Recent Work on Neutron Standards

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Outline of Work on the Neutron Standards Since the Completion of the Standards Evaluation

- Measurements of Neutron Cross Section Standards Proposed, Underway or Completed
    - Including results presented at the Oct 2020 Standards meeting
- Work related to the ^{252}Cf nubar standard
- Due to time limitations for this presentation and limited amount of work done on some standards related activities, the following will not be presented here
    - ^{252}Cf spontaneous prompt fission neutron spectrum measurements
    - Prompt γ-ray production reference cross section measurements
        - ^{7}Li(n, n')γ and ^{48}Ti(n,n')γ reference cross sections

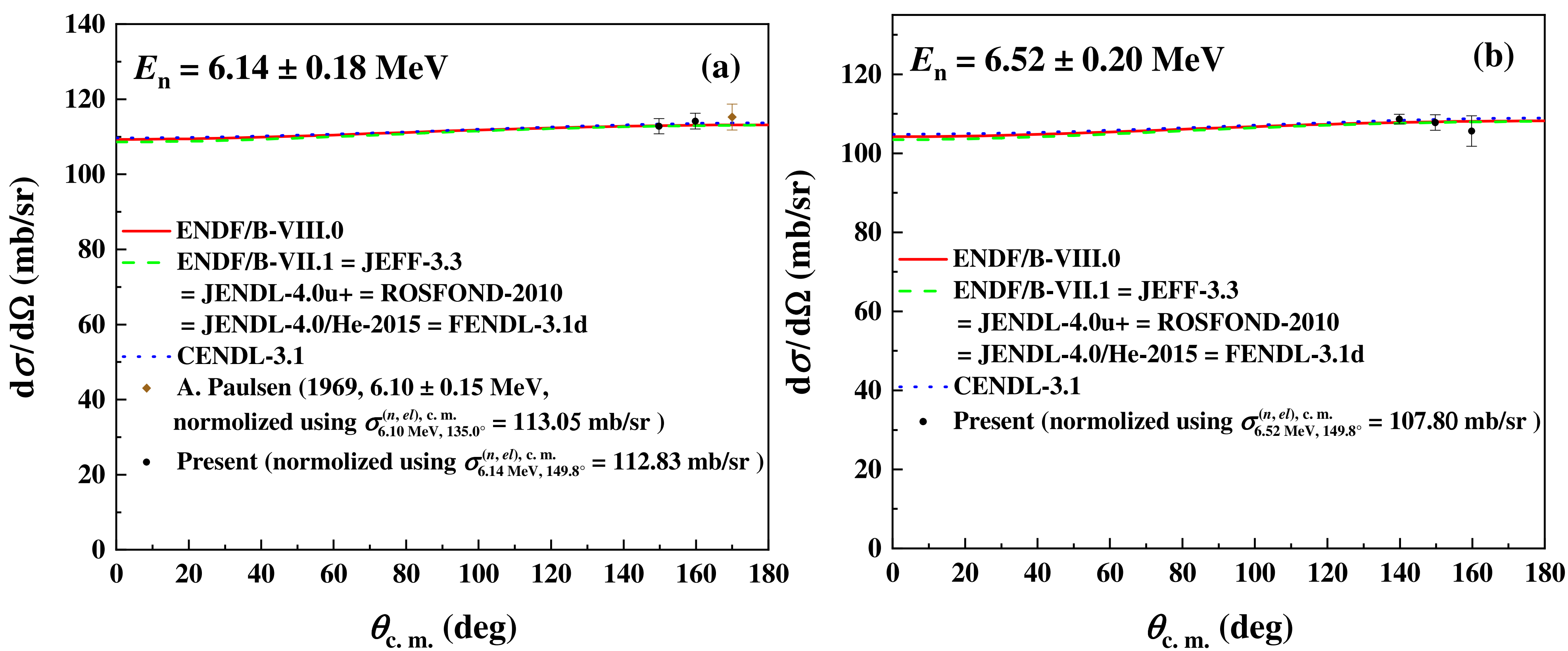
The Neutron Cross Section Standards

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

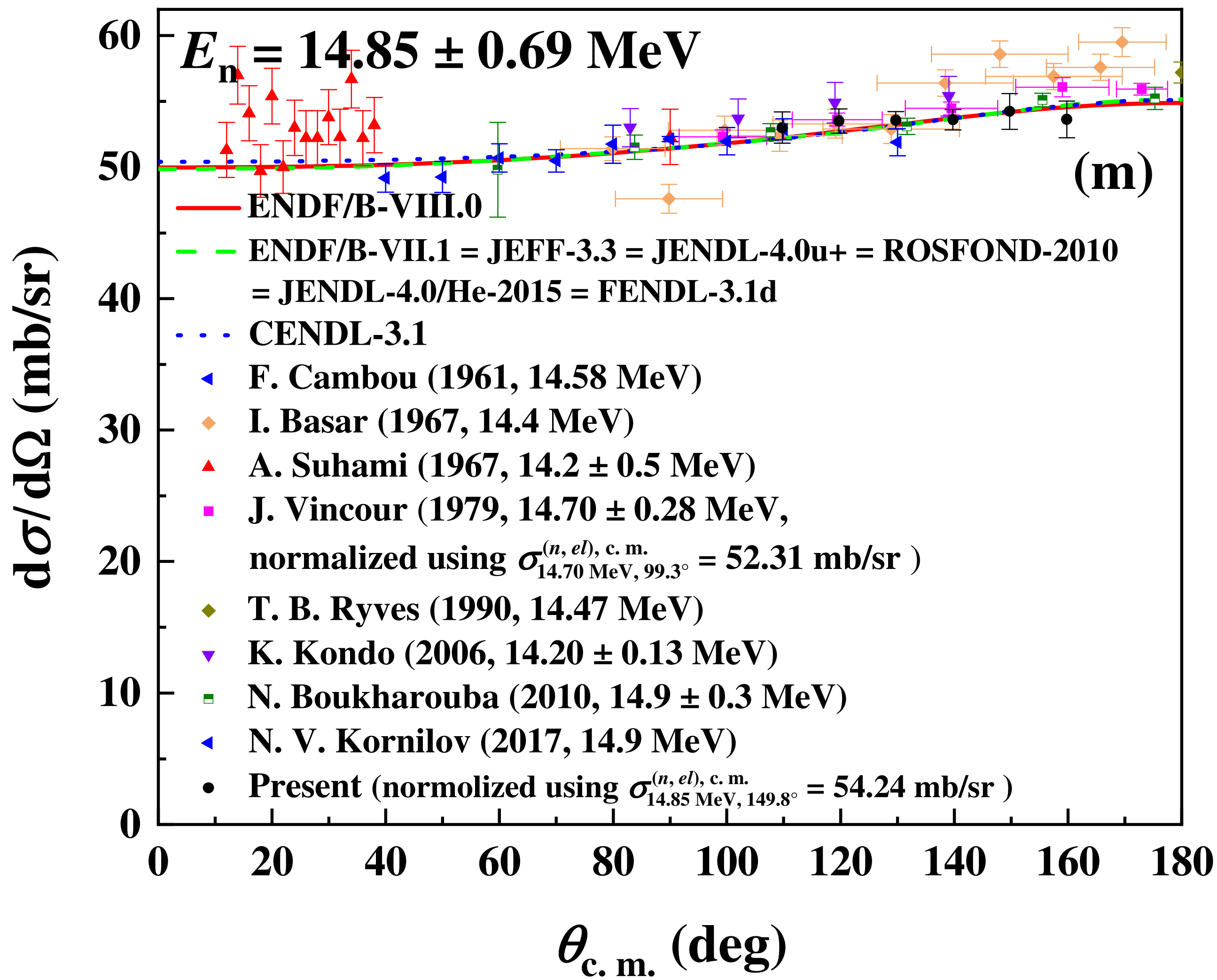
H(n,n)H Angular Distribution Work at the China Spallation Neutron Source (CSNS) by Jiang et al.

- This work is one of several important standards measurements made at the CSNS. The facility uses 1.6 GeV protons on a tungsten target to generate a white spectrum of neutrons.
- The experiment uses 10 E-ΔE detector arrays to make measurements at 10 angles from 10 to 55 degrees. The measurements extend from 6 MeV to 52 MeV with 23 energy points. The flight path was 57.99m
- The experiment employed a vacuum chamber with a polyethlene sample bombarded by CSNS neutrons.
- All angles were measured simultaneously. Uncertainties vary from 1 to 8%.
- It is important to extend the hydrogen standard to higher neutron energies. It is now limited to 20 MeV.
- A paper on this work was submitted to Eur. Phys. J. **A**

