTEUS reactor is cleanest test case for graphite



Calculation curtesy of S. Van der Marck

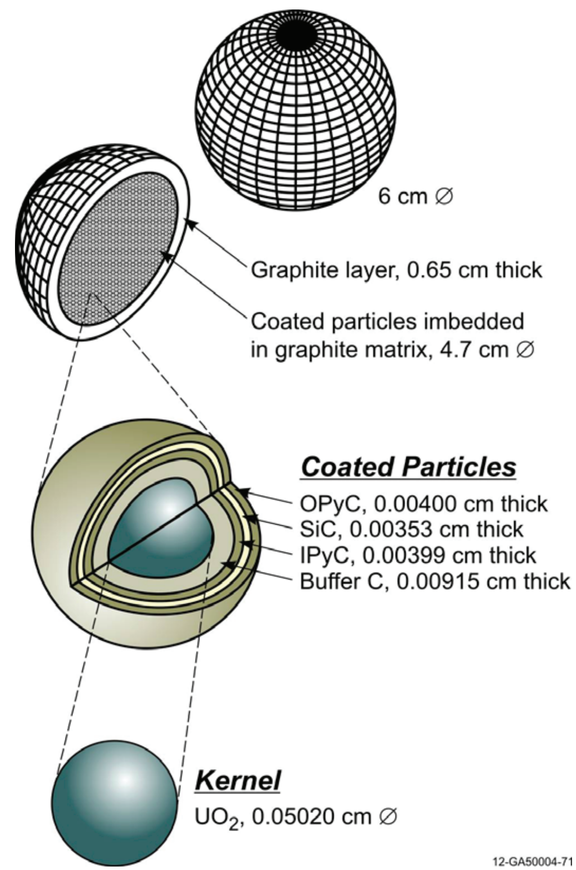


Figure 3.1-8. Fuel Pebble and TRISO Particle.

J.D. Bess, *et al.* NEA/NSC/DOC(2006)1

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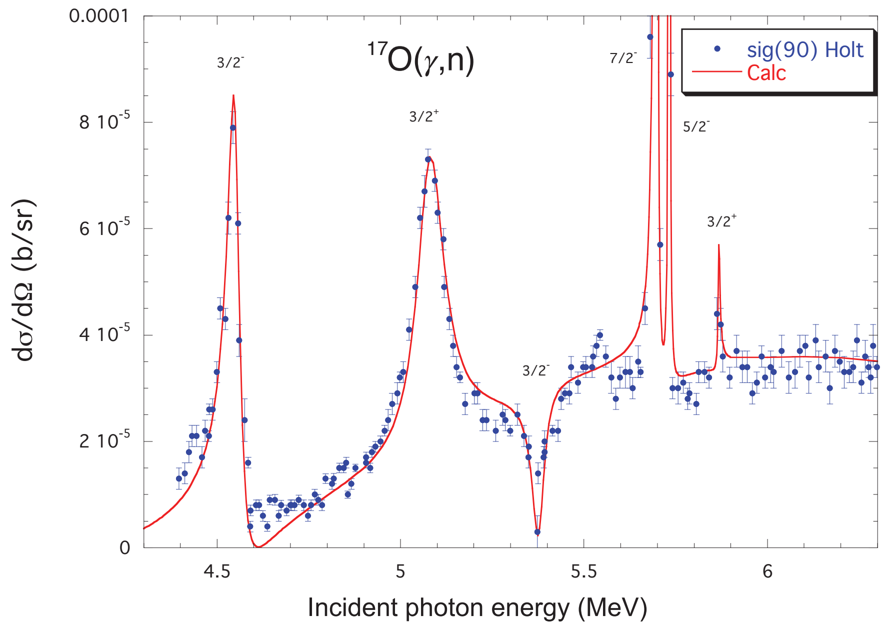
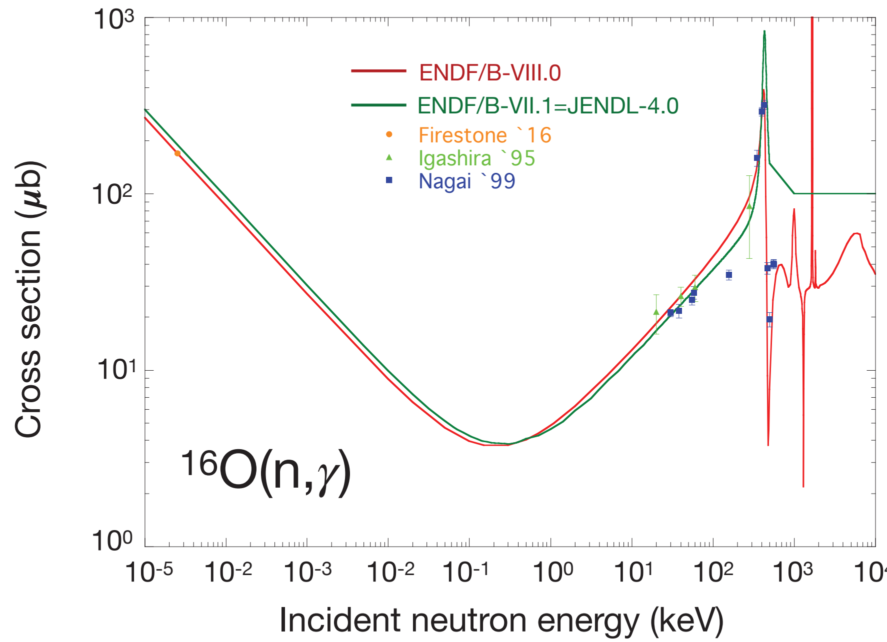
^{16}O is product of R-matrix evaluation from LANL for CIELO





