Recent Standards Work

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The Neutron Cross Section Standards

Reaction	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

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 will not be shown:
    - Prompt γ-ray production Reference cross section measurements
        - $^{7}Li(n, n')\gamma$ and $^{48}Ti(n,n')\gamma$ Reference cross sections

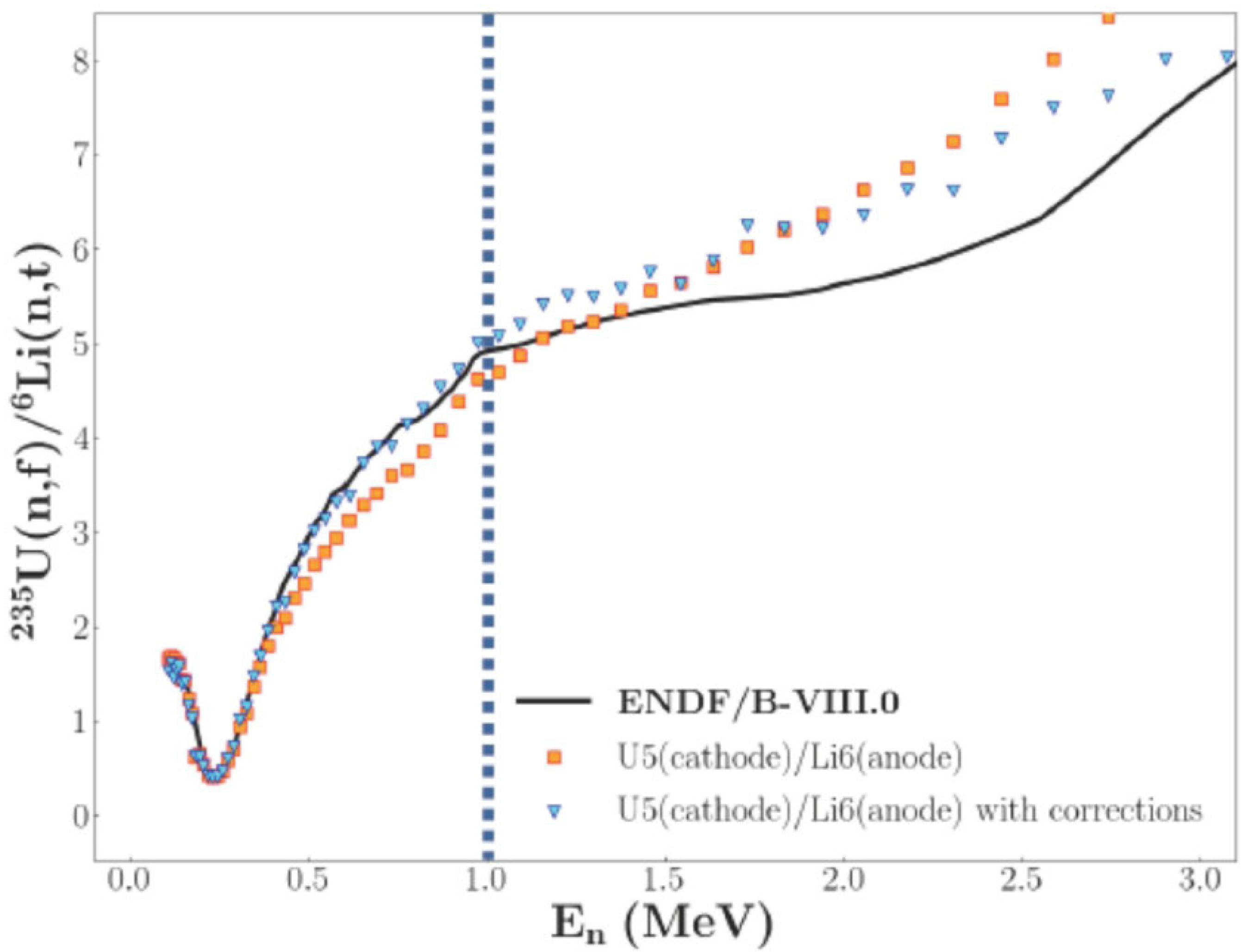
Previous CSNS Measurements

- The measurements at the Chinese Spallation Neutron Source discussed last year have been published
- Light element standards
  - Measurements by Jiang, *et al*. of the hydrogen angular distribution from 6-52 MeV *
  - Measurements of the ^{6}Li(n,t) angular distribution by Bai *et al*. for energies from 1 eV to 3 MeV*
  - Angular distribution data obtained by Jiang *et al.* for the boron standards from 1 eV to 2.5 MeV*
  - Ratios of the ^{10}B(n, α)^{7}Li reaction to the ^{6}Li(n, t)^{4}He reaction by Liu *et al*. to several MeV*
- Fission Data
  - The ^{235}U(n,f) and ^{238}U(n,f) cross sections relative to n-p scattering by Chen *et al* from 10 to 66 MeV*
- All the experiments above (with*) were done using the double bunch mode for the accelerator.
  - That mode has 2 bunches of pulse width ~ 41 ns: 410 ns was the interval between proton bunches.
  - the neutron energy distribution caused by the double proton bunches was unfolded using an iterative unfolding method.