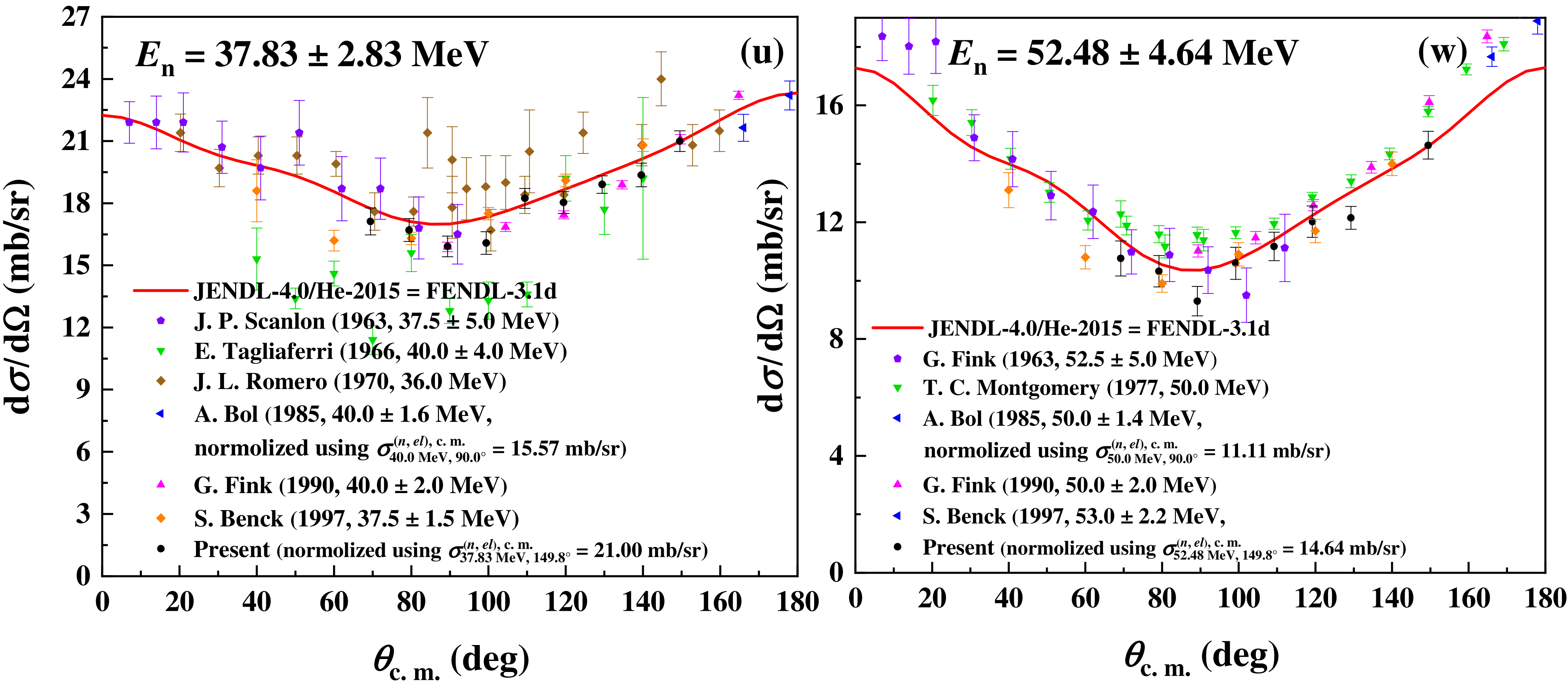
H(n,n)H Angular Distribution Measurements at CSNS by Jiang et al., submitted to EPJA



H(n,n)H Angular Distribution Measurements at CSNS by Jiang et al., submitted to EPJA



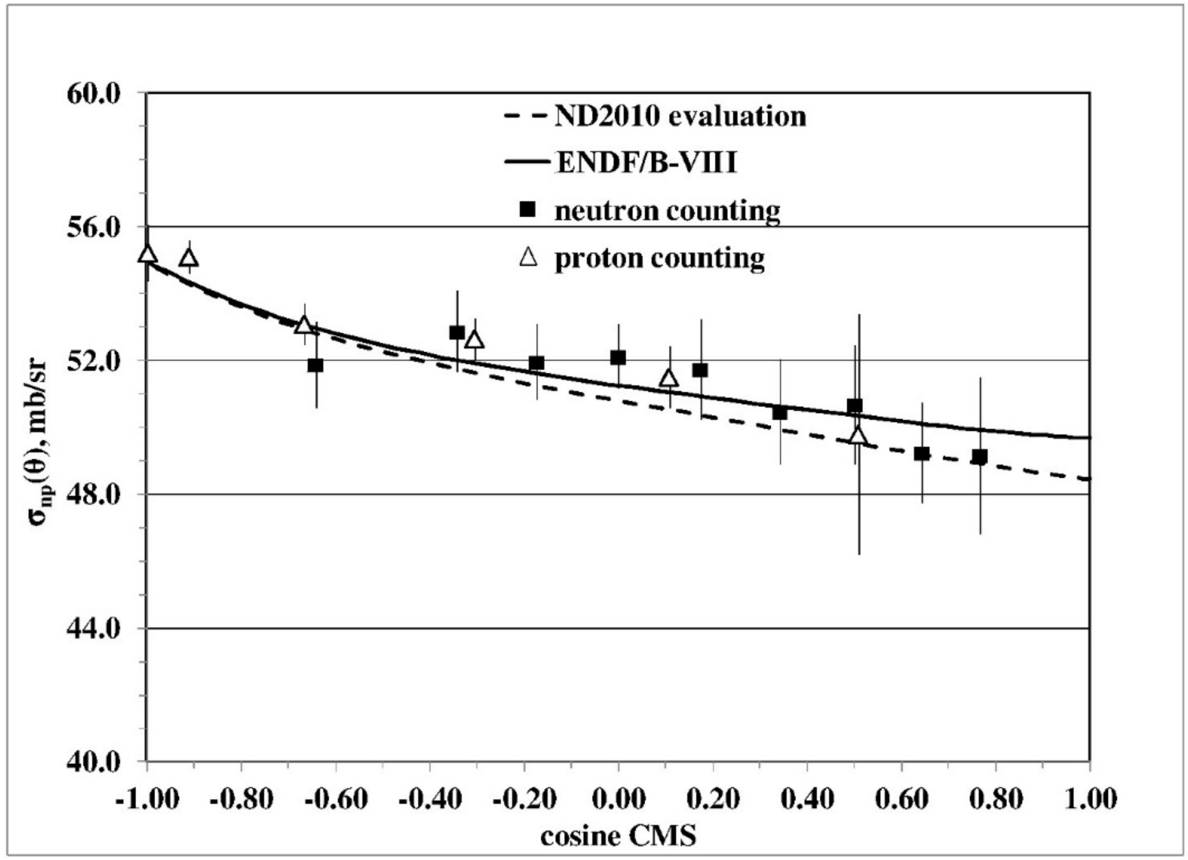
H(n,n)H Angular Distribution Measurements at CSNS by Jiang et al., submitted to EPJA



H(n,n)H Standard Angular Distribution Measurements at Ohio University, Kornilov et al.

- The collaboration previously made measurements at 10 and 14.9 MeV by detecting the recoil proton.
- The present measurements at 14.9 MeV have been made detecting the neutron in coincidence with the associated proton so that data can be obtained at smaller CMS angles.

The present results here are compared with previous data obtained using detection of the recoil proton and with the ENDF/B-VIII standards evaluation . There is excellent agreement with the within the uncertainties overall but there is a trend toward lower values at small CMS angles for both experiments.



N.V. Kornilov, *et al.* A High-Precision Tagged Neutron n-p Scattering Measurement at 14.9 MeV, Nucl. Sci. Eng. 194, 335 (2020)

Collaboration of Ohio University, Lincoln Memorial University, NIST and the University of Guelma)

^{6}Li(n,t) Measurements

- The NIST measurement is the first direct and absolute measurement of this cross section in this neutron energy range using monoenergetic neutrons (4 meV).
- A primary effort was focused on measuring the neutron fluence accurately. It was determined with an uncertainty of 0.06%.
  - Much investigation has gone into the uncertainty of this cross section measurement.
  - Most of the uncertainty is from uncertainty in the ^{6}Li mass.
  - There is concern about the IRMM mass determination. That value yields a cross section value with an uncertainty of 0.3% that is 1% lower than the ENDF/B-VIII value.
- **Samples are being measured by Isotope Dilution Mass Spectrometry to obtain a very accurate value for the mass. The pandemic has slowed down progress in this area.**

- **The low energy (thermal) ENDF/B-VIII ^{6}Li(n,t) cross section value is largely determined by three measurements made in 1970-1971.**
  - It is not clear how well they determined their ^{6}Li masses.

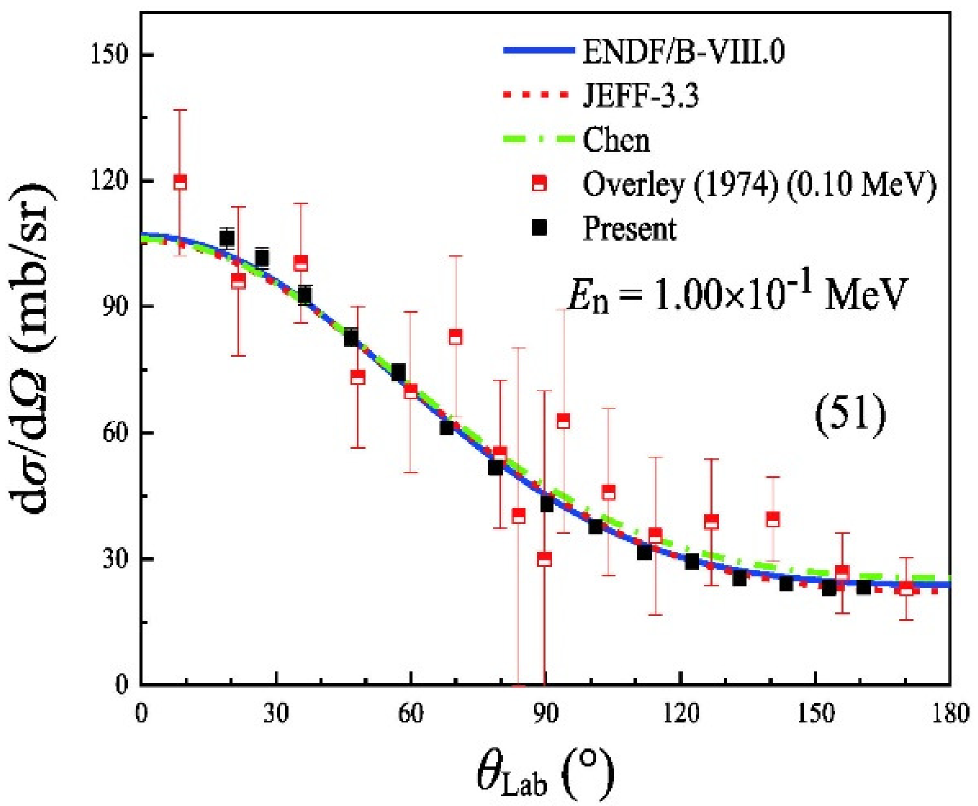
(collaboration of NIST with the University of Tennessee and Tulane University)

