Recent Standards Work
(High Fidelity Covariances result from this Work)

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Outline of Recent Work on the Neutron Standards

- Measurements of Neutron Cross Section Standards Proposed, Underway or Completed.
  - Including results presented at the Oct 2023 Standards meeting.
- Due to time limitations for this presentation mostly very recent work will be discussed. The reference cross section areas below will not be shown:
  - Prompt γ-ray production Reference cross section measurements.
    - ^{7}Li(n, n')γ and ^{48}Ti(n,n')γ Reference cross sections.
- There is an emphasis on encouraging experiments using new methods for obtaing data to help the understanding of unrecognized systematic uncertainties.

Neutron cross section standards	
Reaction	Standards incident neutron 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 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
High energy reference fission cross sections	
Reaction	Reference incident neutron energy range
^{nat}Pb(n,f)	$\approx$ 20 MeV up to 1 GeV
^{209}Bi(n,f)	$\approx$ 20 MeV up to 1 GeV
^{235}U(n,f)	200 MeV to 1 GeV
^{238}U(n,f)	200 MeV to 1 GeV
^{239}Pu(n,f)	200 MeV to 1 GeV
Prompt γ-ray production reference cross sections	
Reaction	Reference incident neutron energy range
^{10}B(n,$\alpha_1\gamma$)	0.0253 eV to 1 MeV
^{7}Li(n,n'γ)	0.8 MeV to 8 MeV
^{48}Ti(n,n'γ)	3 MeV to 16 MeV
Thermal neutron constants	
Prompt fission neutron spectra (PFNS)	
Reaction	Reference outgoing energy range
^{235}U($n_{\rm th}$,f)	0.00001 eV – 30 MeV
^{252}Cf(sf)	0.00001 eV – 30 MeV

The thermal constants are the responsibility of the standards group because they are accurately known. A non-cross section thermal constant used as a standard is --------- $\overline{\nu}_{tot}$ of ^{252}Cf(sf)