  - The ^{238}U(n,f)/^{235}U(n,f) cross section ratio by Wen, *et al*. from 1 to 20 MeV.
    - This is the only experiment done using the single-bunch mode with ~ 41 ns width .

$^{6}Li(n,t)$ Measurements

- 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 .
    - Preliminary results were given that agree well with the standards evaluation and suggest a rise in the ratio above 1 MeV.

$^{235}U(n,f)/6Li(n,t)$ Cross Section Ratio Measurements by Anastasiou et al.



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

- Massey *et al.* 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))

- More work by Massey *et al.*
  - Several measurements of the $^{10}Be(p,n)^{10}B$ reaction by Massey and Jones-Aberty at Ohio University.
  - They include two angular distributions at 2.5 and 3.5 MeV.

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

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

- Extension in the energy ranges to above 1 MeV of the $^{6}Li(n,t)$ and ^{10}B standards may be possible with the work by Anastasiou *et al*., Bai *et al*., Jiang *et al*. and the Massey *et al. d*ata.
- 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.

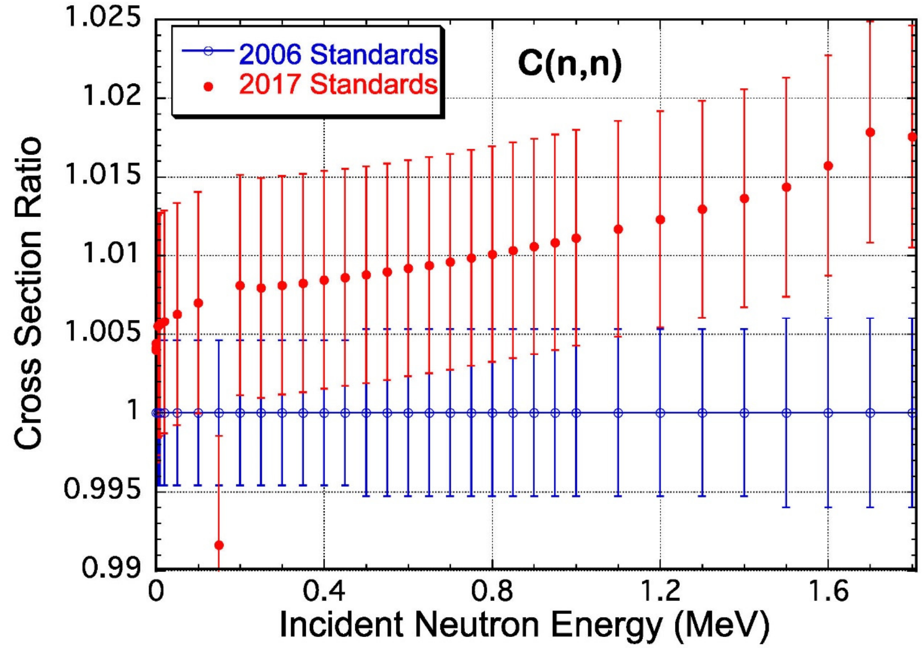
C(n,n) Cross Section

- 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. That evaluation, the ENDF/B-VIII standards evaluation (the 2017 standard), is somewhat higher than the ENDF/B-VII standards evaluation (the 2006 standard). The difference is most noticeable at the highest energies.