Must consider all channels that connect to ^{17}O compound nucleus

D. Brown *et al.*, Nuclear Data Sheets 418, 1 (2018)

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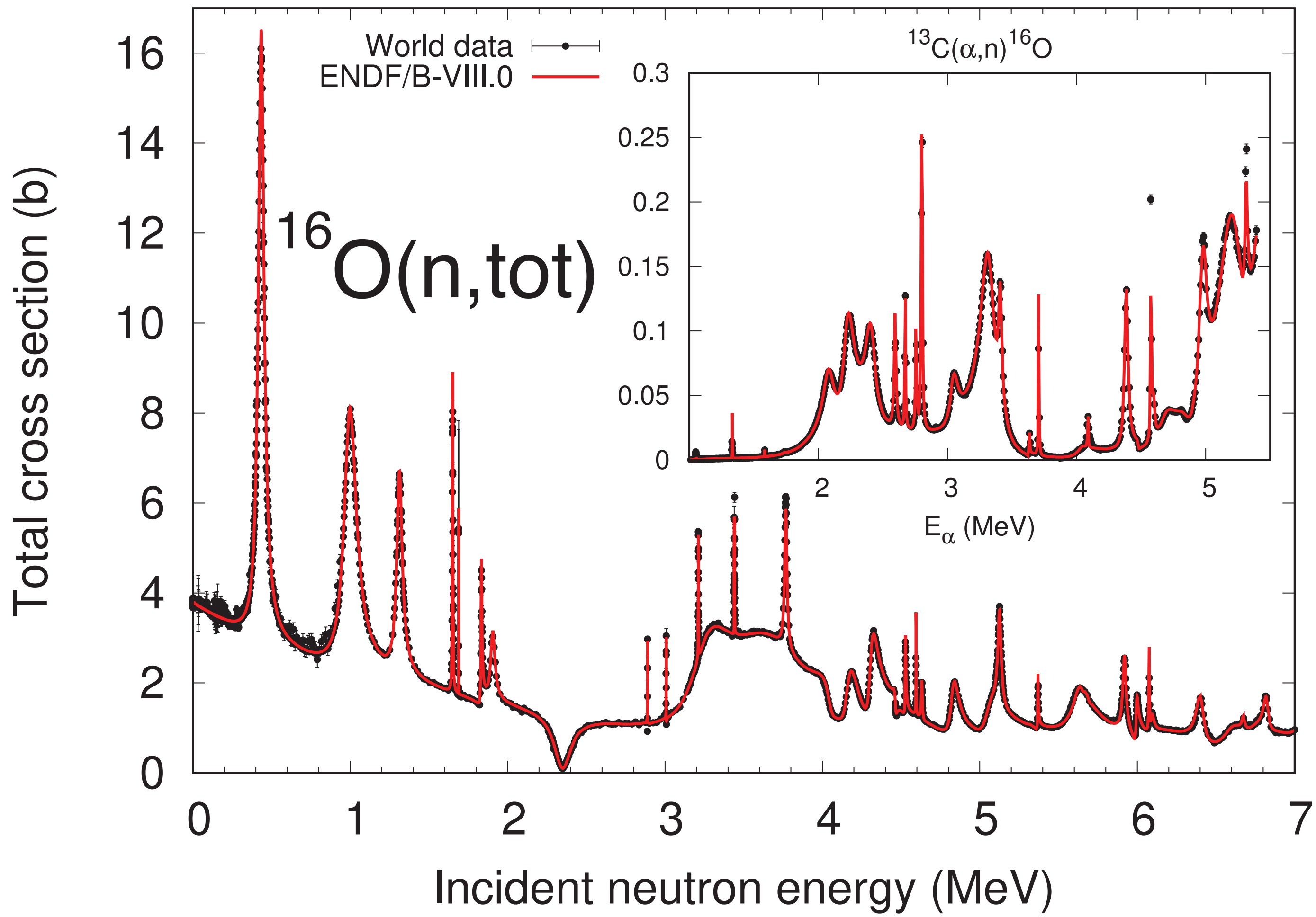
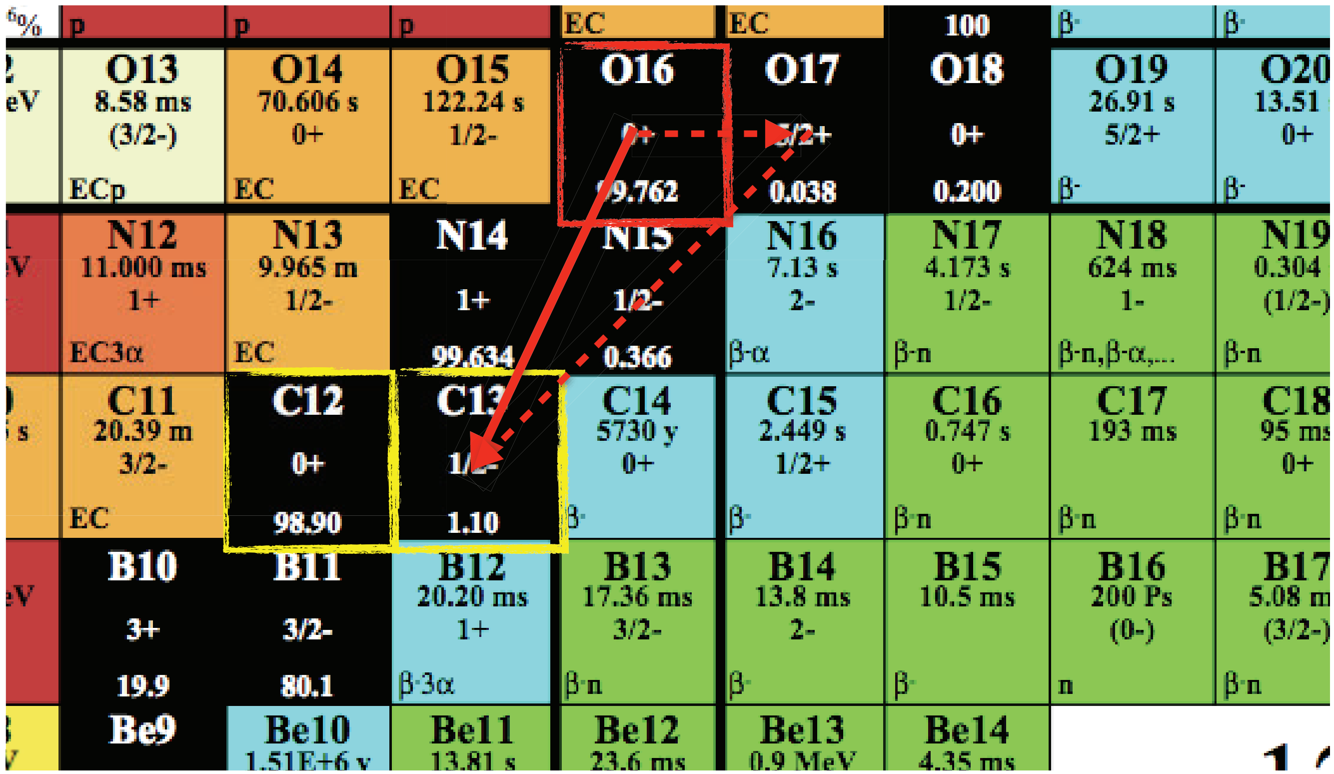
^{16}O



D. Brown *et al.*, Nuclear Data Sheets 418, 1 (2018)

Consideration of ^{16}O(n,α) requires consideration of ^{13}C(α,n) and therefore C standards