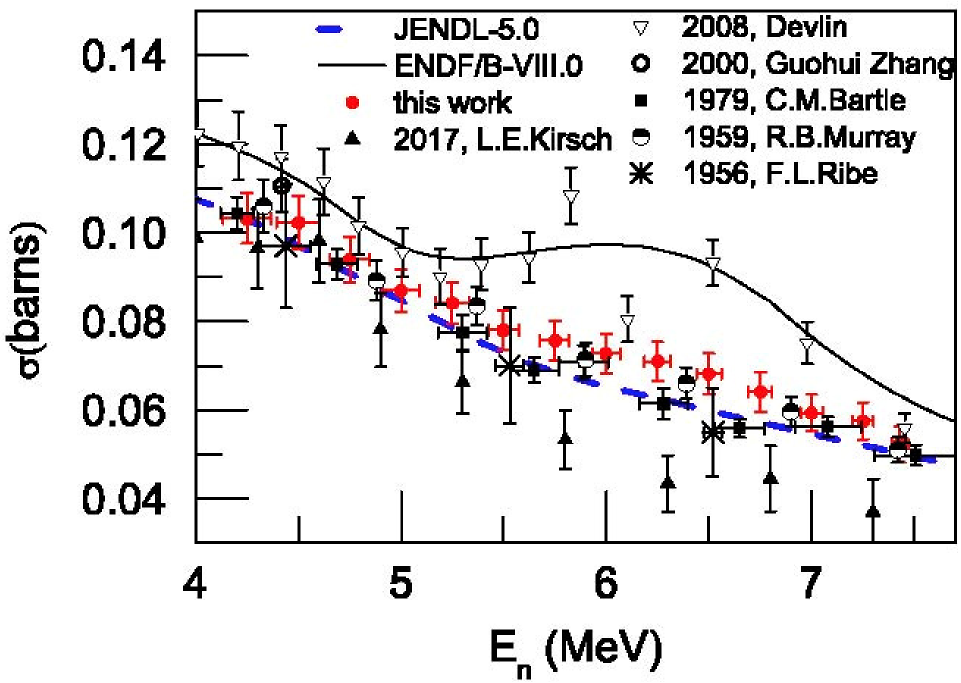
The subject of Denise's talk

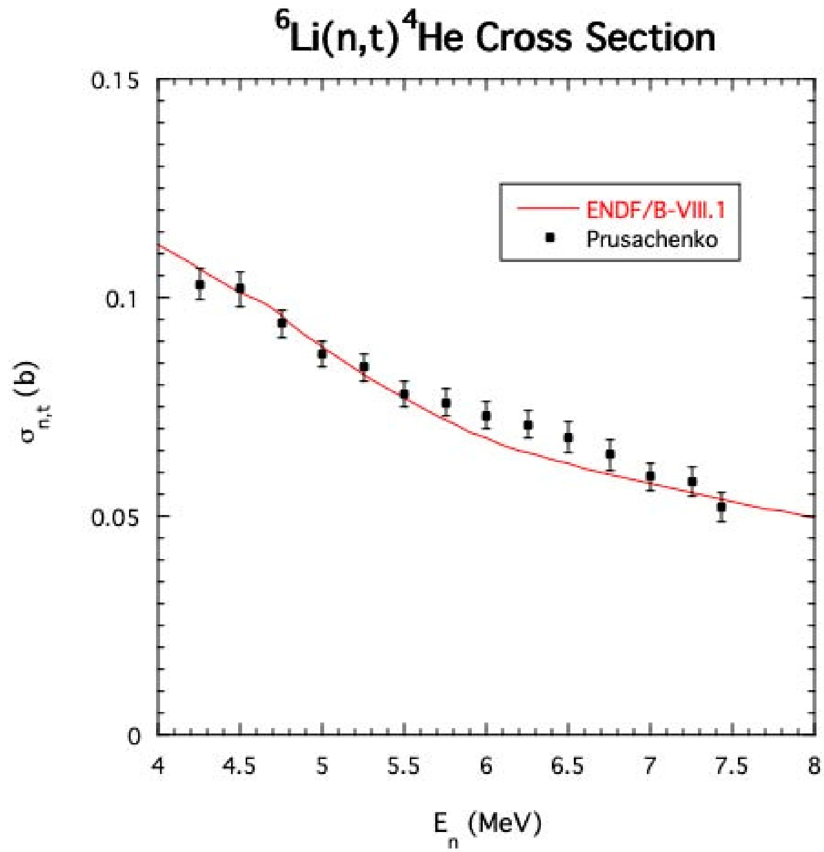
^{6}Li(n,t) Measurements

- New measurements were made of the ^{6}Li(n,t) cross section relative to the ^{235}U(n,f) standard at IPPE by Prusachenko.
  - A pulsed quasi-monoenergetic neutron beam from the ^{2}H(d,n)^{3}He reaction was used to obtain measurements for energies from 4.75 to 7.5 MeV.
  - Though these data are significantly above the present standards energy region, they will have an impact through the use of R-Matrix analyses and can possibly allow extension of the standard..

- Measurements are being made by Anastasiou et al. of the ^{235}U(n,f)/^{6}Li(n,t) cross section ratio with the NIFFTE fission TPC.
  - The expected energy range is from about 0.1 MeV up to 3 MeV (possibly 4 MeV). The data will impact evaluations of both the ^{235}U(n,f) and ^{6}Li(n,t) cross sections.
  - Some results of this work were given by Anastasiou at the ND2022 conference and the 2023 standards meeting .
    - The present results are very preliminary.

$^6Li(n,t)$ Cross Section Measurements by Prusachenko

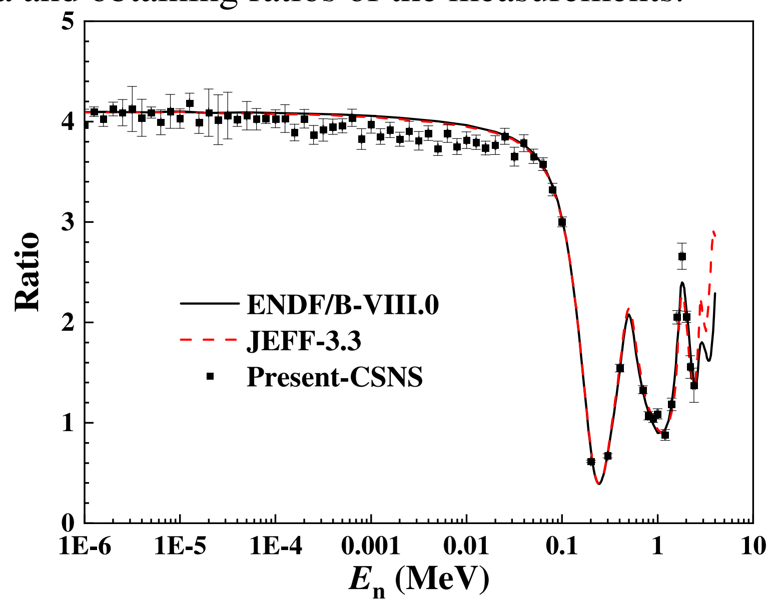




^{6}Li(n,t) and ^{10}B(n,α) and ^{10}B(n,α_1) Measurements at CSNS

- Extensive measurements of the ^{6}Li(n,t) angular distribution by Bai et al. for energies from 1 eV to 3 MeV
- Angular distribution data were also obtained by Jiang et al. for the boron standards from 1 eV to 2.5 MeV
  - For both of these experiments there are some concerns due to the use of the ^{235}U(n, f) cross section for fluence determination where it is not a standard.
  - Since the experimental conditions for the two measurements were the same, the fluence concern was eliminated by re-processed the experimental data and obtaining ratios of the measurements.

The integrated data shown here will be used using GMApy, a Python based analysis replacing the GMA analysis formerly used. The angular distribution shape data for the two experiments will be used in R-matrix analyses. These data will be used with earlier measurements to obtain final results.



The ^{6}Li angular distribution data can be seen in Huaiyong Bai, *et al* Chinese Phys. C **44**, 2020 014003.
The ^{10}B angular distribution data can be seen in The Haoyu Jiang *et al* *Chinese Phys. C* **43,** 2019 124002.

The ratios of the angle-integrated cross sections for the ^{10}B(n, α)^{7}Li divided by the ^{6}Li(n, t)^{4}He reactions *vs* energy

Measurements Directly Related to the $^{10}B(n,\alpha)$ Standard and $^{10}B(n,\alpha_1\gamma)$ Measurements

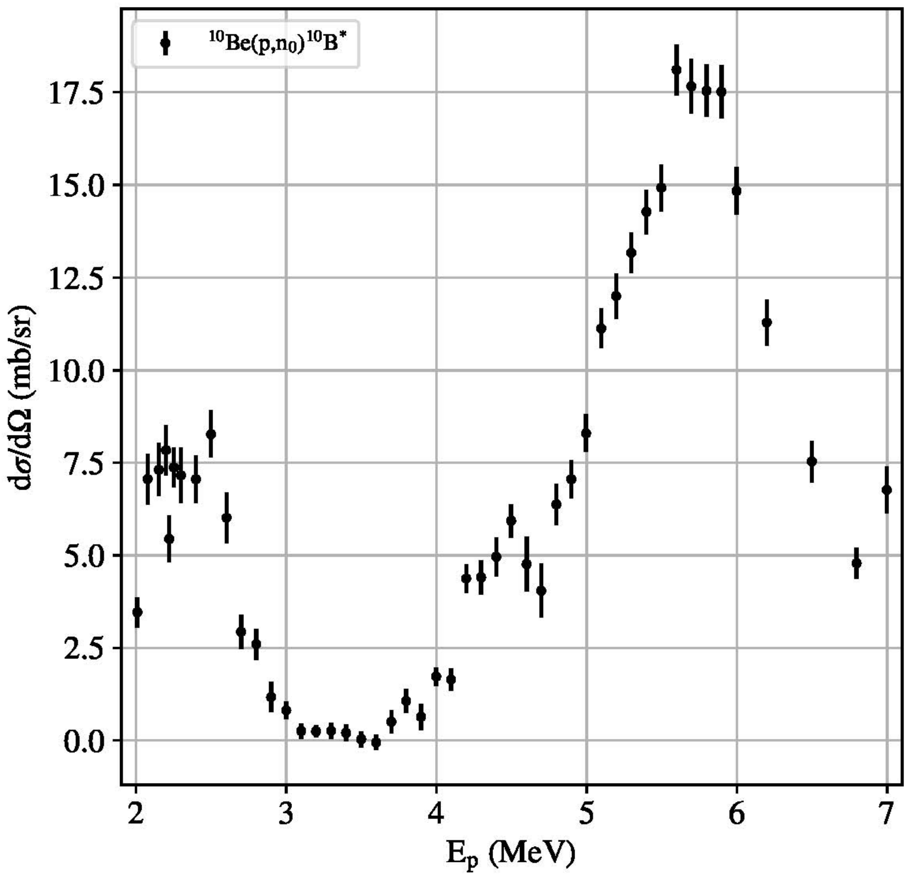
- Very recent work at Ohio University.
  - Several measurements of the $^{10}Be(p,n)^{10}B$ reaction in the thesis of Jones-Aberty.