- At the standards meeting in October, Hale indicated he is working on a new evaluation of neutrons on carbon.
  - The use of high energy data in the evaluation has caused an decrease in the C(n,n) cross section in the standards energy region by about a percent .
  - So now it is closer to the 2006 standards values in the higher energy region

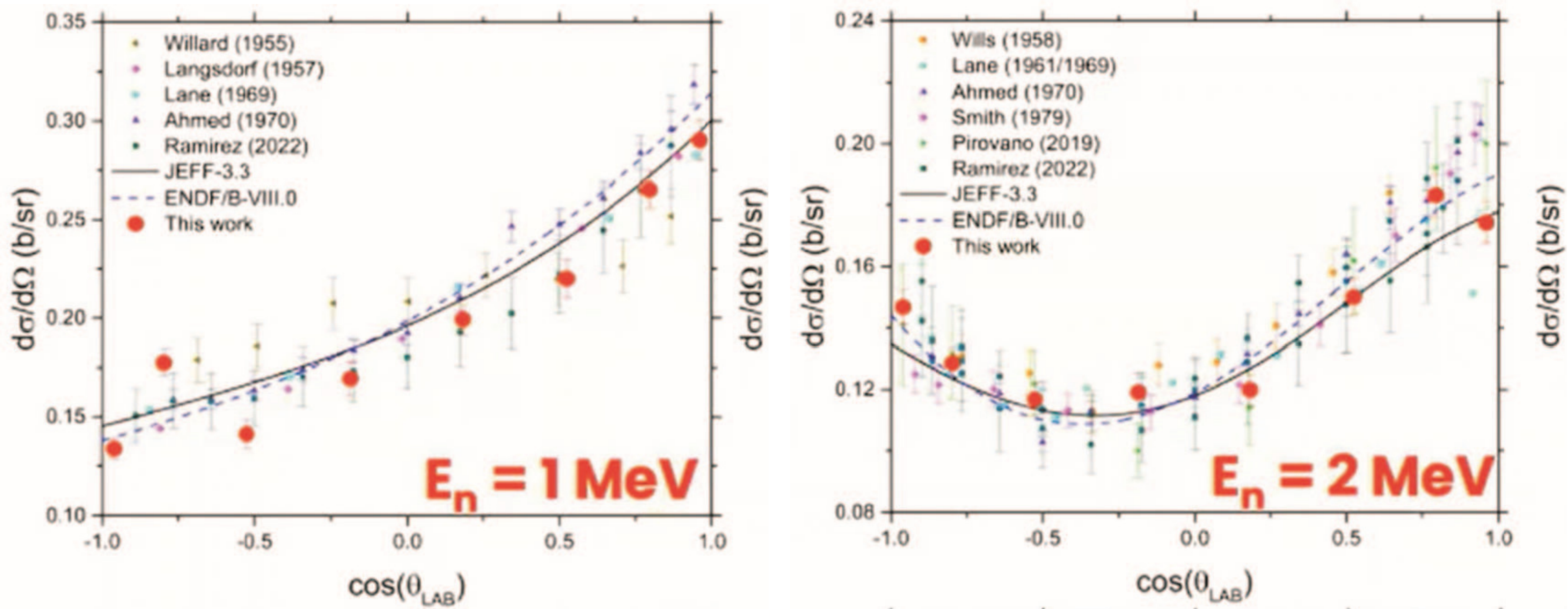
- Measurements have been made by Vanhoy on ^{13}C that should improve the new evaluation of the carbon Standard.