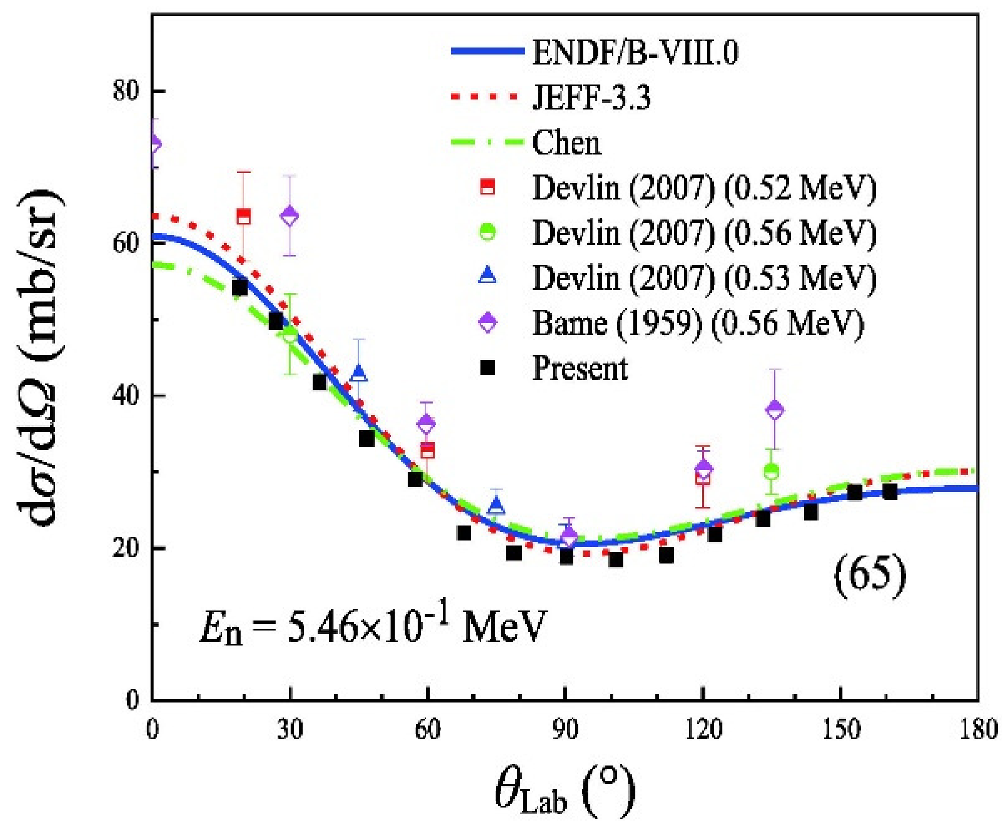
^{6}Li(n,t) Measurements at the CSNS by Bai et al.

- The work extends from 1 eV to 3 MeV with 80 energy groups with 15 E- ΔE detector arrays at 15 angles between 19.2 and 160.8 degrees. A ^{6}LiF target was used.
- The neutron energy spectrum was not measured at the position of the experiment. It is expected that this will affect the cross section values. It will not affect the angular distributions
- There are deviations from an isotropic angular distribution in the eV energy region. Some of this may be from problems due to the use of the ^{235}U(n,f) cross section for determining the neutron fluence in regions where it is not smooth.
- Also the integrated cross sections are below the standard for energies above 0.5 MeV. The agreement with the standard in many regions is relatively good. More work is planned.
- The experiment was done at a 58 m flight path. All angles were measured simultaneously.
- Uncertainties for the differential cross sections vary from 1.7 to 74.3%. The larger uncertainty is for the highest neutron energies. Integrated cross sections from the differential results have uncertainties of 1.5% – 21.5%. Those data were normalized to the present standard in the interval from 0.1 to 0.4 MeV

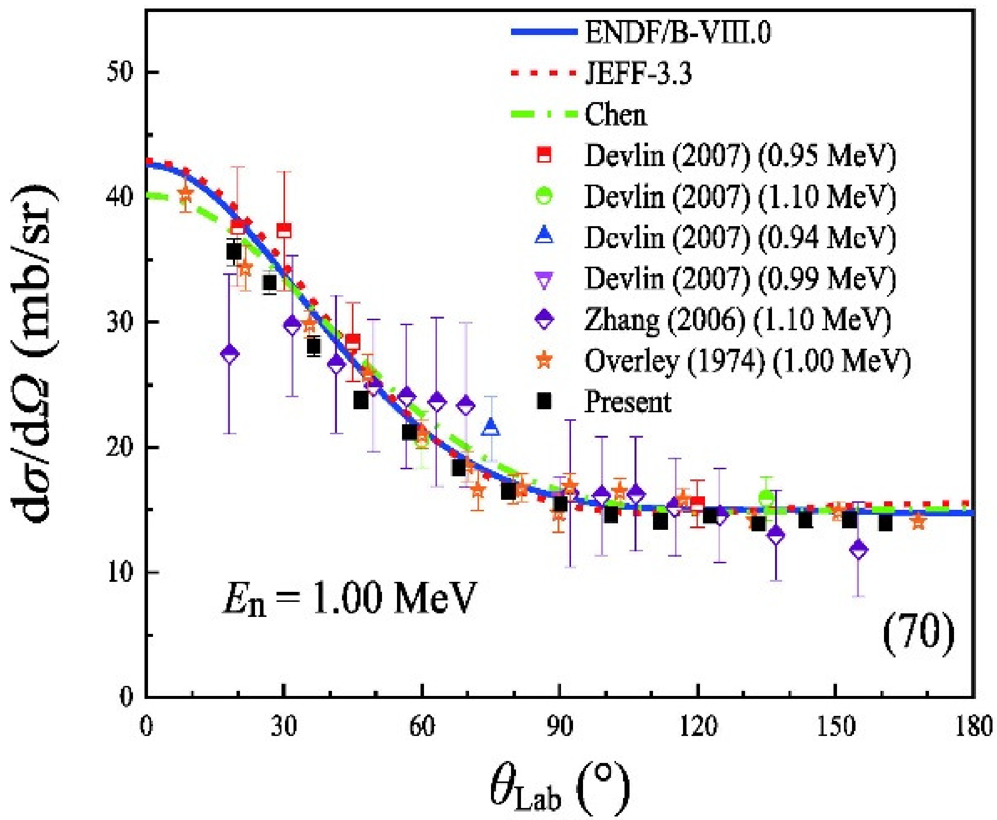
This work is published in, H. Bai, *et al.,* Measurement of the differential cross sections and angle-integrated cross sections of the ^{6}Li(n, t)^{4}He reaction from 1.0 eV to 3.0 MeV at the CSNS Back-n white neutron source, Chin. Phys. **C 44** 014003 (2020)

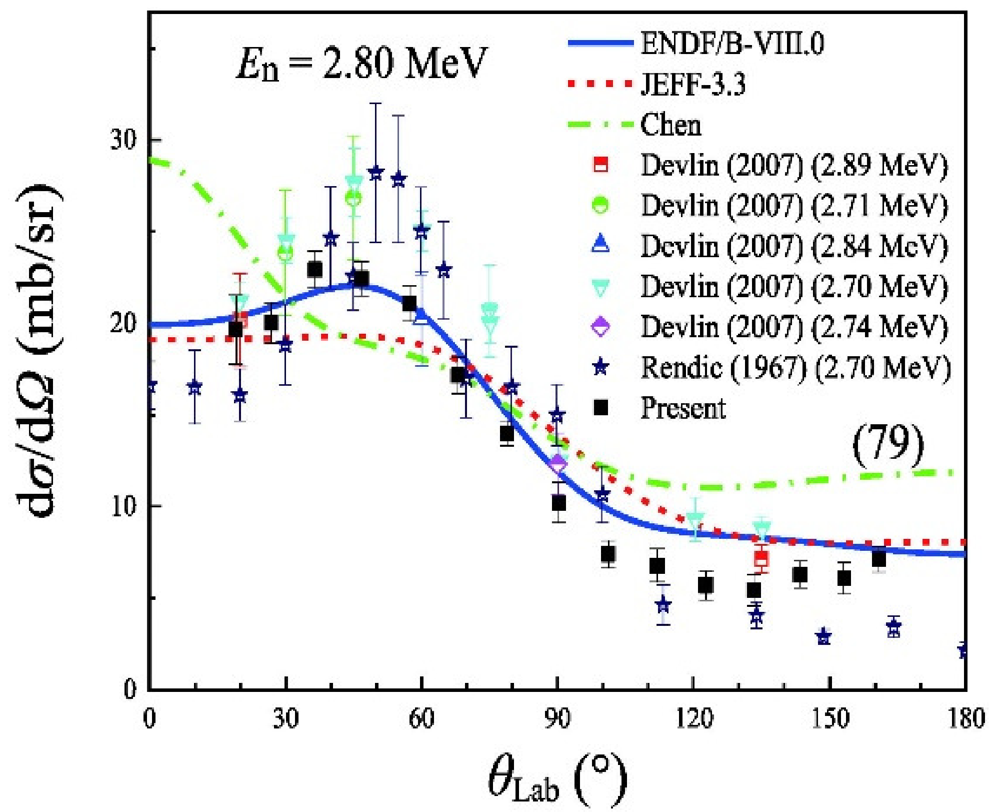
$^{6}Li(n,t)$ Angular Distributions Measurements by Bai *et al.*