- Massey *et al.* at Ohio University have measured $^{10}B(n,Z)$ reactions for neutron energies from 2 to 20 MeV.
  - The work was done at the LANSCE WNR facility (Phys. Rev. C **105**, 054612 (2022)).

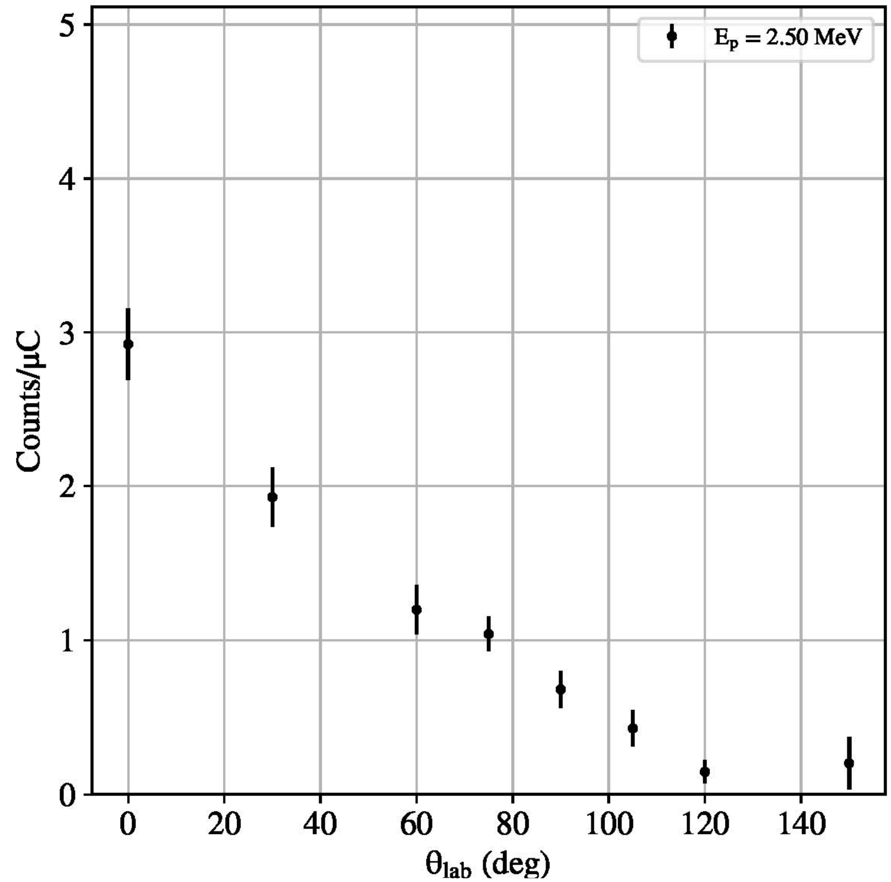
- All of these data can be used in R-matrix fits to improve the $^{10}B(n,\alpha)$ standards.

Measurements Directly Related to the $^{10}B(n,\alpha)$ Standard and $^{10}B(n,\alpha_1\gamma)$ Measurements

Measurements of the $^{10}Be(p,n_0)^{10}B$ diferential cross section at 0° by Jones-Aberty



Measurements of the $^{10}Be(p,n_0)^{10}B$ angular distribution versus θ_{lab} by Jones-Aberty



$^{10}B(n,x)^7Li$ and Li Measurements

- Extension in the energy ranges to above 1 MeV of the $^6Li(n,t)$ and ^{10}B standards may be possible with the work by Anastasiou *et al*., Bai *et al*., Jiang *et al*. and the Ohio University data.
- The It is important to extend the energy range of these standards to above 1 MeV, the present limit of this standard. That would allow convenient overlap with the H(n,n) standard.

C(n,n) Cross Section

- The most recent evaluation of the carbon standard by Hale was done by combining ^{12}C and ^{13}C R-matrix evaluations to obtain the elemental cross section that is the standard.

- Measurements have been made by Vanhoy on ^{13}C that should improve the new evaluation of the carbon Standard.