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



C(n,n) Cross Section

- Angular distribution measurements have recently been completed at GELINA by Gkatis *et al.*
  - The data were obtained with the ELISA setup
  - Energies from 10 mV to 20 MeV (thus covering the standards energy range)
  - With 8 angles between 16.2 and 163.8 degrees



Uranium Fission Cross Section Measurements

- Absolute measurements by the n_TOF collaboration were made of the ^{235}U(n,f) cross section relative to hydrogen scattering from 20 MeV to about 1 GeV.
  - The status of the analysis of the data was discussed by Manna *et al.* at the October standards meeting. The analysis is essentially completed for the energy region up to 450 MeV.
  - 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 an extension to higher neutron energies that may be possible with these data if high accuracy can be obtained.**
  - Their plan is to have a further "campaign" to
    - Improve the accuracy (reduce the statistical uncertainty)
    - Go to higher neutron energy
      - The fission fragment detectors already extend to 1 GeV
      - Getting to higher proton energy data will require being able to separate the elastic and inelastic protons since inelastic scattering is a problem at the higher neutron energies

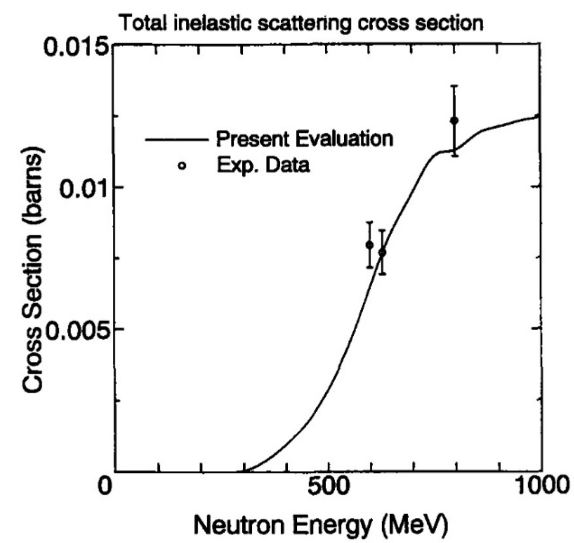
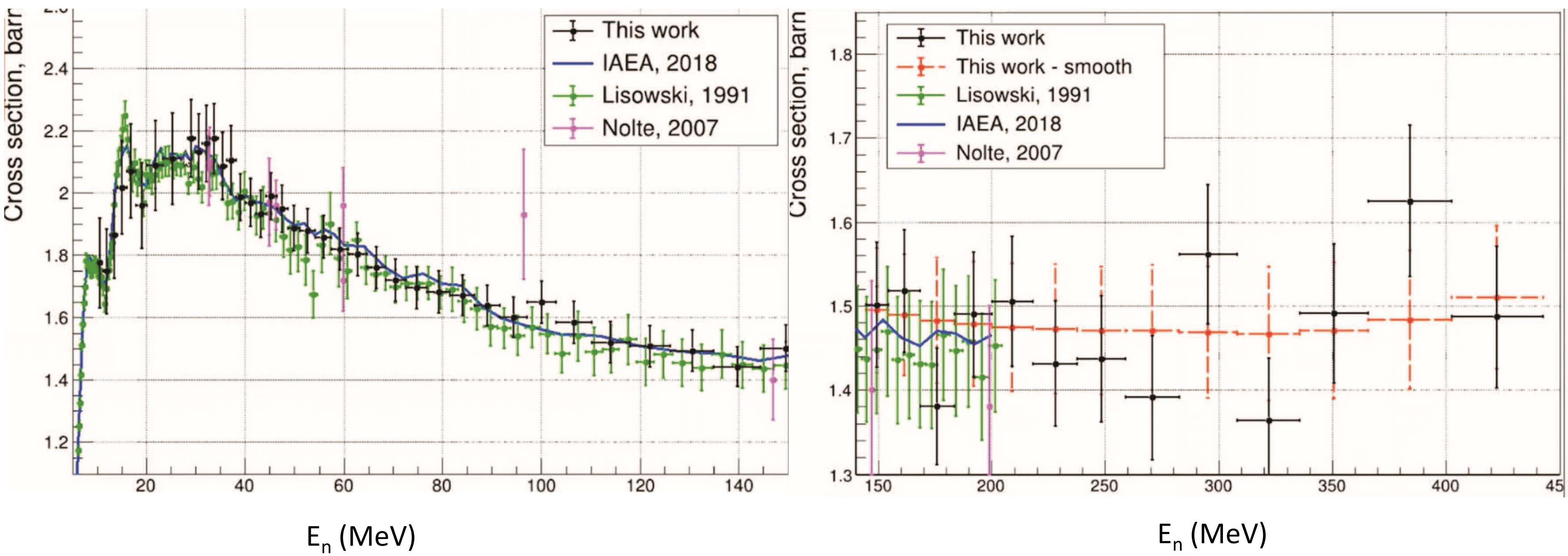