ENDF B-VIII.0



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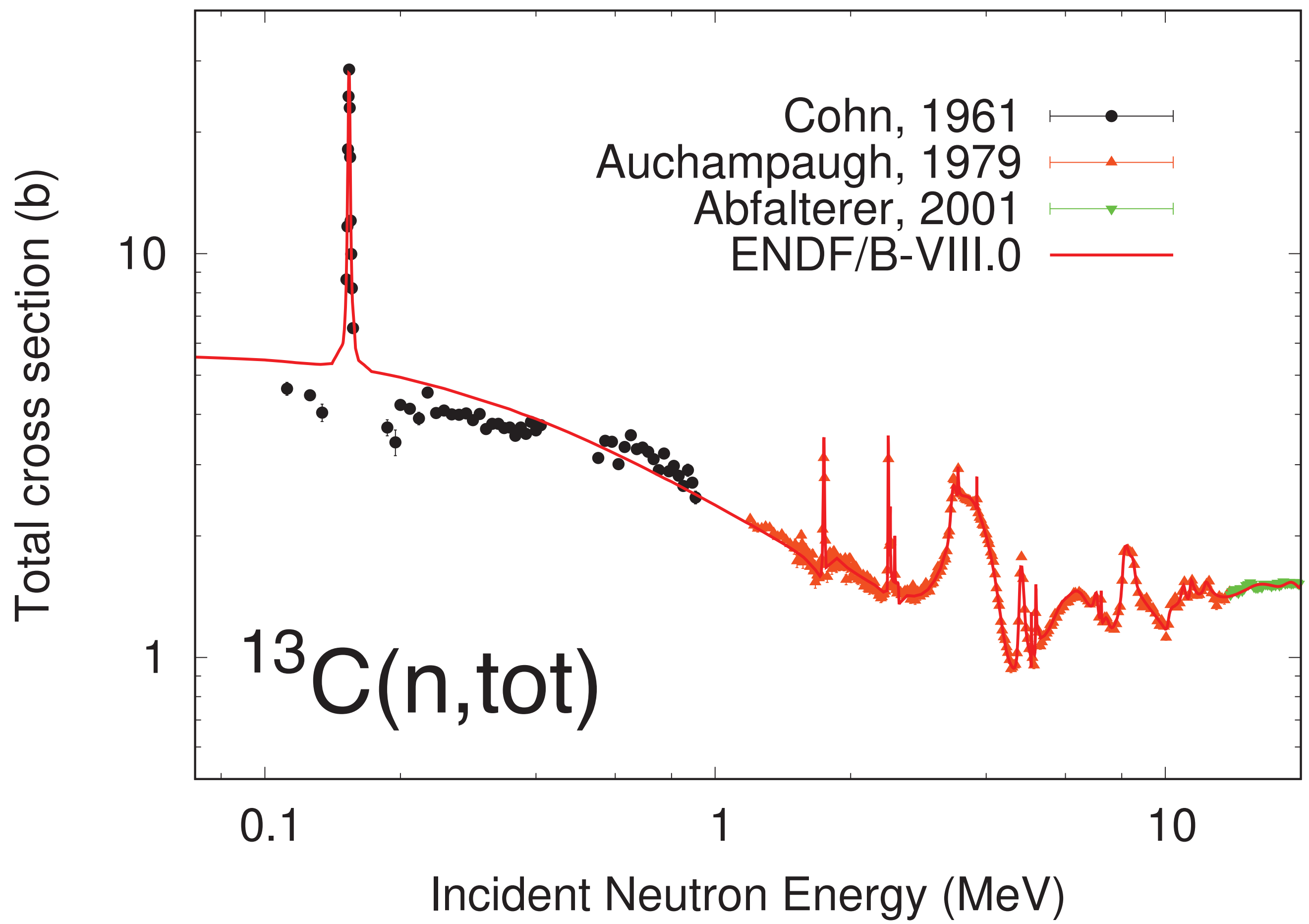
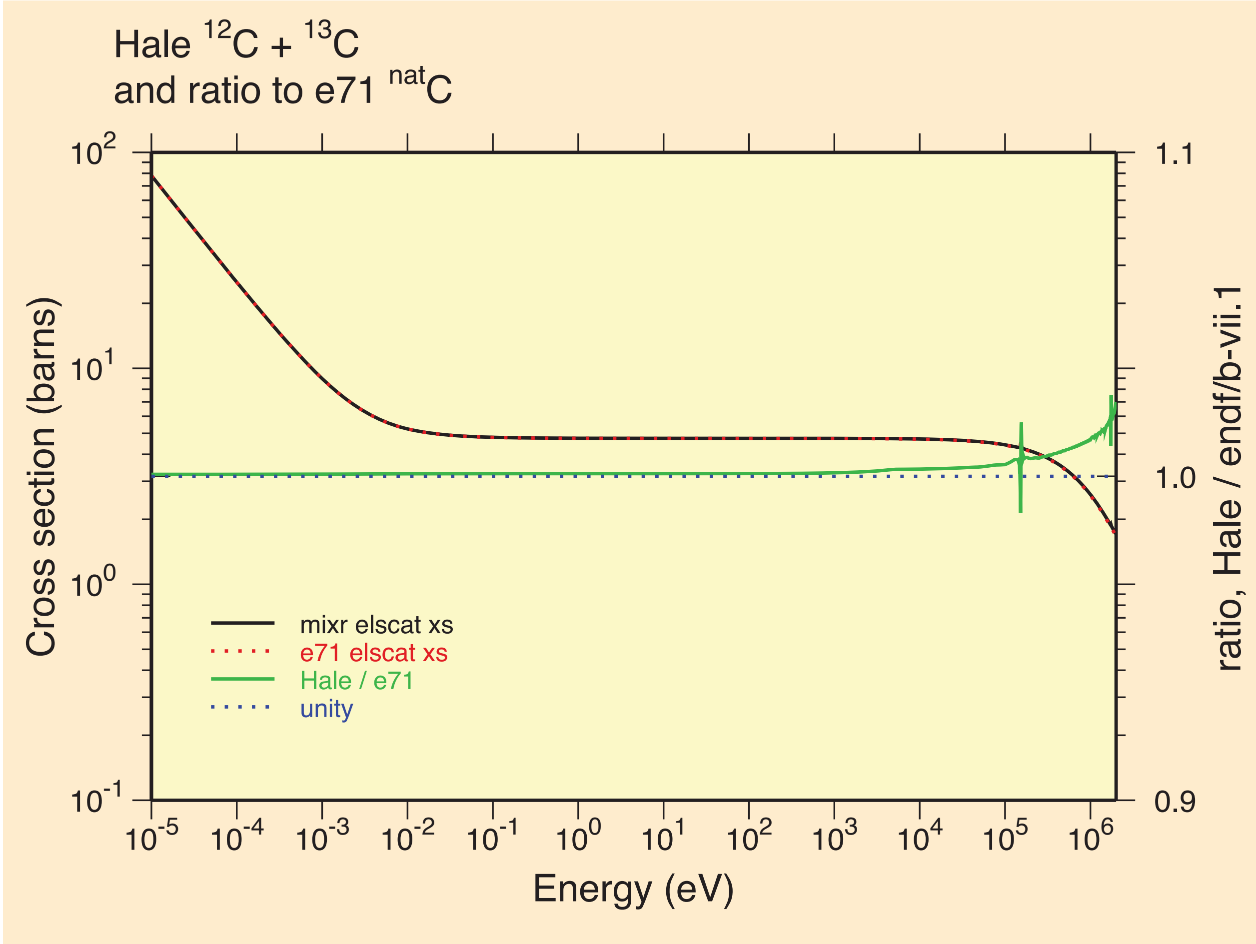
^{13}C