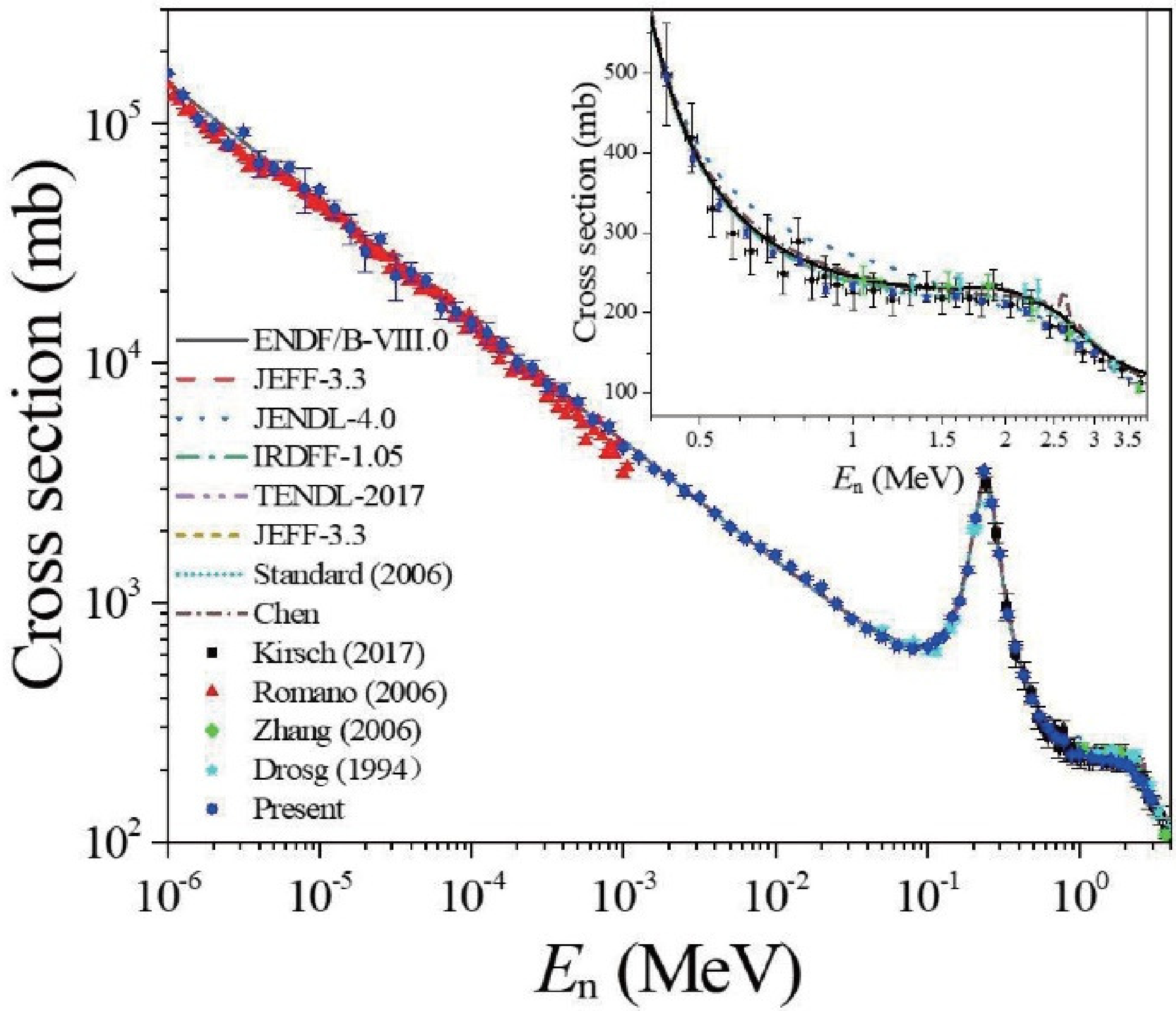


^{6}Li(n,t) Angular Distributions Measurements by Bai *et al. (cont.)*

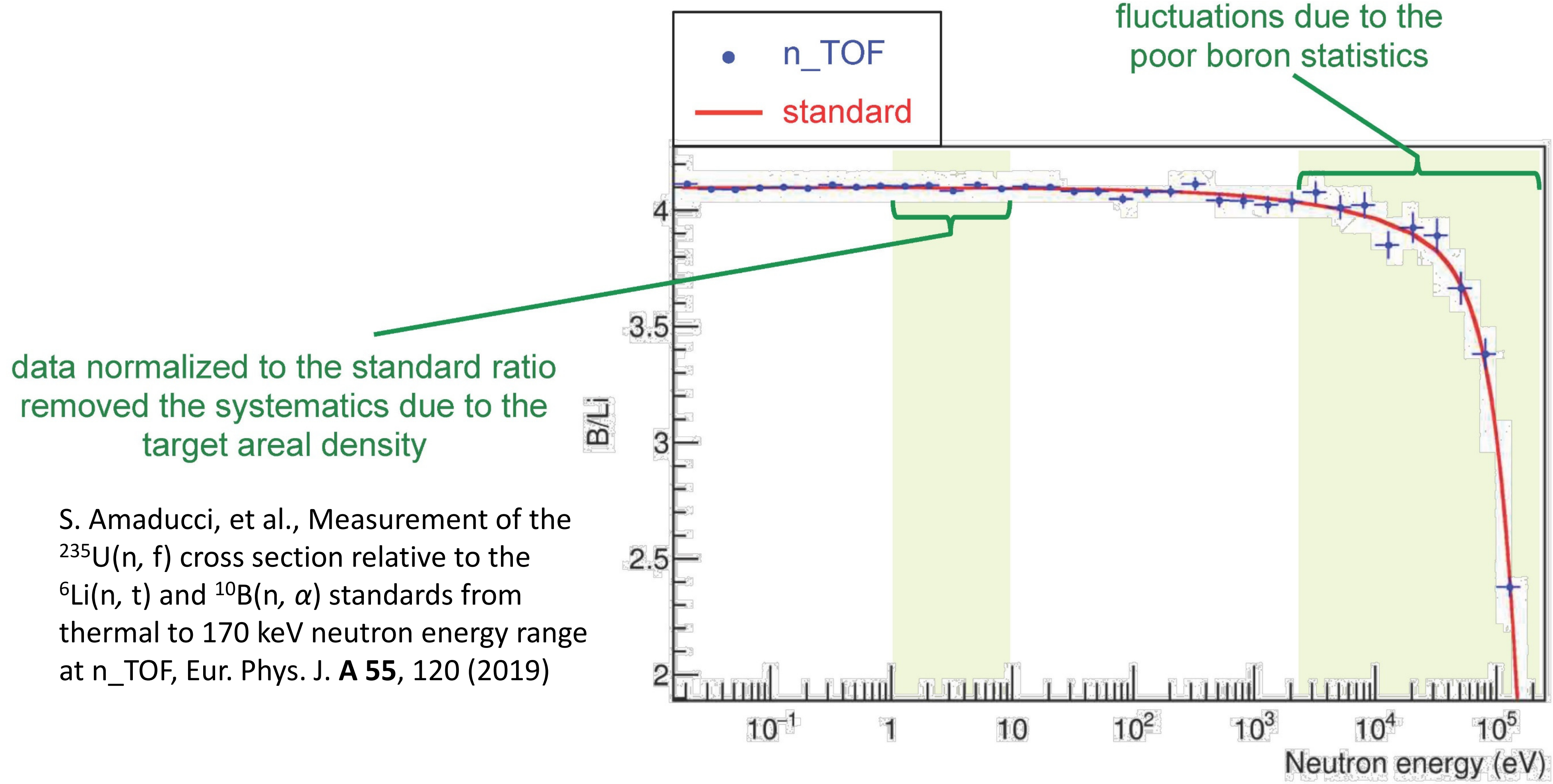




^{6}Li(n,t) Cross Section Measurements by Bai *et al.*



Finocchiaro, Amaducci *et al.* n_TOF Measurements of $^{10}B(n,\alpha)/^{6}Li(n,t)$ Cross Section Ratio Compared with the Calculated Result, **Recently published**



S. Amaducci, et al., Measurement of the $^{235}U(n, f)$ cross section relative to the $^{6}Li(n, t)$ and $^{10}B(n, \alpha)$ standards from thermal to 170 keV neutron energy range at n_TOF, Eur. Phys. J. **A 55**, 120 (2019)

$^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1\gamma)$ 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
  - Proton, triton and alpha particles were measured at four angles
  - Differential cross sections were obtained for the $^{10}B(n,p_0)^{10}Be$, $^{10}B(n,t_0)^{8}Be$, $^{10}B(n,a_2)^{7}Li$ and $^{10}B(n,a_3)^{7}Li$ reactions.
  - The sum of the $^{10}B(n,a_0)^{7}Li$ and $^{10}B(n,a_1)^{7}Li$ differential cross section was measured
  - Partial angular distributions were obtained for the $^{10}B(n,p_1)^{10}Be$, $^{10}B(n,t_1)^{8}Be$ and $^{10}B(n,d_0)^{9}Be$ reactions
  - These data can be used in R-matrix fits to improve the standards
  - They can help in extending the energy of this standard to higher energies.