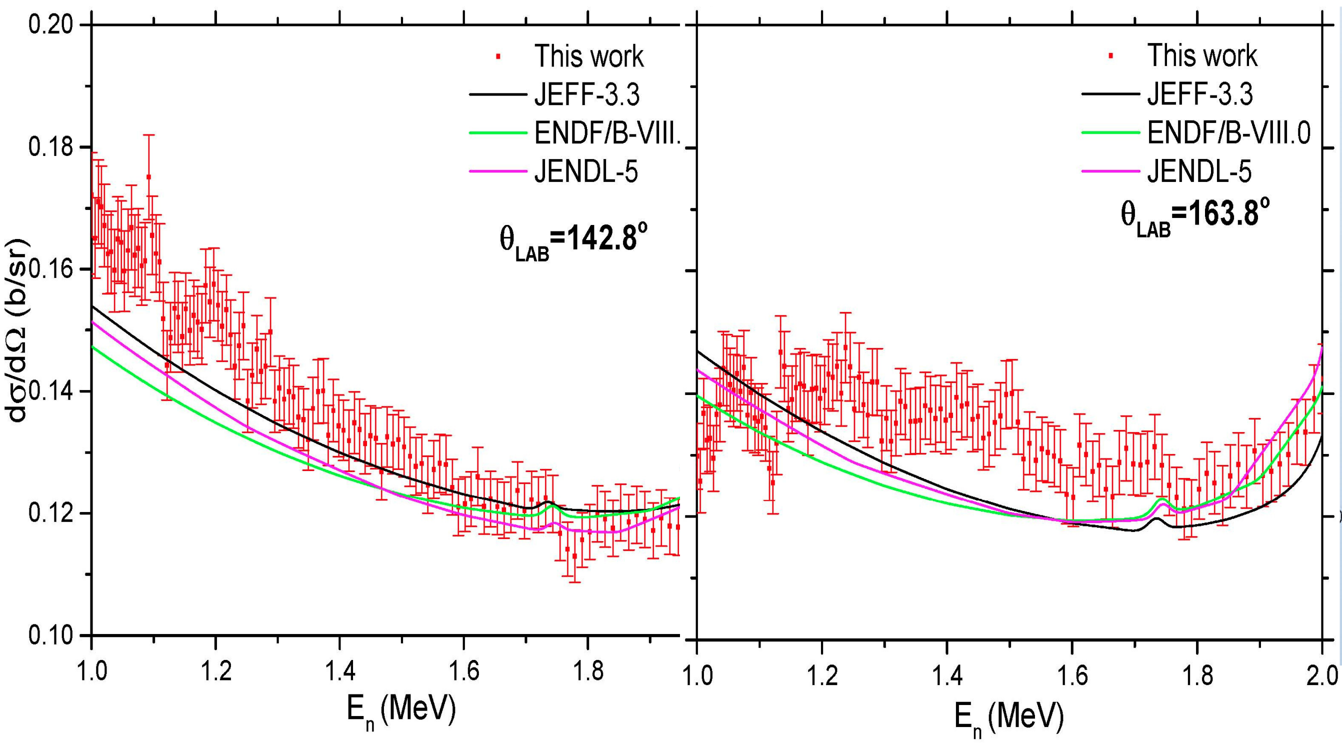
- Carbon scattering measurements by Kelly at LANL are also underway that should impact the new evaluation.

- The most recent angular distribution measurements have been completed at GELINA by Gkatis *et al.*
  - Energies were covered from 10 mV to 20 MeV (thus covering the standards energy range).
  - 8 angles were measured between 16.2 and 163.8 degrees.

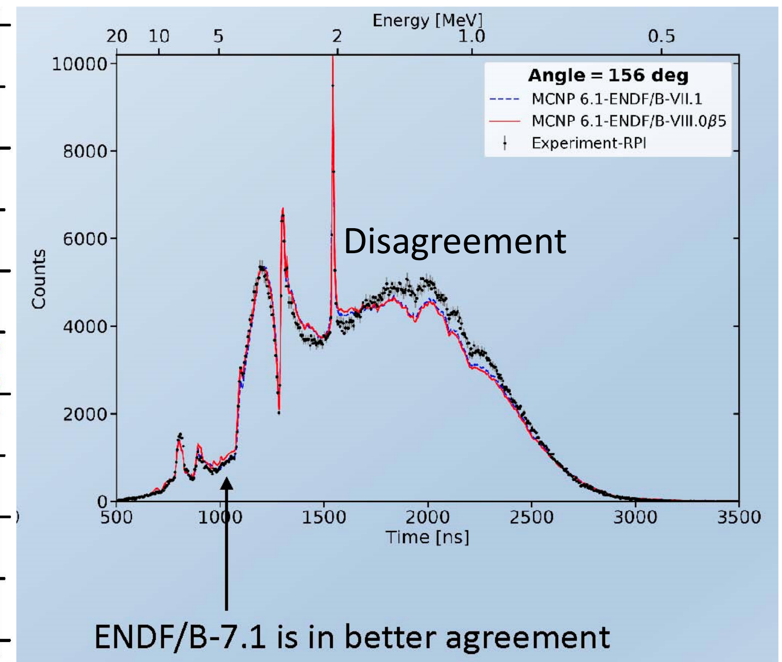
C(n,n) Cross Section

- Comparison of Angular distribution measurements by Gkatis *et al.* with Danon

Gelina Measurements by Gkatis et al.



RPI Measurements by Danon



Uranium Fission Cross Section Measurements

- Absolute measurements by Manna *et al. in* the n_TOF collaboration were made of the ^{235}U(n,f) cross section relative to hydrogen scattering from 20 MeV to 450 MeV.
  - These data have been finalized and the publication is just now available.
  - The results up to 450 MeV are similar to those of the ^{235}U(n,f) Reference cross section The present standard is limited to 200 MeV. **There is a strong need for these measurements to higher neutron energies.**
  - They had to contend with problems at higher neutron energies where inelastic scattering produces proton energies such that it is difficult to separate the elastic and inelastic protons.