D. Brown *et al.*, Nuclear Data Sheets 418, 1 (2018)

Elastic cross section for natural Carbon is a Standard



G. Hale CSEWG Meeting, Nov. 2017

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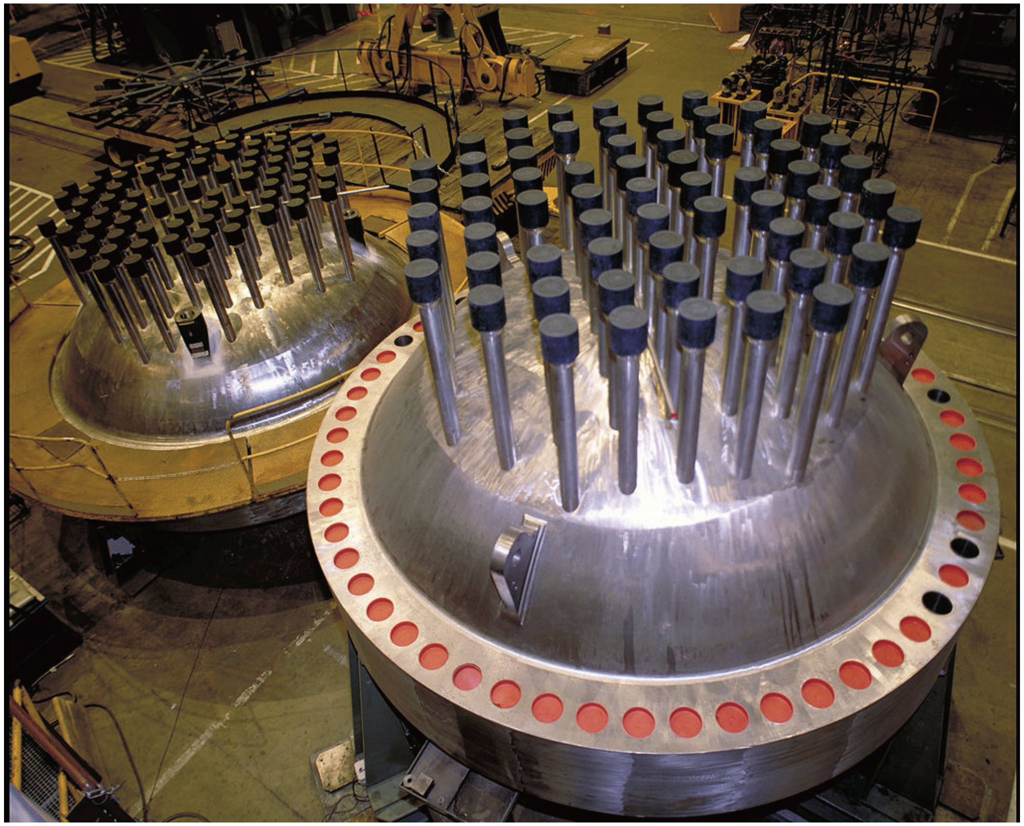
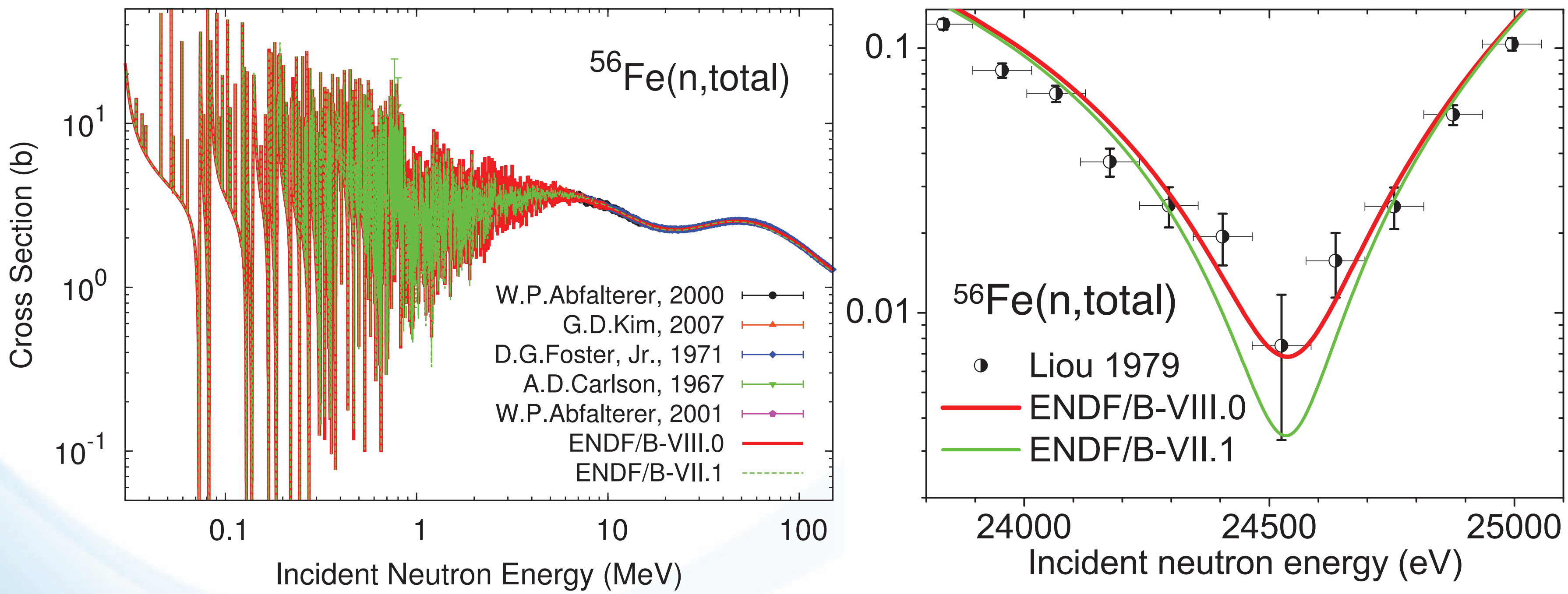
New ^{56}Fe evaluation really aimed at improving steel

- **^{56}Fe (CIELO)**
- $^{54,57,58}Fe$
- ^{59}Co
- $^{58\text{-}62,64}Ni$
- **$^{12,13}C$ (Neutron Data Standards)**