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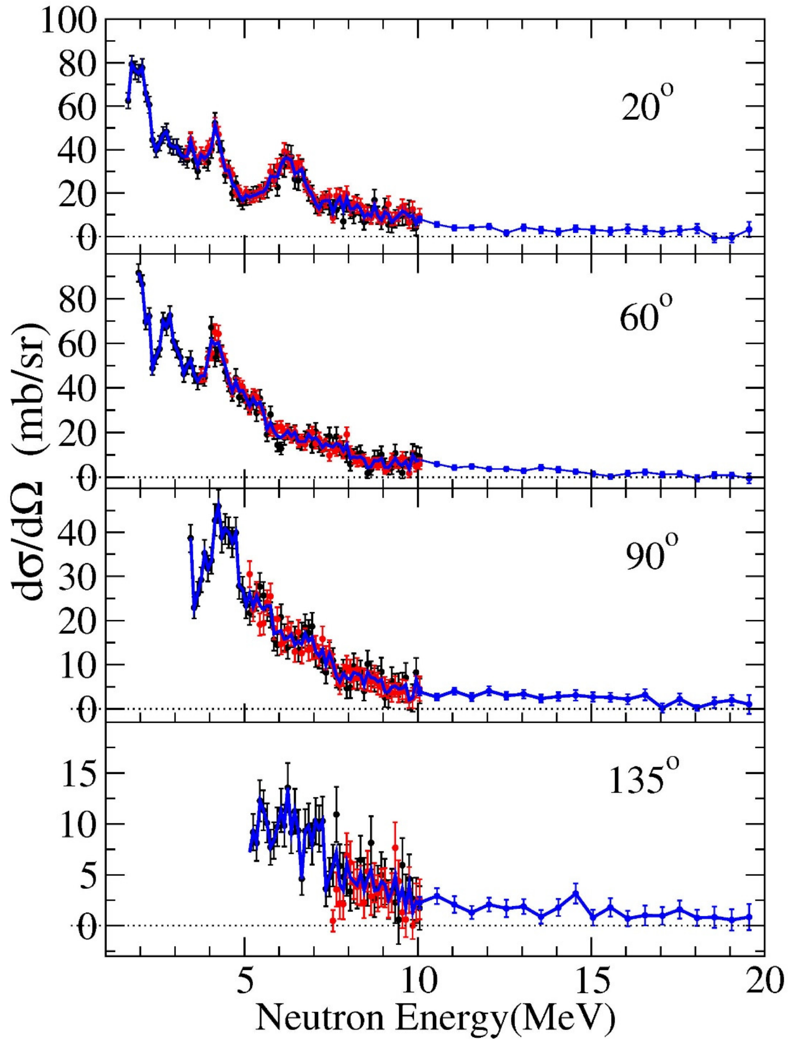
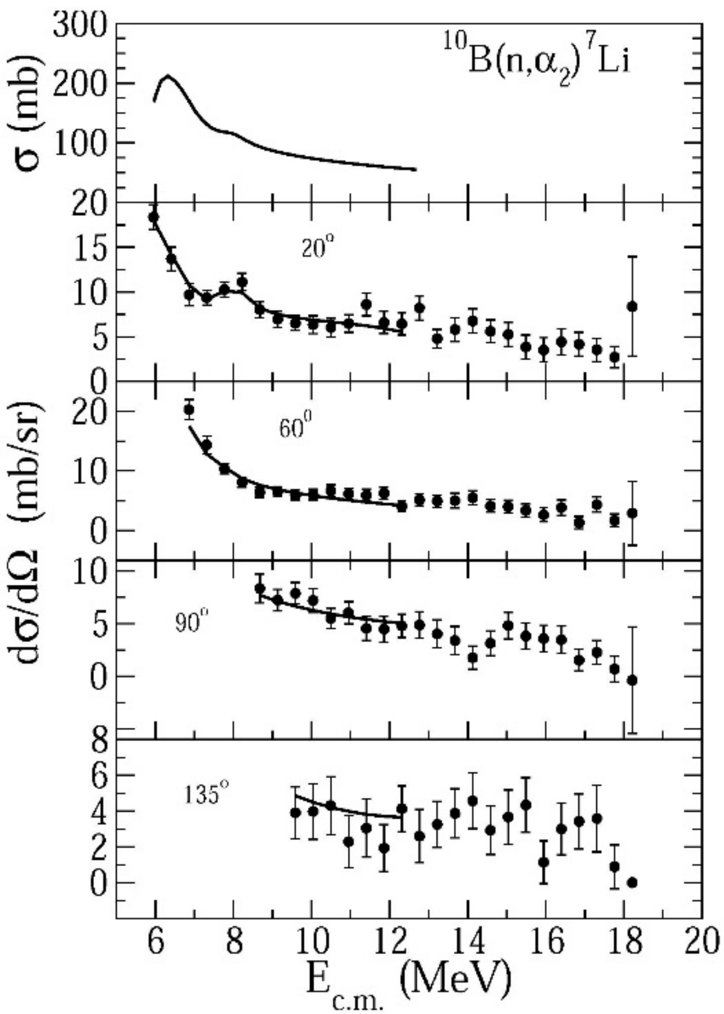
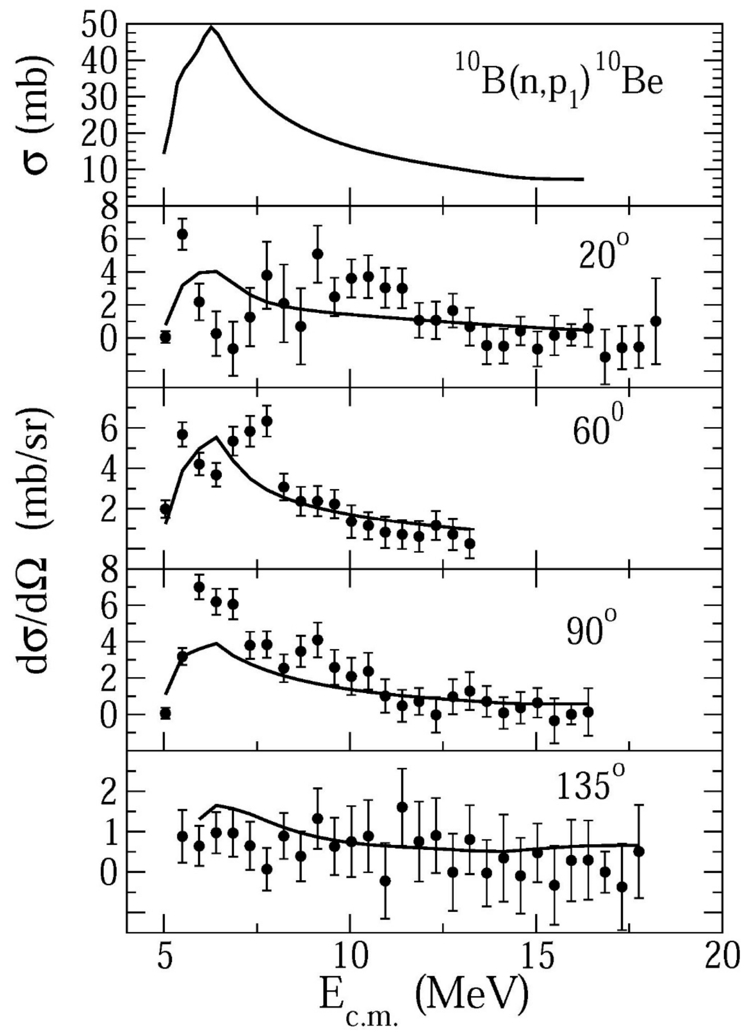
$^{10}B(n,\alpha)$ Measurements by Massey et al.



$^{10}B(n,Z)$ Measurements by Massey et al.



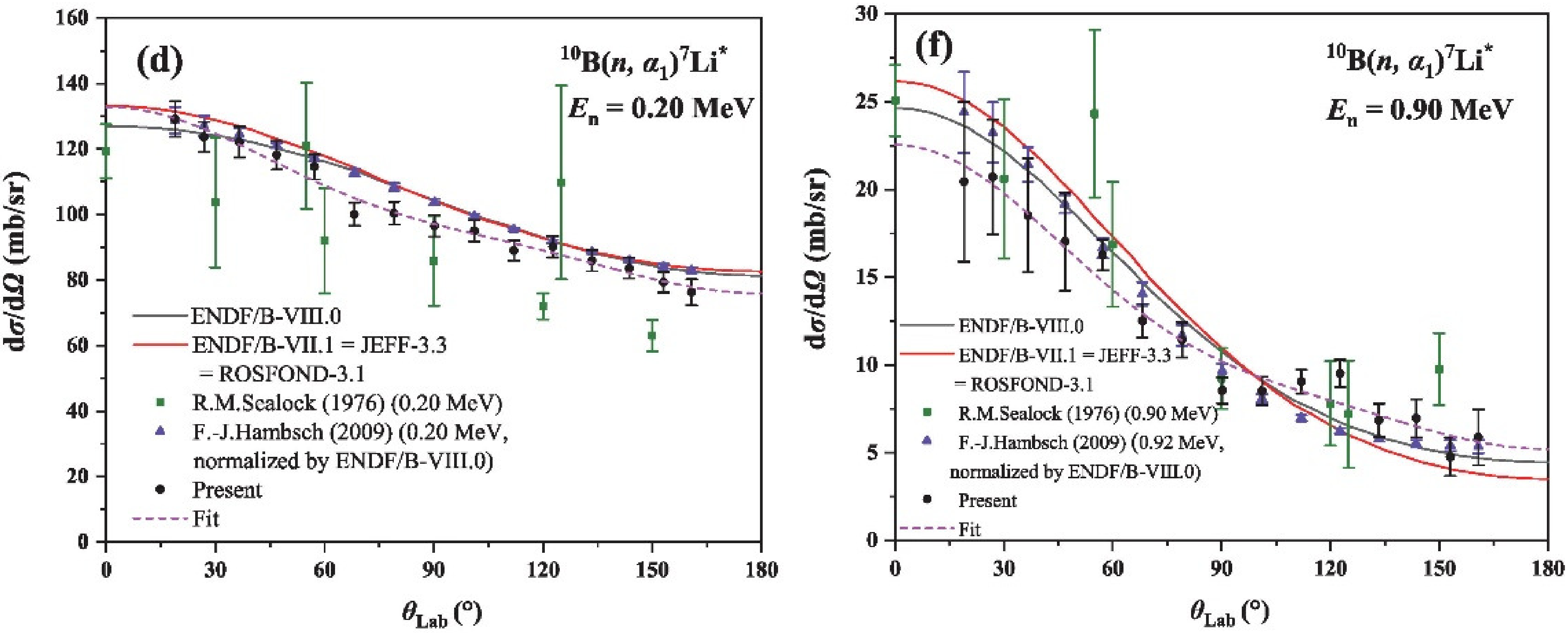


$^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1)$ Measurements at CSNS by Jiang et al.