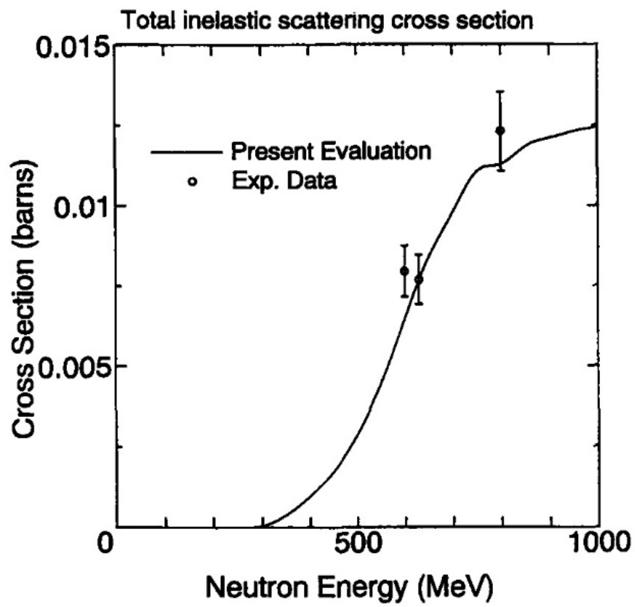
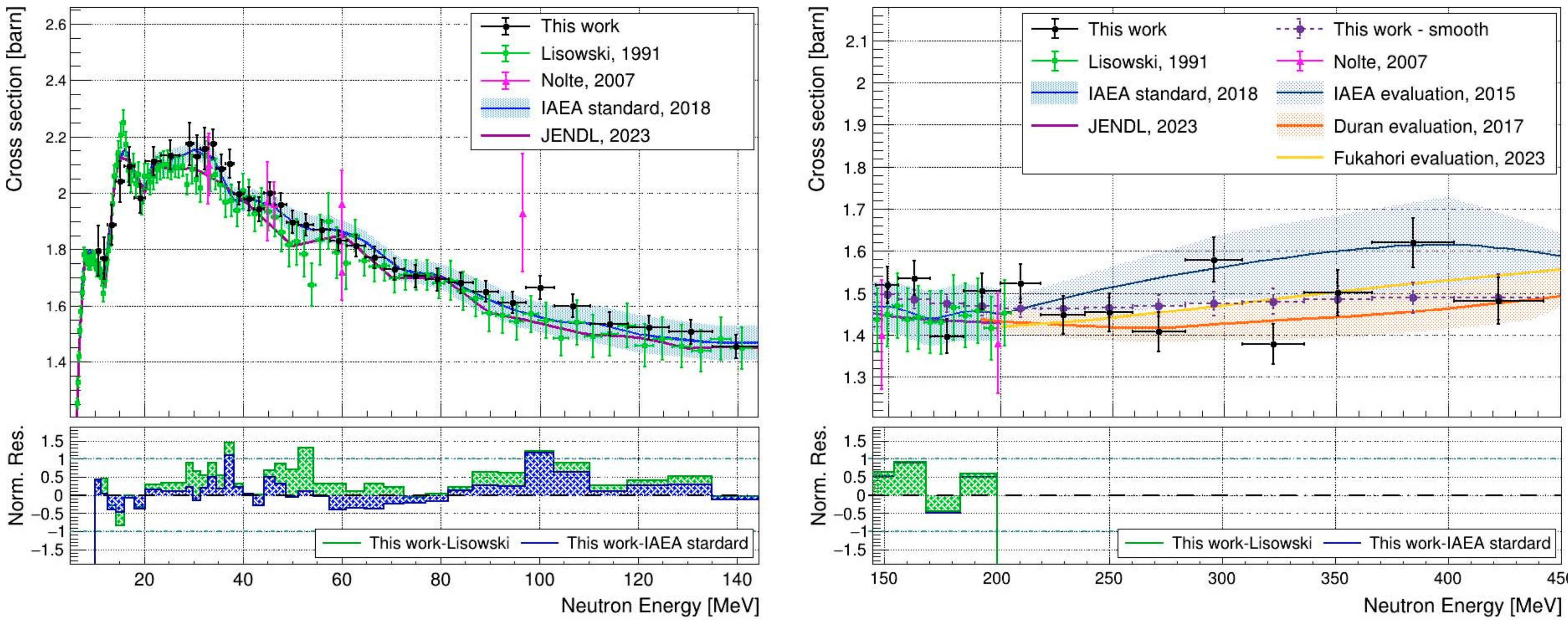


Fig. 6 Total inelastic scattering cross section of hydrogen

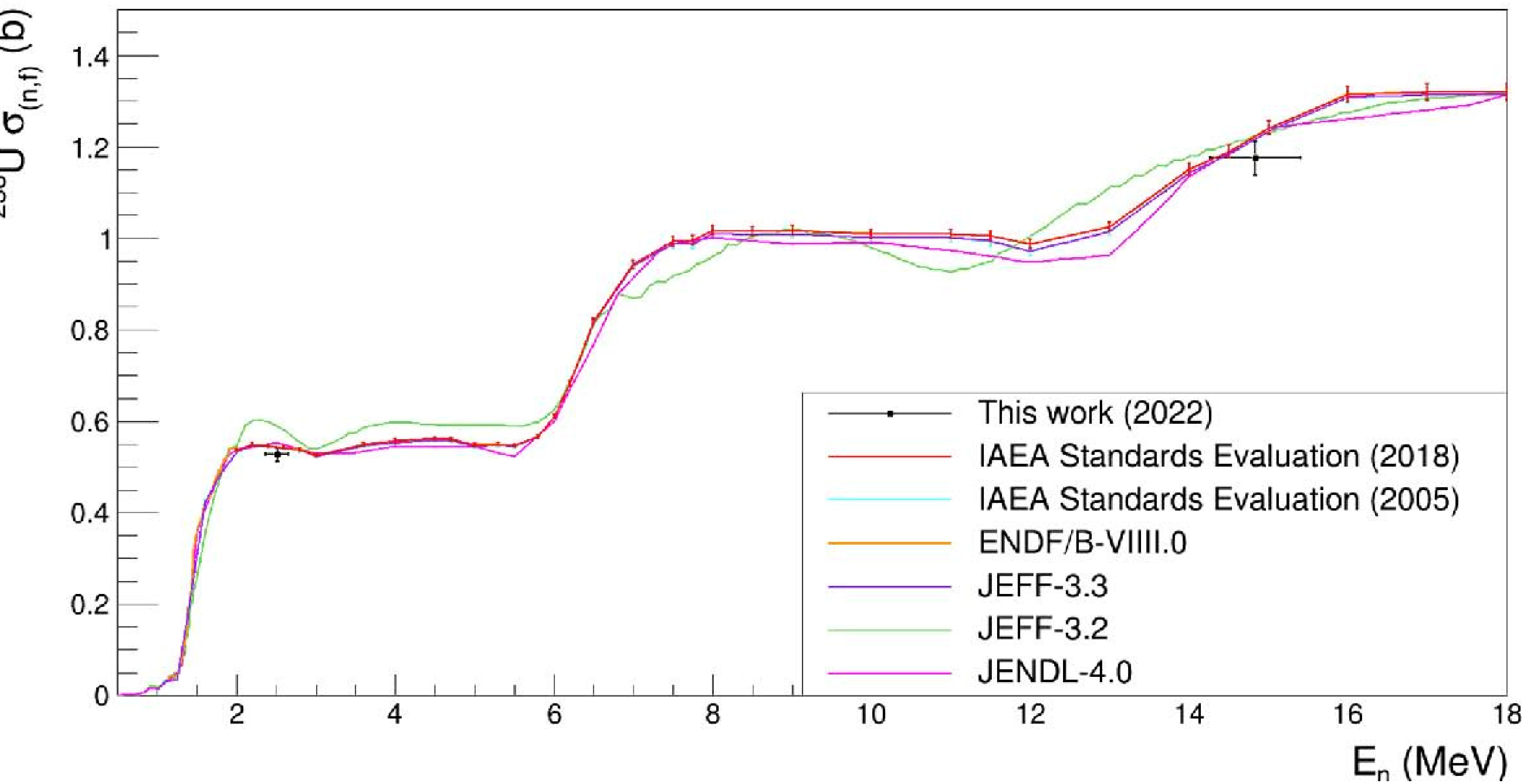
^{235}U(n,f) Cross Section Measurements by Manna et al.