Resonances in ^{56}Fe go back to Froehner

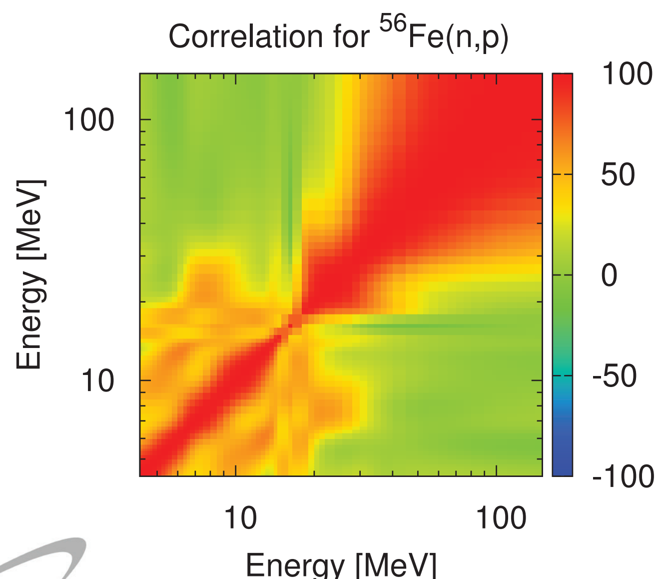
- Minor correction to the previous evaluations
- Fluctuations extend high in energy

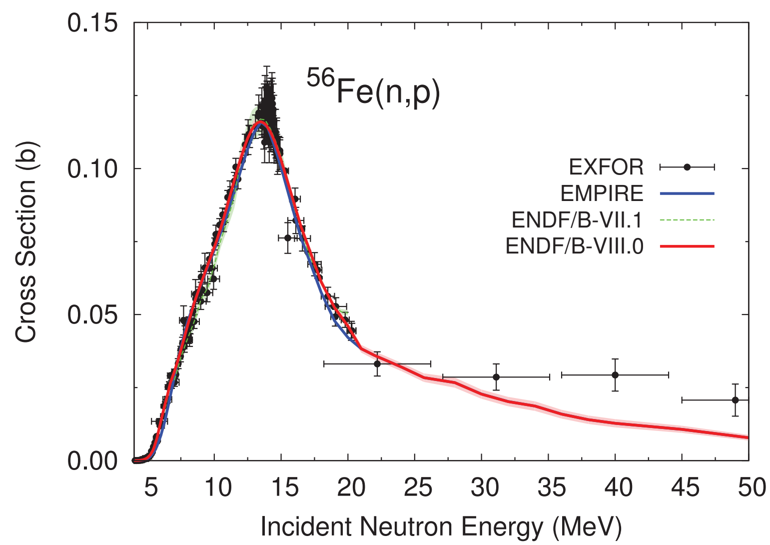


M. Herman et al., CIELO meeting, IAEA, Vienna -Dec 16-22, 2017

Fitted EMPIRE calculation to all available experiments

- Generate energy dependent covariance data on cross sections
- Angular distributions not done yet
- Allowed us to match well known dosimetry reactions





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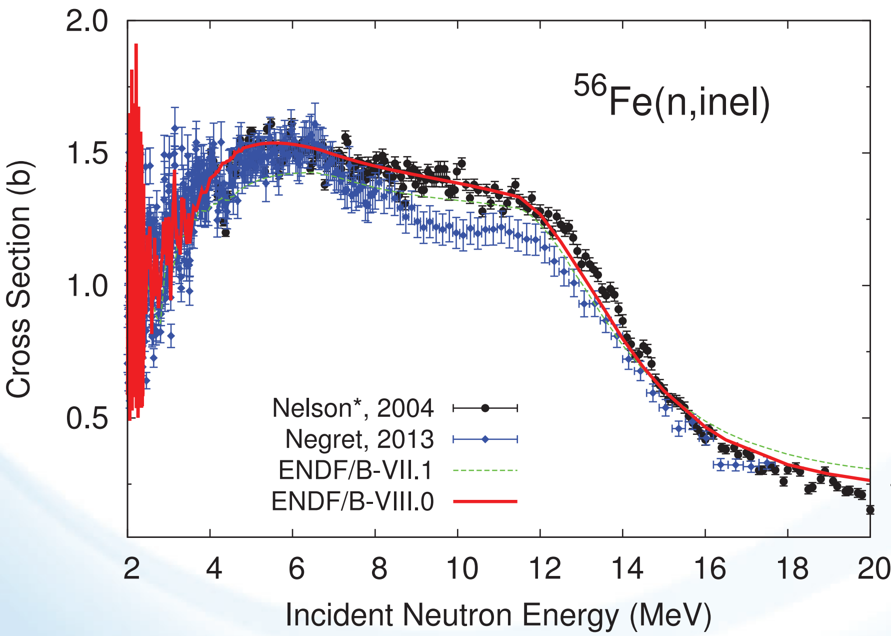
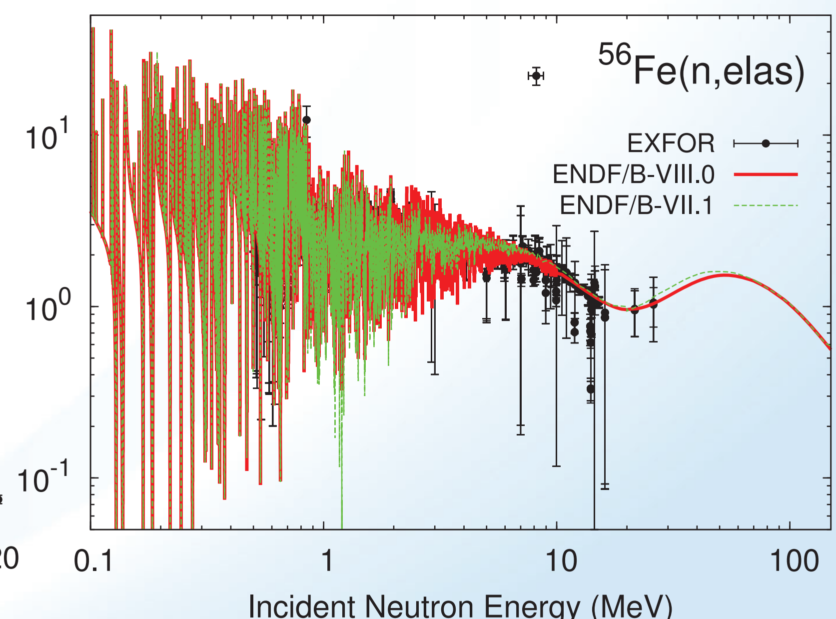
Elastic & inelastic for ^{56}Fe

Fluctuations imposed on inelastic scattering to the first and second excited states taken from experimental data