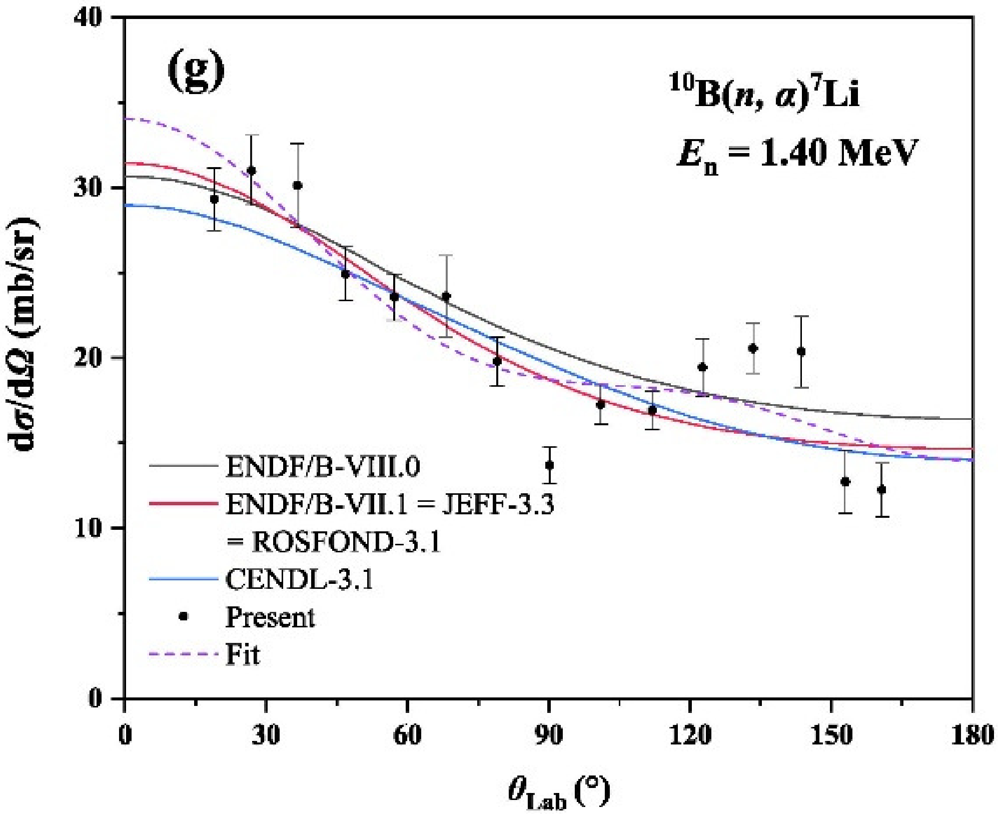
- The work extends from 1 eV to 2.5 MeV with 59 energy groups. Data were obtained with 15 E- ΔE detector arrays at 15 angles between 19.2 and 160.8 degrees. An evaporated ^{10}B target was used. All angles were measured simultaneously. The flight path was 58 m.
- The neutron energy spectrum was not measured at the position of the experiment. It is expected that this will affect the cross section values.
  - It will not affect the angular distributions.
  - A more precise spectrum measurement that corresponds to the location of the experiment is planned.
- It was not possible to separate the a_0 and a_1 peaks for energies above 1 MeV. To improve separation, a thinner sample and higher resolution detectors will be used in a new experiment.
- There are a number of cases where both the $^{10}B(n,\alpha_1)$ and $^{10}B(n,\alpha)$ differential cross section data are somewhat low compared with the standard. The integrated $^{10}B(n,\alpha)$ cross section data are largely in good agreement but somewhat low in the several hundred keV energy region compared with the standard.
- Uncertainties for the differential cross sections vary from 2.6% to 53%. Integrated cross sections from the differential results have uncertainties of 2.1% – 21.5%. Those data were normalized to the present standard in the interval from 0.3 to 0.5 MeV.

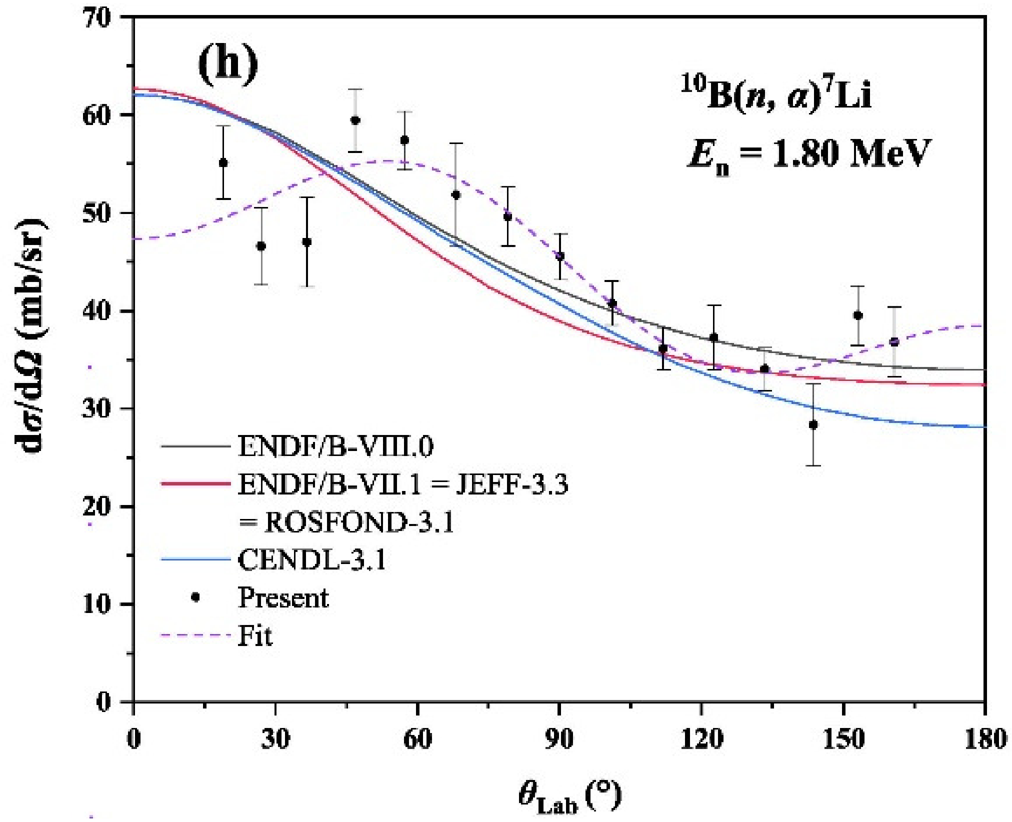
The work is published in: H. Jiang *et al.,* Measurements of differential and angle-integrated cross sections for the $^{10}B(n,\alpha)^7Li$ reaction in the neutron energy range from 1.0 eV to 2.5 MeV, 2019 *Chin. Phys.* ***C*** **43** 124002 (2019)

$^{10}B(n,\alpha_1)$ Angular Distribution Measurements by Jiang *et al*.