Fig. 6 Total inelastic scattering cross section of hydrogen

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



^{235}U(n,f) Cross Section Uncertainties for Manna et al. Measurement

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

The energy range studied in different regions

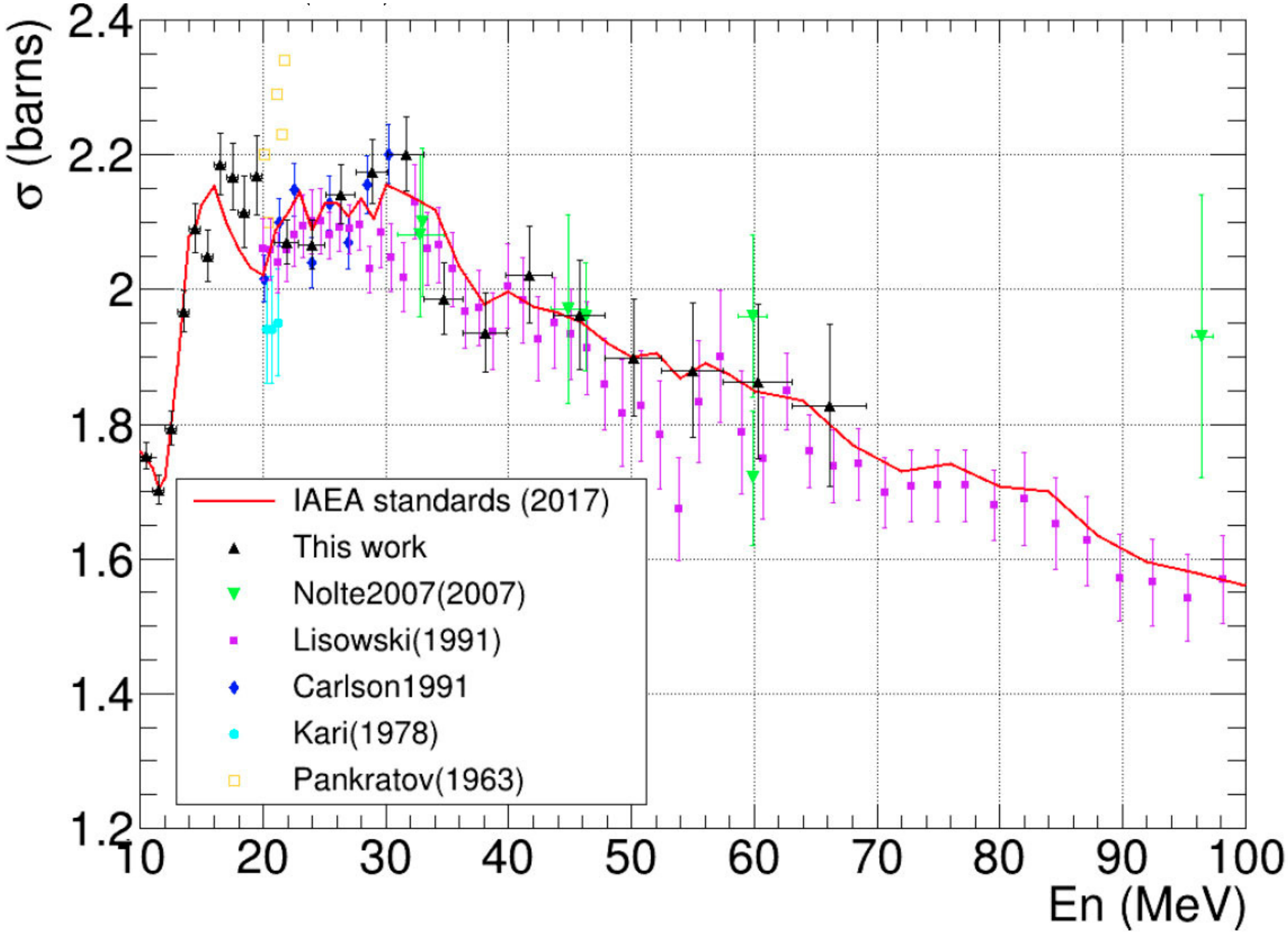
→ different detectors used or different working conditions