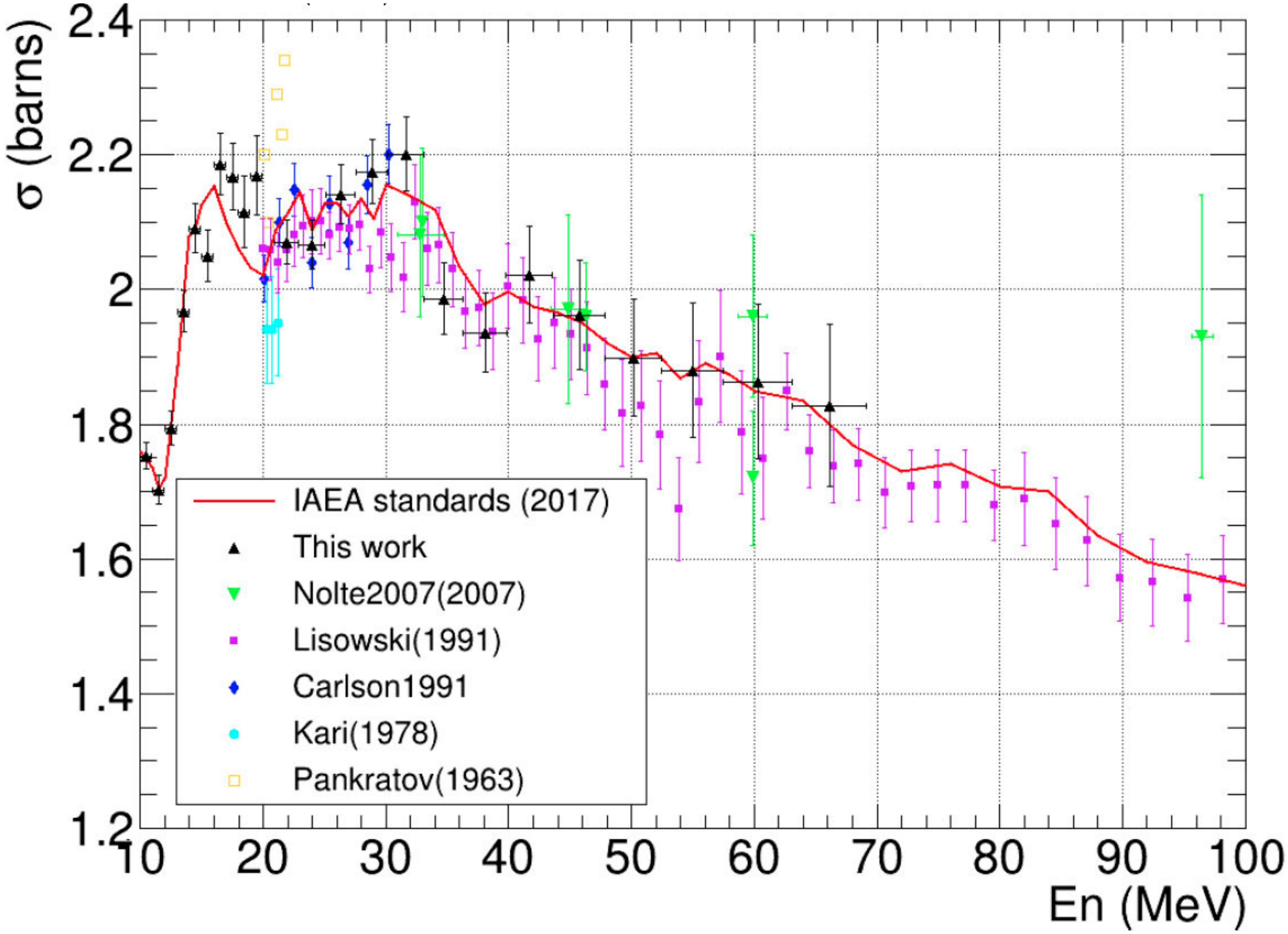
Uranium Fission Cross Section Measurements (cont.)

- New measurements at PTB of the $^{238}U(n,f)$ fission cross section by Belloni.
  - Made at 2.5 and 14.8 MeV relative to hydrogen scattering.
- Measurements at the China Spallation Neutron Source.
  - $^{235}U(n,f)$ cross sections measurements by Chen.
    - Relative to the hydrogen scattering standard-shape data.
    - For the extension up to 70 MeV problems were noted due to the use of double bunches. The unfolding causes a problem that is worsened when statistical uncertainties are large.
    - More work is planned.
    - They now extend from 10 to 66 MeV.
  - The $^{238}U(n,f)/^{235}U(n,f)$ cross section ratio by Wen, *et al*. from 1 to 20 MeV.