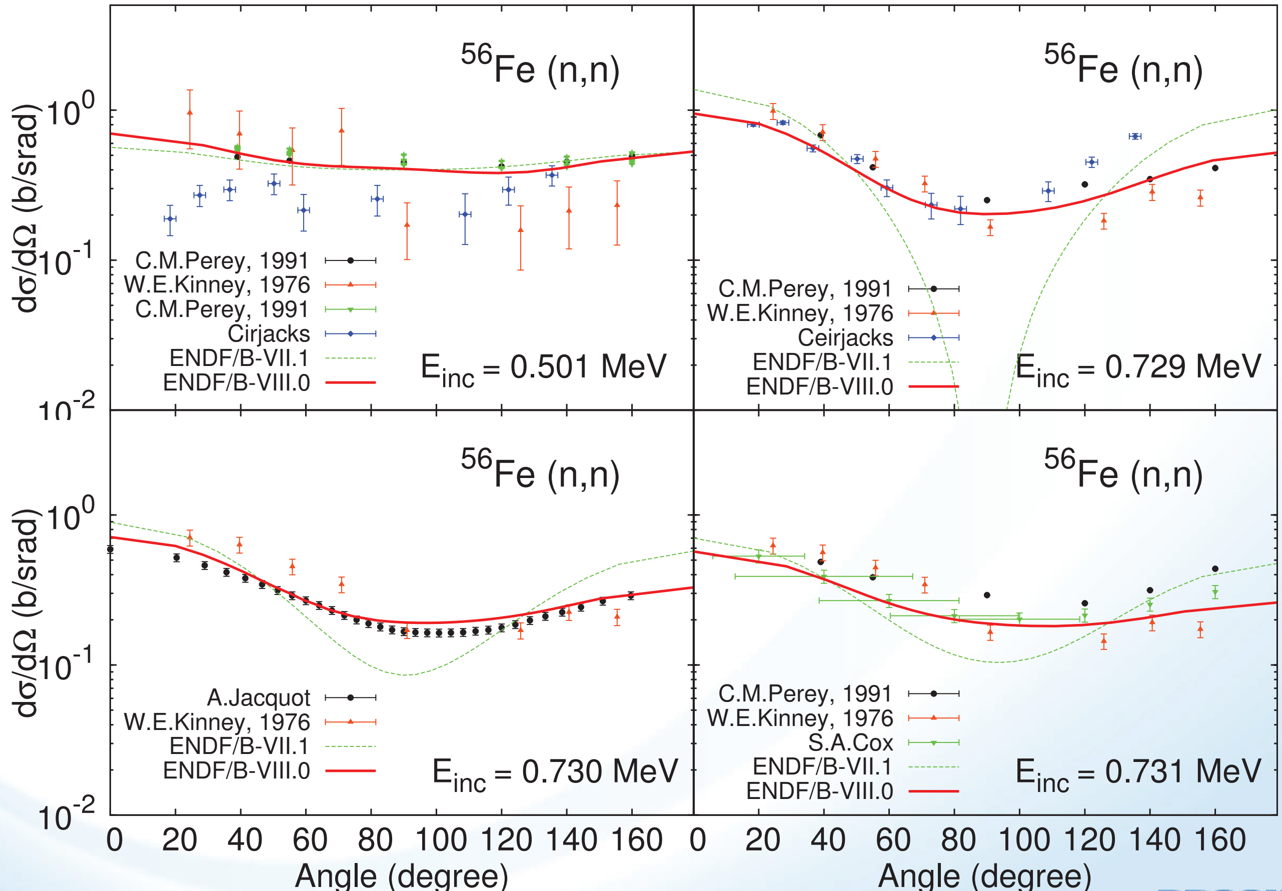


Elastic obtained by subtracting the sum of all reactions from the total



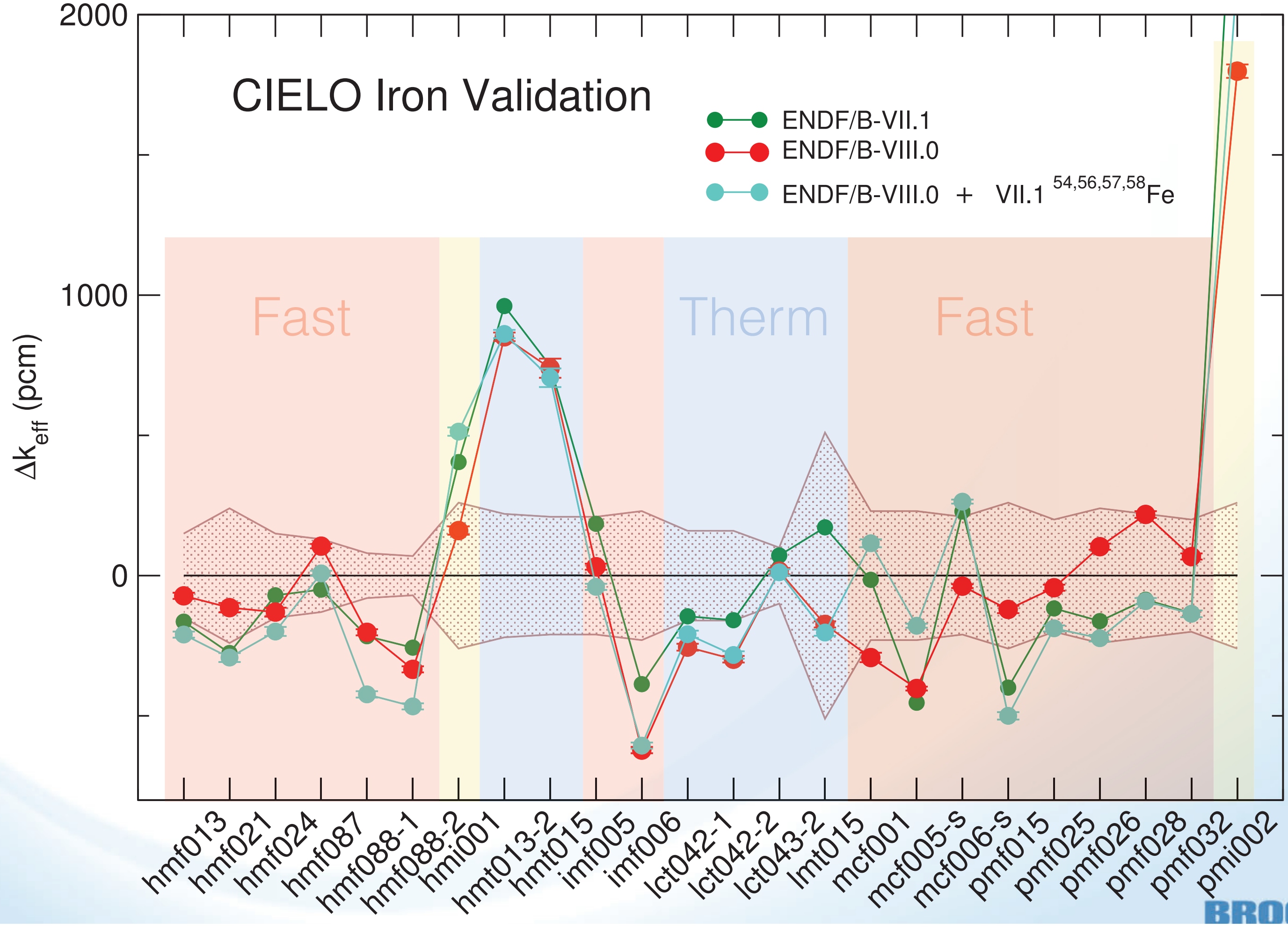
M. Herman et al., CIELO meeting,
IAEA, Vienna -Dec 16-22, 2017