	Uncertainty En = [10-27] MeV	Uncertainty En = [28-38] MeV	Uncertainty En = [38-140] MeV	Uncertainty En > 140 MeV	
Systematics		4.5%	4.5%		...xs extracted with FC and 3s-RPT
Statistics		2.4-3.5%	2.2-7.3%		
Systematics	6.5%		3.5%	4.0-4.3%	...xs extracted with PPAC and MS-RPT
Statistics	2.5-4.2%		2.7-3.6%	2.6-3.7%	
			1.7-2.2%		Correlated
Total	5.7-8.1%	5.7-5.2 %	3.7-4.9%	4.8-5.6%	Final

Uranium Fission Cross Section Measurements

- ^{235}U(n,f) and ^{238}U(n,f) cross sections measurements at CSNS
    - Shown by **Chen**. at the October standards meeting.
        - 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

^{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 spectrum (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.**

- An improvement in use of these SACS would be possible if ratios can be used.
    - With ratios, the dependence on neutron fluence is **removed.**
    - GMAP unfortunately can not handle SACS ratios

- A new Python based code was written by Schnabel (GMA-py) so that ratios can now being used.
    - Using the the $^{239}Pu(n,f)$/ $^{235}U(n,f)$ SACS ratio data and 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 example, more than a 0.6% increase in the $^{239}Pu(n,f)$ /$^{235}U(n,f)$ cross section ratio occurs.