^{238}U(n,f) Cross Section Measurements by Belloni *et a*l. at PTB



$^{235}U(n,f)$ Cross Section Measurements by Chen at CSNS Facility



Use of Integral Data

- Beginning with the standards for the ENDF/B-VI evaluation, very “clean” integral data were used.

- The data used were measurements of the ^{235}U(n,f) and ^{239}Pu(n,f) cross sections in the ^{252}Cf spontaneous fission neutron field (Spectrum Averaged Cross Sections, SACSs).

- Since there is a relatively small change in the cross section for these nuclides over most of the energy range of the ^{252}Cf spectrum, an accurate determination of the cross section is possible. The result is also only weakly dependent on the uncertainty in the spectrum shape. **These integral data basically help provide normalization for the standards evaluation.**

- It was initially not possible to use ratios of SACS since GMA could not handle them.

  - With ratios, the dependence on neutron fluence is **removed.**

- A new Python based code was written by Schnabel (gmapy) so that ratios can now being used.

  - Using the the ^{239}Pu(n,f)/ ^{235}U(n,f) SACS ratio data, the ^{238}U(n,f)/ ^{235}U(n,f) SACS ratio data and the data in the GMA data base has led to **a new preliminary evaluation** of the standard cross sections. For this evaluation an energy dependent USU is being investigated. A number of energy regions are selected and USU is determined for each region as an average for the different datasets in that region,

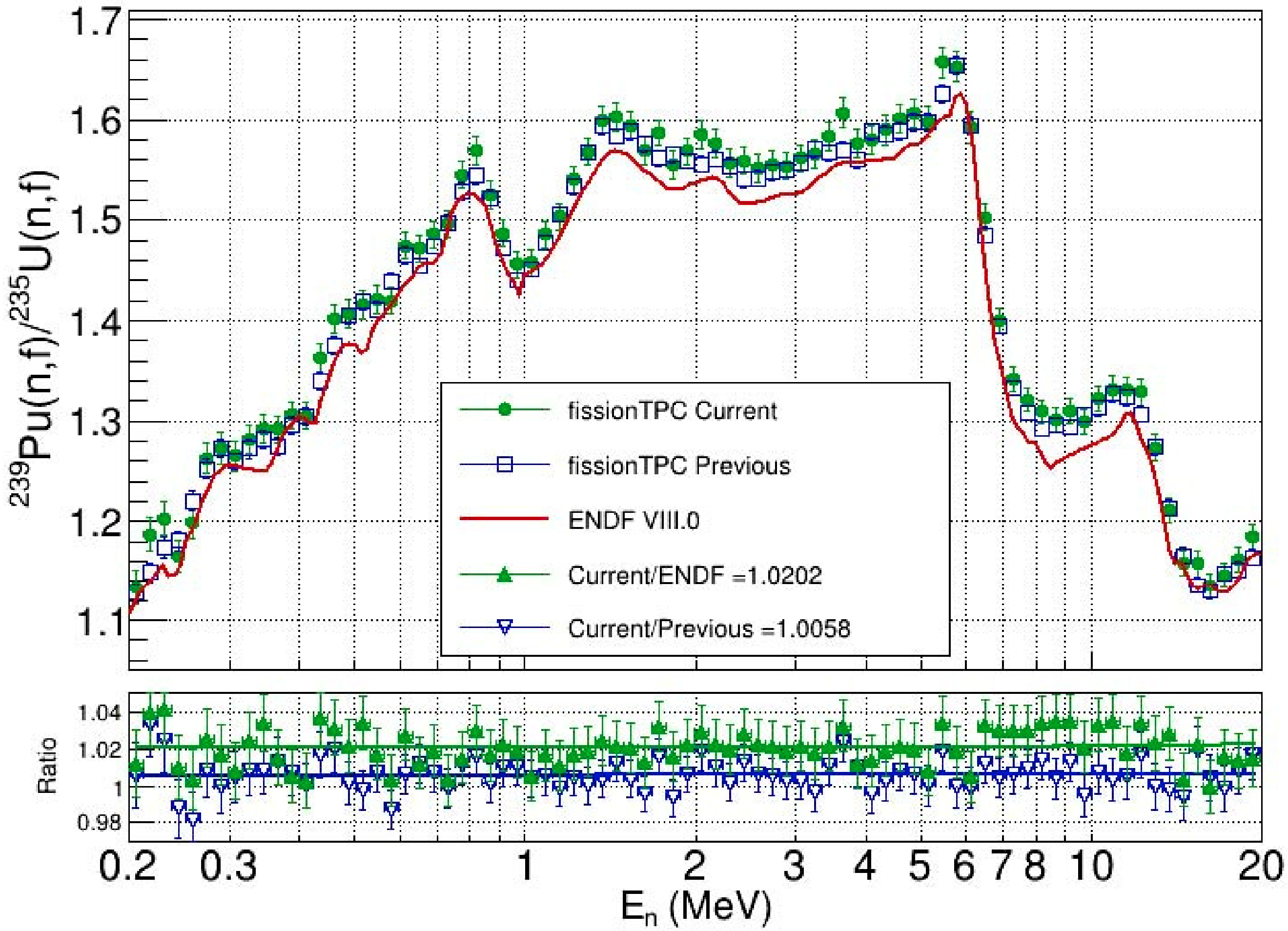
    - This work has led to improved agreement of the evaluation with experimental SACS values and significant agreement with the NIFFTE ^{239}Pu(n,f) /^{235}U(n,f) cross section ratios.