Elastic angular distributions



M. Herman et al., CIELO meeting,
IAEA, Vienna -Dec 16-22, 2017

Validation in critical assemblies

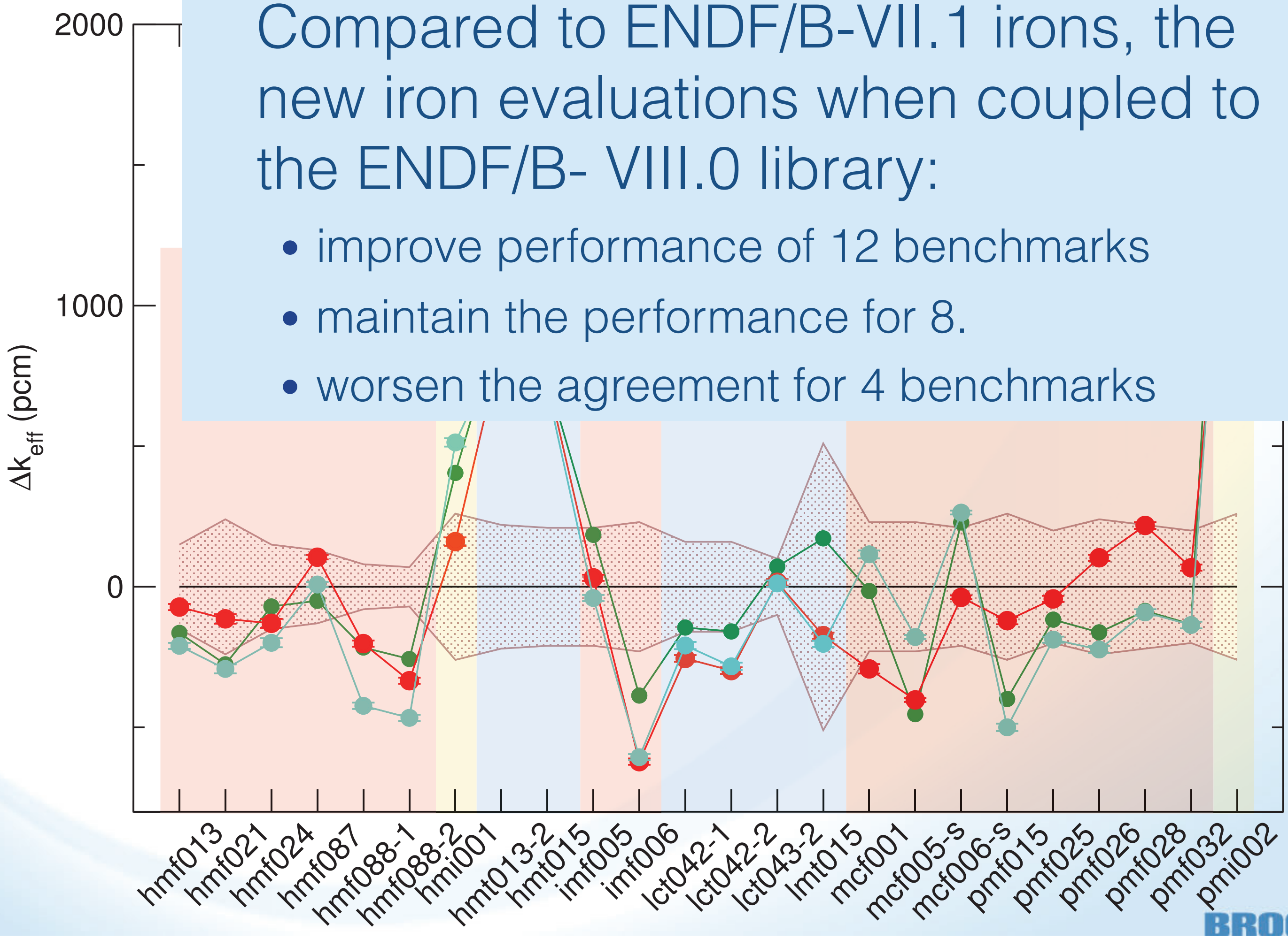


M. Herman et al., CIELO meeting,
IAEA, Vienna -Dec 16-22, 2017

Validation in critical assemblies

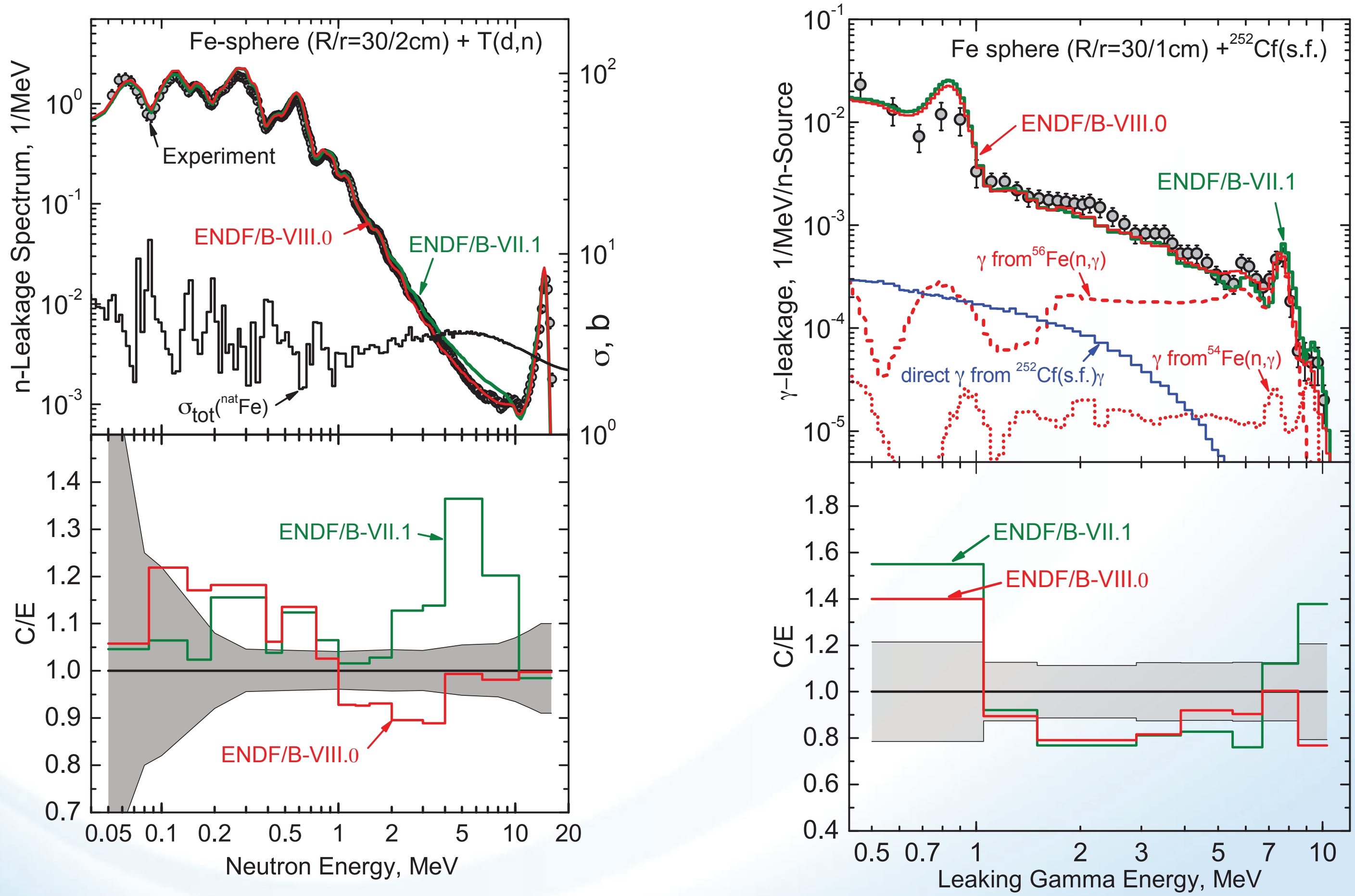
Compared to ENDF/B-VII.1 irons, the new iron evaluations when coupled to the ENDF/B- VIII.0 library:

- improve performance of 12 benchmarks
- maintain the performance for 8.
- worsen the agreement for 4 benchmarks



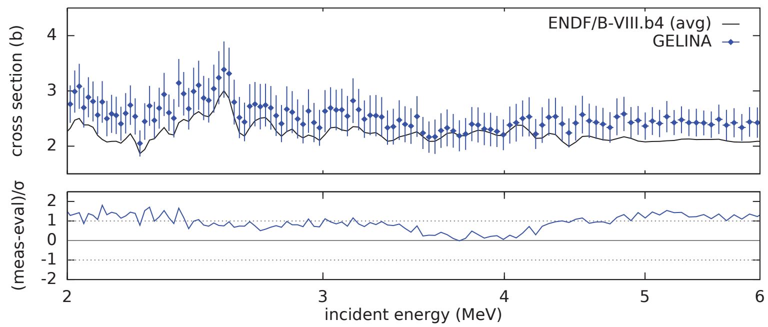
M. Herman et al., CIELO meeting, IAEA, Vienna -Dec 16-22, 2017

Validation - better results in some transmission experiments

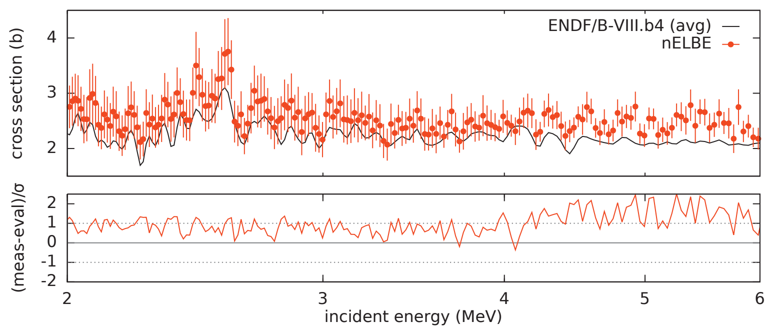


M. Herman et al., CIELO meeting,
IAEA, Vienna -Dec 16-22, 2017

…but worse in some others



(a) Comparison with the GELINA dataset.

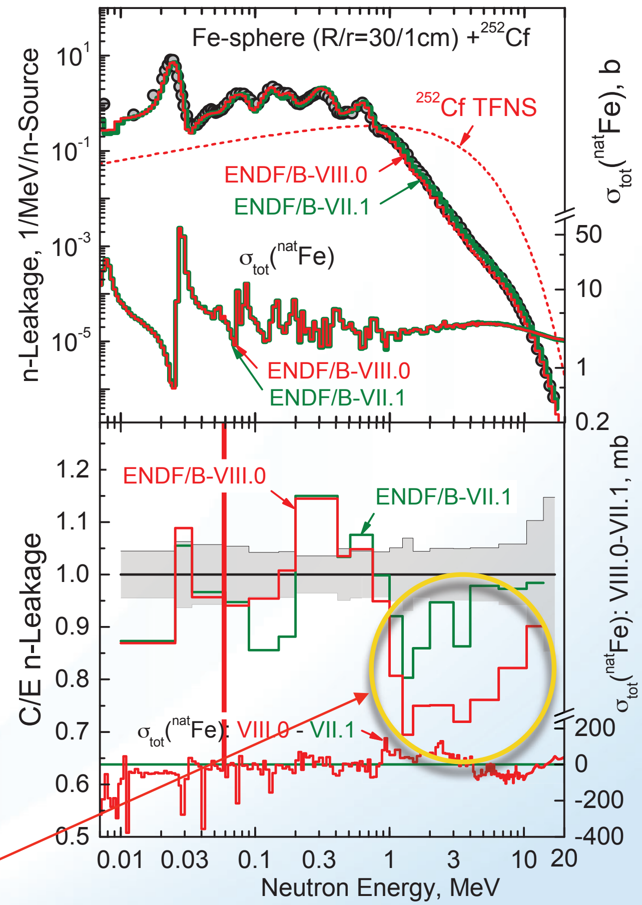


(b) Comparison with the nELBE dataset.

UNIVERSITEIT GENT

Neutron scattering cross section measurements with a new scintillator array

Elisa Pirovano



Our elastic is too low or not enough forward peaked!

M. Herman et al., CIELO meeting, IAEA, Vienna -Dec 16-22, 2017

Main messages

- **ENDF/B-VII.1 was very good**
  - k_{eff}=1 is "baked in", which surprisingly is a problem for many customers
  - k_{eff}=1 but with really big uncertainty does mean we biased the mean somehow, but were conservative with our uncertainty estimates

- **But… ENDF/B-VIII.0 is much better**

- **There is still a lot of room for improvement**

- **Files available at http://www.nndc.bnl.gov/endf/b8.0/download.html**

Happy 50 ± 1 Anniversary!*

* CSEWG formed in 1966
ENDF/B-I released in 1968