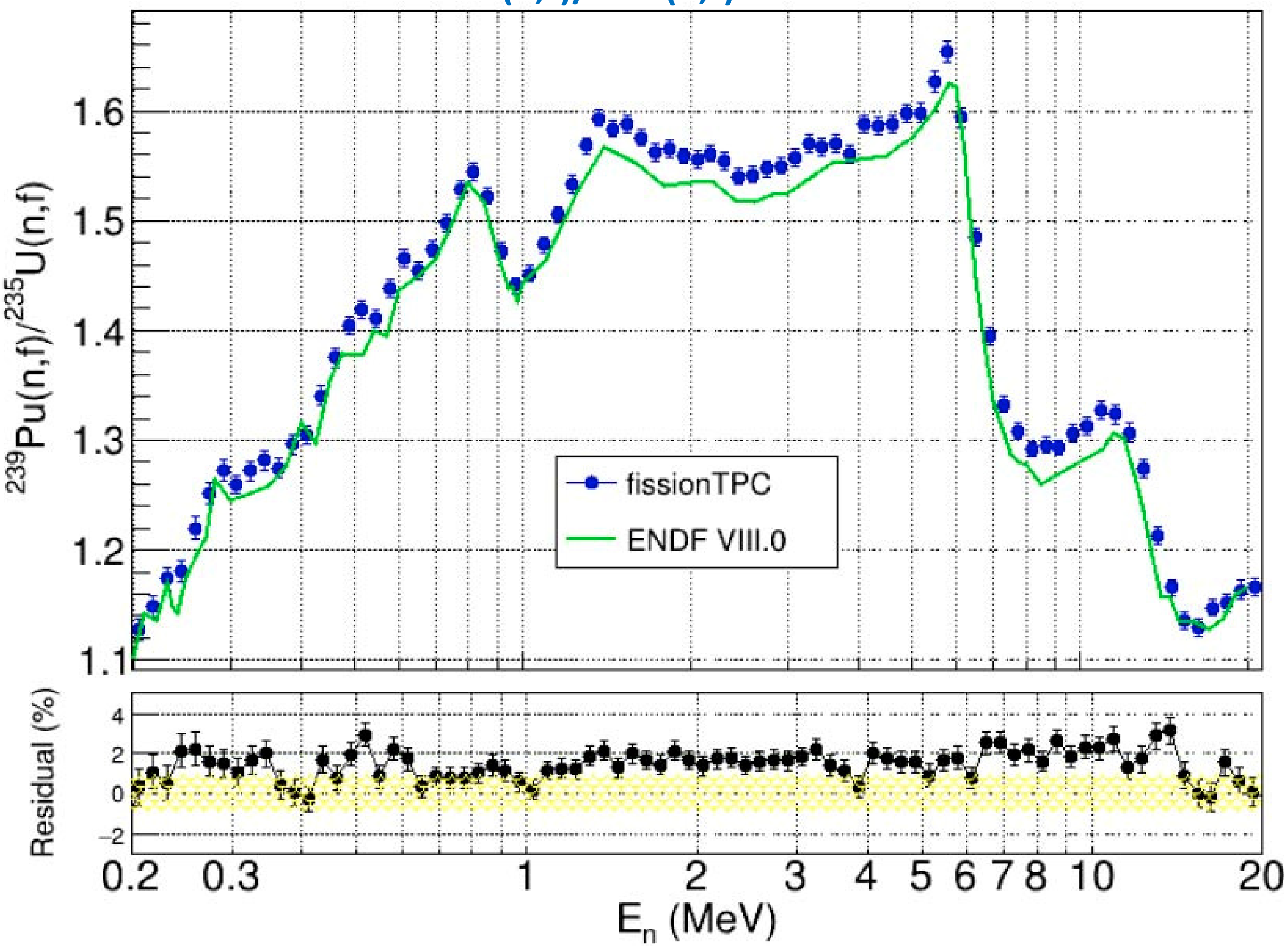
Plutonium Fission Cross Section Related Measurements

- ^{239}Pu(n,f)/^{235}U(n,f) cross section ratio measurements by Snyder *et al*. made at LANSCE by the NIFFTE collaboration have been published (L. Snyder, Nuclear Data Sheets **178** 1 (2021)). These data are higher than the standards evaluation by slightly less than 2%. They are recommended to be used as ratio shape data. They agree in shape with the 2017 standards evaluation. New measurements have been made with an improved sample. They were shown at the ND2022 conference and at the recent Oct. standards meeting by Snyder. The new data look identical to the former measurements. But each of those measurements was normalized at the same low energy. It's normalization is still under investigation.

    - As noted previously, work with GMA-py led to a new preliminary standards evaluation that yielded a ^{239}Pu(n,f)/^{235}U(n,f) cross section ratio with a value that is more than 0.6% larger than the value obtained with the 2017 standards evaluation. So the difference now instead of 2% it is just slightly more than 1% compared with the present preliminary standards evaluation.

- 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.

Comparison of the *Published* NIFFTE ^{239}Pu(n,f)/ ^{235}U(n,f) Cross Section Ratio with the Standards Evaluation



Nuclear Reaction Activities- Measurements

Comparison of measurements of neutron source emission rate CRR(III)-K9.Cf 2016

- NIST is a participant in an international project measuring source intensity
- A single ^{252}Cf is sent to a number of laboratories throughout the world
  - Brazil, Canada, China, England, France, Italy, Russia, S. Korea and USA
- The measured rate at each laboratory using their techniques is sent to a pilot institute
  - The results are being tabulated leading 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