Plutonium Fission Cross Section Related Measurements

- New $^{239}Pu(n,f)/^{235}U(n,f)$ cross section ratio measurements by Dongwi *et al*. made at LANSCE by the NIFFTE collaboration have very recently been published. They were made with an improved sample.
  - These data are higher than the standards evaluation by about 2% but are in agreement in shape. They do agree within their uncertainties. The new data agree very well with the previous NIFFTE work. In their recent paper they indicate that the new and previous results should both be treated as absolute but highly correlated. In the publication of their previous measurement, because of concerns about normalization, they indicated the data should be treated as shape results.
  - As noted previously, work with gmapy led to a new preliminary standards evaluation that yielded a $^{239}Pu(n,f)/^{235}U(n,f)$ cross section ratio in very good agreement with the new NIFFTE $^{239}Pu(n,f)/^{235}U(n,f)$ cross section ratio measurements.

- Also measurements have been made of the $^{239}Pu(n,f)/^{6}Li(n,t)$ cross section ratio with the NIFFTE fission TPC. These data will impact evaluations of both the $^{239}Pu(n,f)$ and $^{6}Li(n,t)$ cross sections. These data are not finalized.

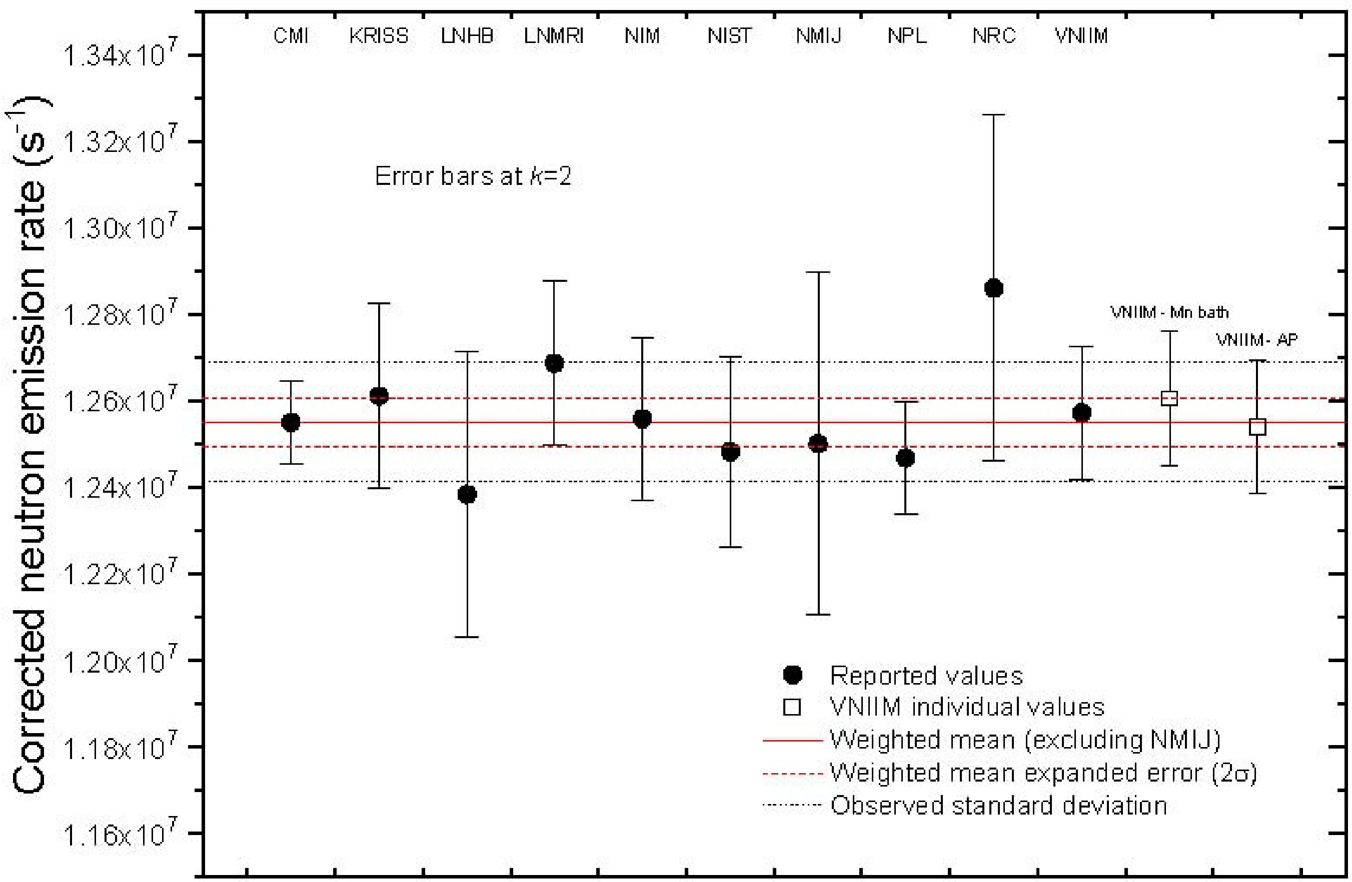
New NIFFTE ^{239}Pu(n,f)/ ^{235}U(n,f) Cross Section Ratio compared with the Standards Evaluation



Comparison of measurements of neutron source emission rate CRR(III)-K9.Cf

- A single ^{252}Cf source is sent to a number of laboratories throughout the world
  - Brazil, Canada, China, Czech Republic, Britain, France, Italy, Japan, Russia, and USA
- The measured rate at each laboratory using their techniques is sent to an impartial pilot institute
  - The results were tabulated and led to a publication in Metrologia
- Such work is valuable to ensure that each laboratory is obtaining consistent results
  - Results that deviate from the mean require investigation to find sources of error

Results of the ^{252}Cf Inter-comparison Work



Summary-what is needed

- Improved experimental work is necessary for all the standards

- An emphasis is on work using different experimental methods to improve our understanding of uncertainties.
  - Especially the boron and lithium standards so the upper energy bound can be increased.
    - Also for gold capture that has some of the largest uncertainties for the standards.

- Extension of the hydrogen standard to about 150 MeV and possibly higher (work is underway by Hale and Paris).
  - It is now 20 MeV but there are cross section ratio data to much higher energies
  - Note that changes to a standard are not allowed for a given version but extensions are allowed

- Further work on unrecognized sources of uncertainty)USU)
  - An understanding of the energy dependence of USU

- Consider improved evaluation techniques for the standard cross sections