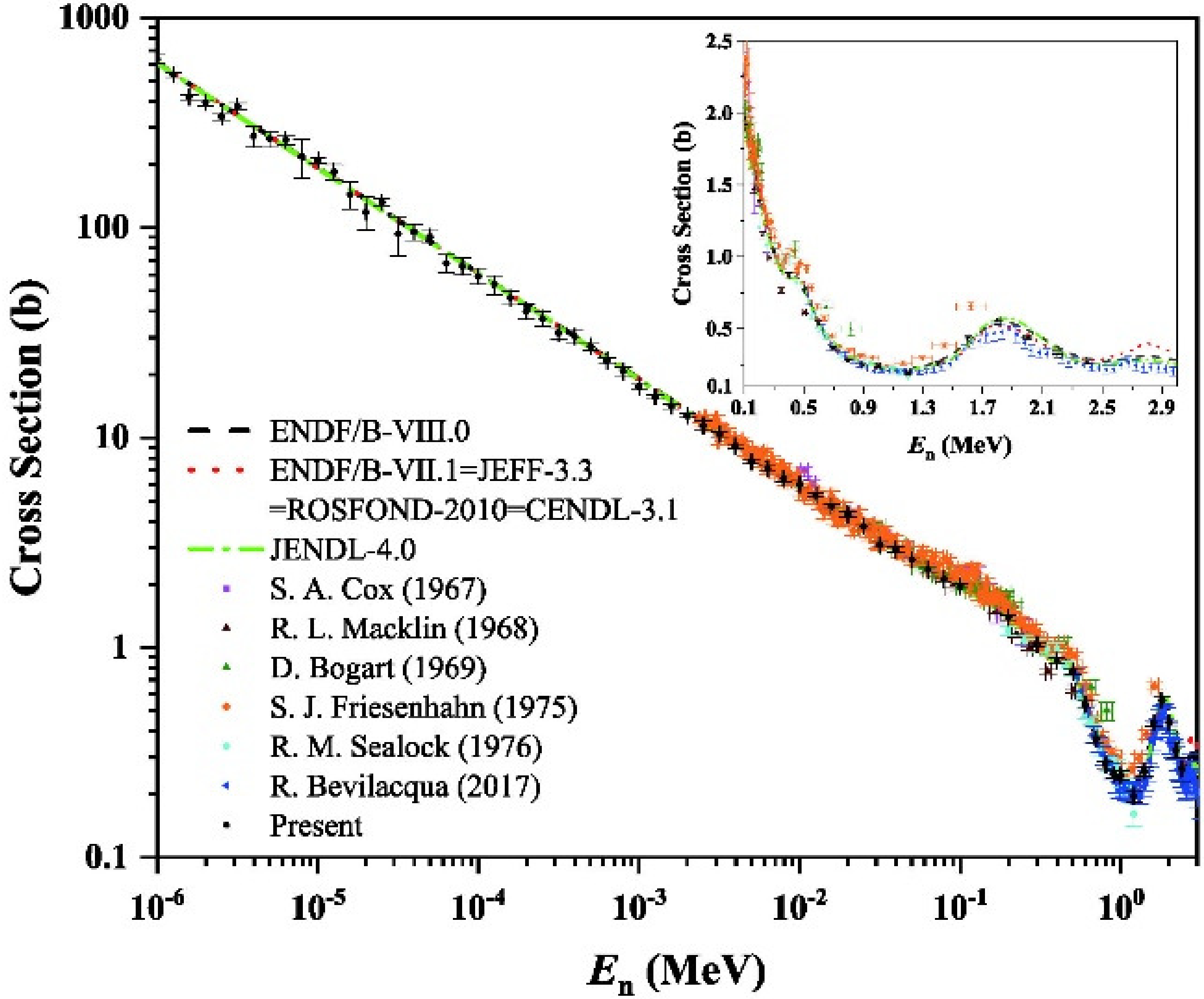


$^{10}B(n,\alpha)$ Cross Section Measurements by Jiang *et al*.





$^{10}B(n,\alpha)$ Cross Section Measurements at CSNS by Jiang et al.



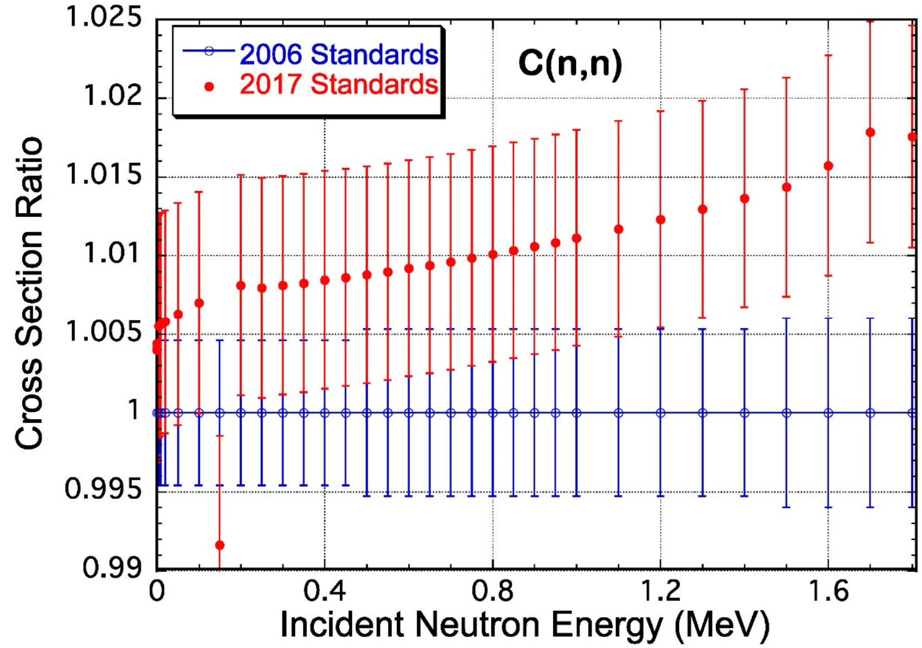
C(n,n) Cross Section

➢ 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.

➢Danon at RPI made total cross section measurements that are slightly lower than the 2017 standard values in the 150 to 400 keV energy region. Those data with uncertainties from a fraction of a percent to about 1% are in better than 1% agreement with the 2006 standards evaluation.

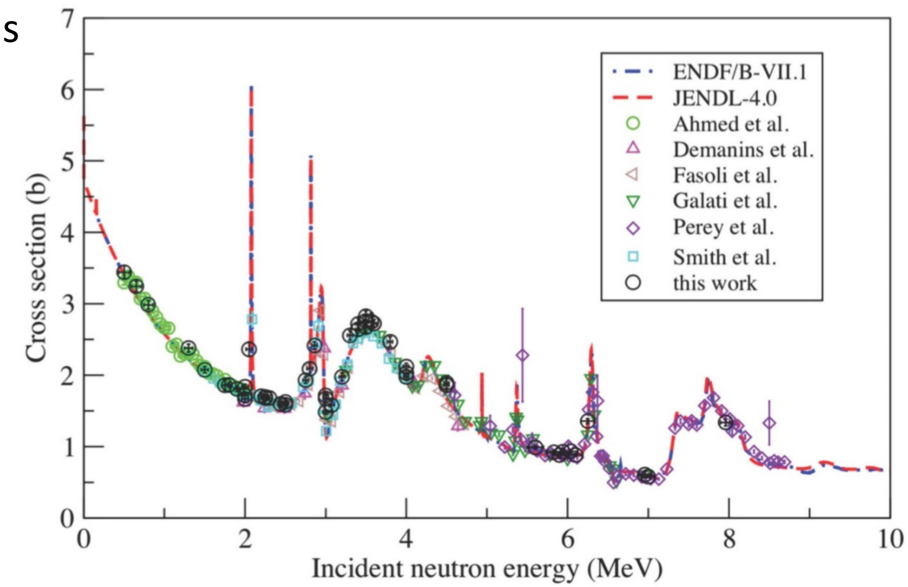
➢Data at RPI also indicate differences with both evaluations at back angles (about 156 degrees) **in the standards energy region**.

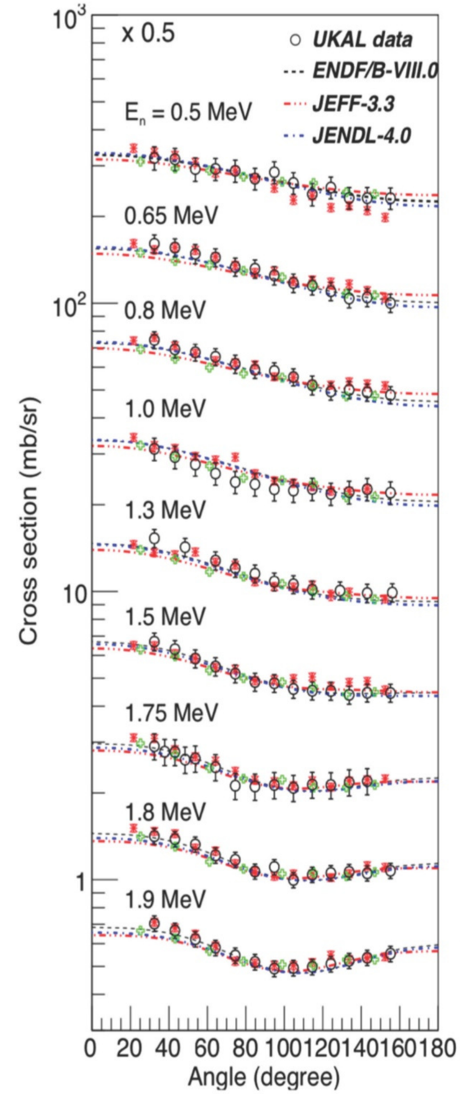
➢Hale is investigating this now



C(n,n) Data

- Measurements by Vanhoy have been made at the University of Kentucky of the carbon total cross section throughout the standards energy range (up to 1.8 MeV). The data have an uncertainty of about 6%.
  - They are relative to H(n,n) scattering
  - Excellent agreement with the ENDF/B-VIII standards evaluation for the angular distributions (shown to the right) and the integrated angular distributions yielding the total cross section (s





New work on the 30 keV MACS problem with gold capture

- Several efforts have been made to understand why the Ratynski and Kaeppeler experiment obtained a 30 keV MACS value for gold capture that is too low.
  - Reifarth *et al.* have made Monte Carlo simulations that show that the effect of the copper backing in the experiment of Ratynski and Kaeppeler was not properly taken into account. Using their corrections leads to a corrected experimental result consistent with the standards evaluation.
  - Improvements to the Reifarth correction were done by Praena and Jiménez-Bonilla with an improved representation of the Maxwellian using two different spectra.
  - They also did calculations for a flat sample such as is used in astrophysical experiments. They obtained in two different experiments, 626 ± 15 mb and 612 ± 12 mb,
  - They made corrections to the Ratynski and Kaeppeler data for copper scattering, spectrum corrections and changes in the half-life of ^{198}Au resulting in a change from 582 mb to 622 mb for the Ratynski and Kaeppeler data. The present standards value is 620 ± 11 mb.

The Praena work is published in J. Praena and P. Jiménez-Bonilla, Two absolute integral measurements of the ^{197}Au(n,γ) stellar cross-section and solution of the historic discrepancies, EPJ Web of Conferences 239, 19002 (2020)

Fission Cross Section Measurements

- Absolute Measurements of the $^{238}U(n,f)/^{235}U(n,f)$ cross section ratio were made at CSNS by Wen et al. up to 20 MeV. The uncertainties range from 2.3% to 3.6% for the $^{238}U(n,f)$ standards energy range.