Summary-what is needed

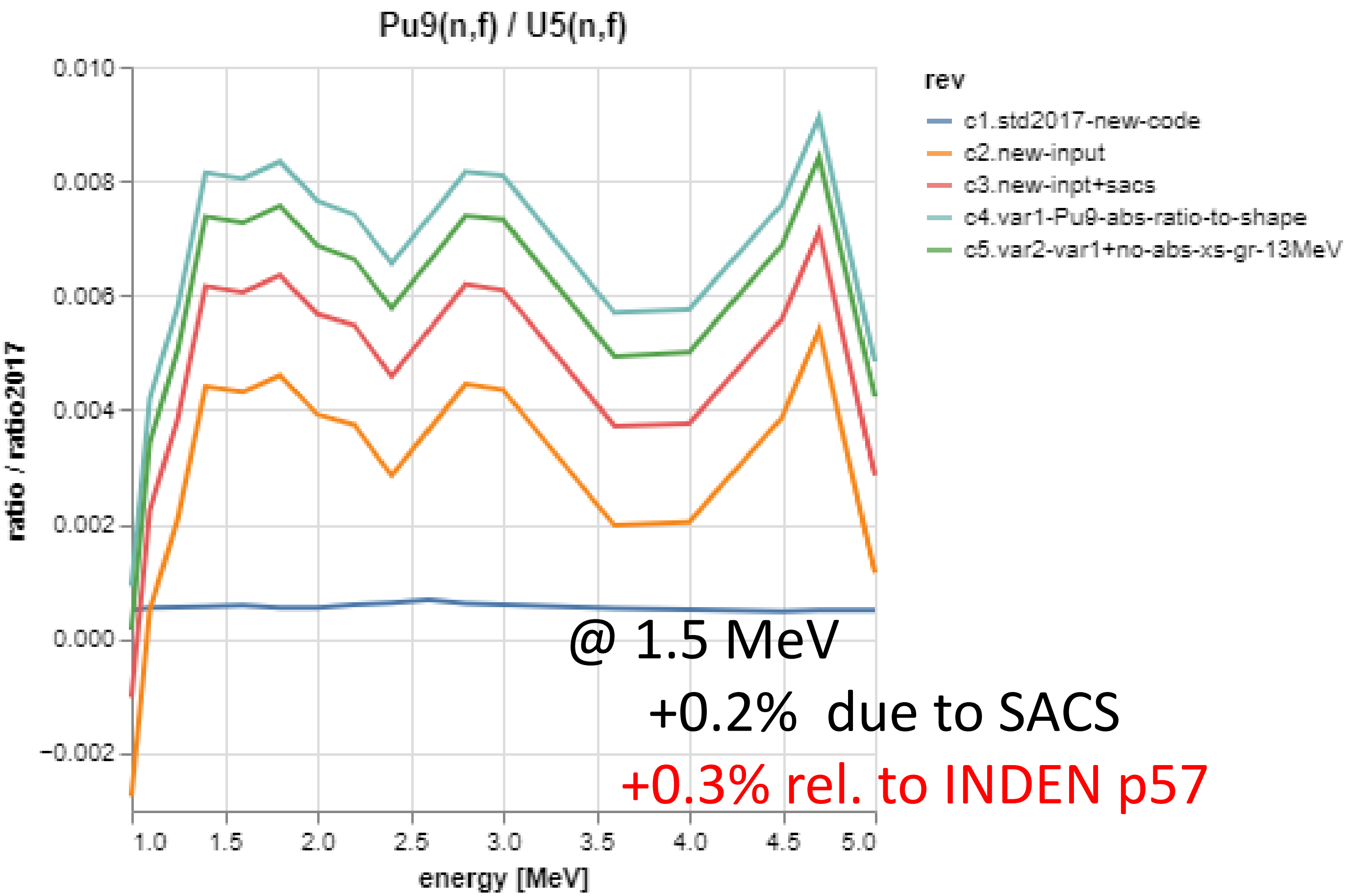
- Improved experimental work is necessary for all the standards
  - Especially the boron and lithium standards so the upper energy bound can be increased
    - Also for gold capture that has some of the largest uncertainties for the standards

- 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
  - An understanding of the energy dependence of USU

- Consider improved evaluation techniques for the standard cross sections

Pu9f/U5f: 2017 vs current – GMA-py



@ 1.5 MeV

+0.2% due to SACS

+0.3% rel. to INDEN p57