Published in: J. Wen, *et al.*, Measurement of the U-238/U-235 fission cross section ratio at CSNS – Back-n WNS, Ann. Nucl. Energy **140,** 107301 (2020)

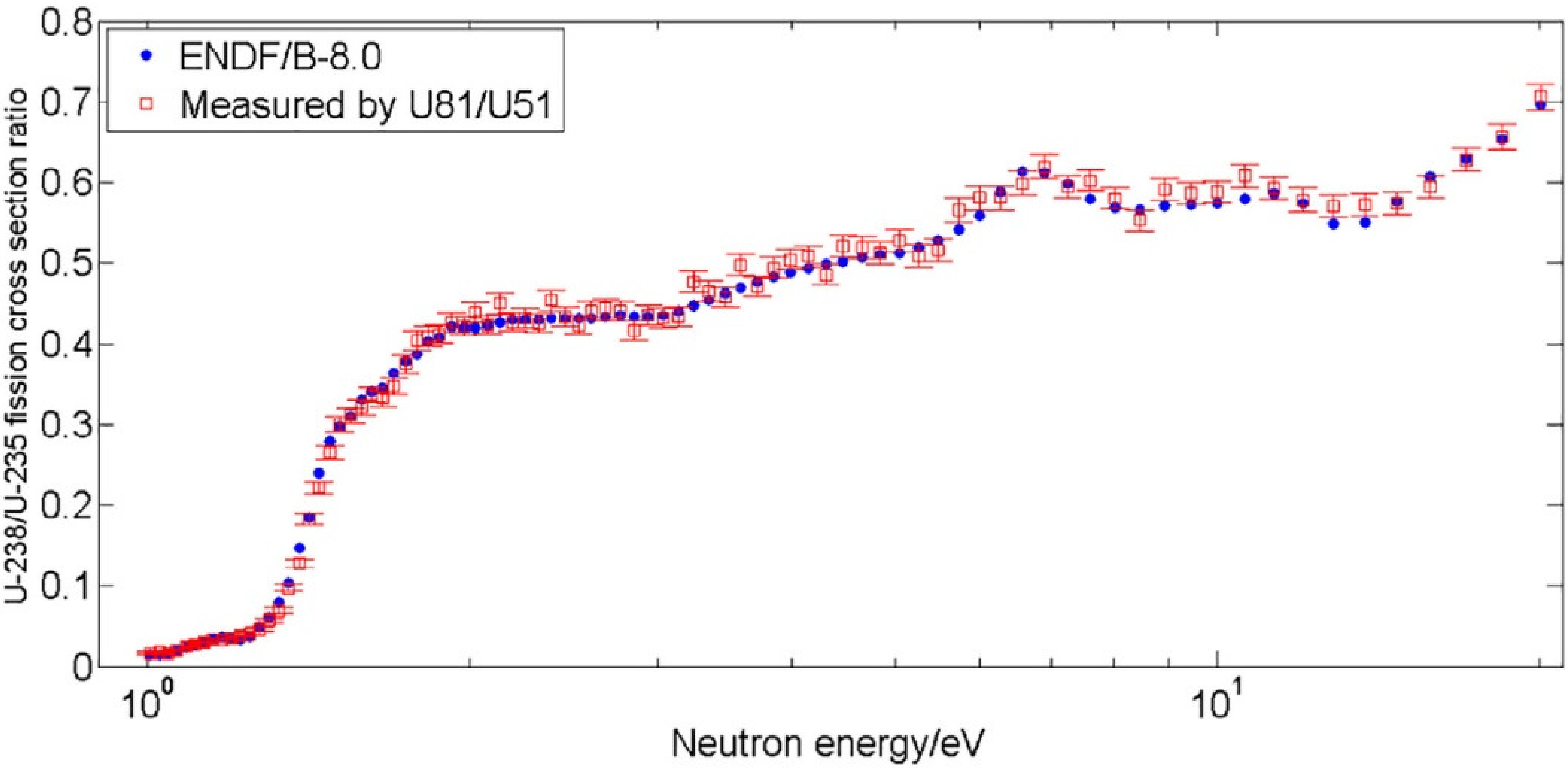
- Work on the $^{235}U(n,f)$ cross section relative to hydrogen scattering from 10 MeV to 150 MeV was discussd by Pirovano at the recent standards meeting. Present statistical uncertainty: 4-10%, systematic uncertainty is being defined. The extension to 1 GeV by Manna *et al.* is underway. (n_TOF collaboration). There is a strong need for data at these very high energies.

- A new measurement has been initiated at NIST of the $^{235}U(n,f)$ cross section at a sub-thermal energy using the same basic setup used for the $^{6}Li(n,t)$ measurement, but with a well characterized ^{235}U deposit. Fraction of a percent uncertainty results are expected.

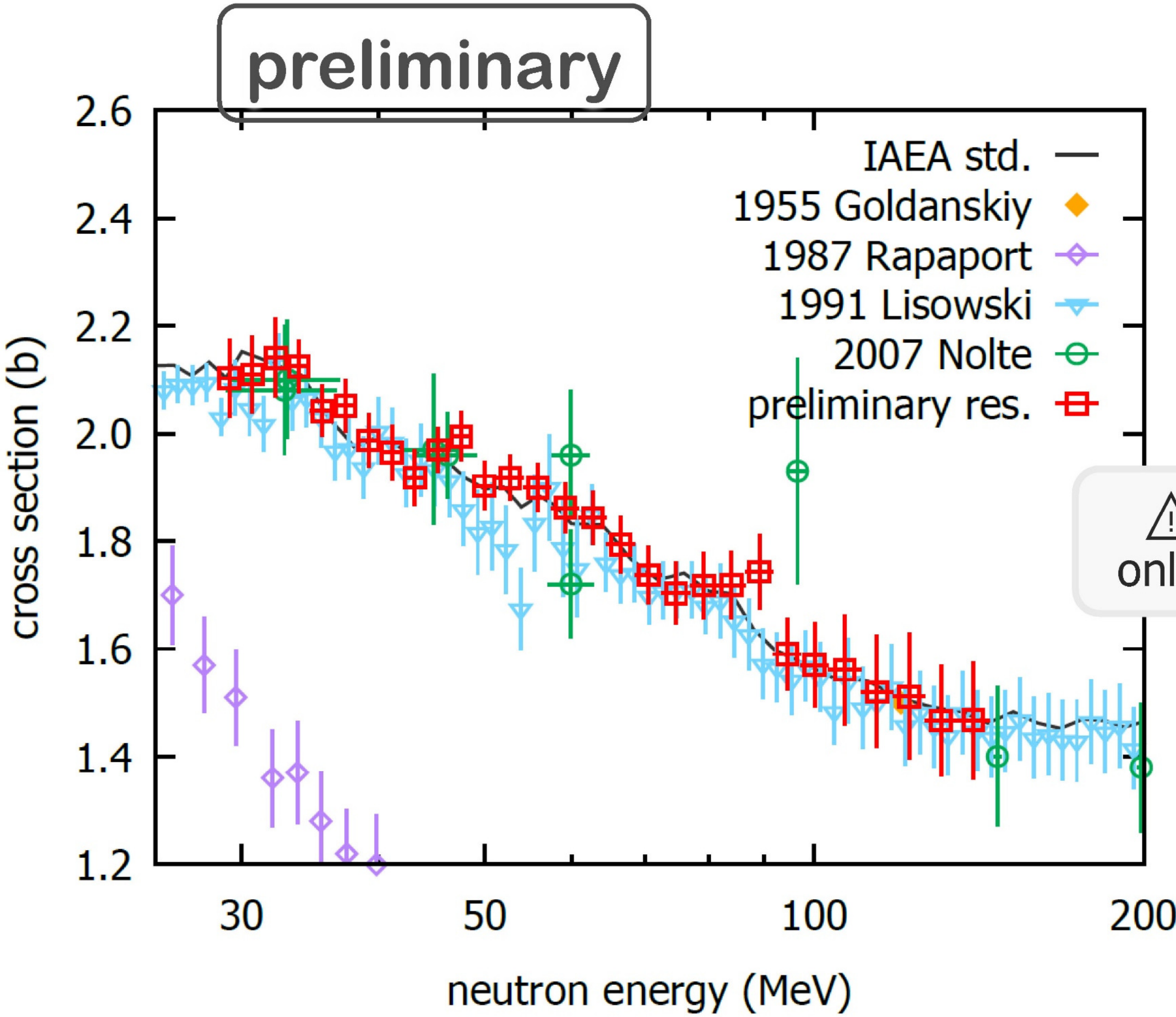
- A measurement was made of the $^{235}U(n,f)$ cross section from thermal to 170 keV by Amaducci *et al*. in the n_TOF collaboration. The data are relative to the $^{6}Li(n,t)$ and $^{10}B(n,\alpha)$ cross section standards - normalized using the 7.8 to 11 eV fission integral. The results obtained in the standards energy region, 150-170 keV agree with the standard. This was recently published.

- $^{239}Pu(n,f)/^{235}U(n,f)$ cross section ratio measurements made at LANSCE by the NIFFTE collaboration are being analyzed.

$^{238}U(n,f)/^{235}U(n,f)$ Cross Section Ratio Measurement at CSNS for One Cell Combination by Wen et al.



^{235}U(n,f) Cross Section Measurement by Pirovano (n_TOF collaboration)



Further analysis of the Recoil Proton Telescope and Fission Chamber data are underway

⚠ uncertainties only from statistics

Hansell Nubar Measurement

- Work done in conjunction with the PROSPECT study that led to a measurement of nubar for ^{252}Cf.

- The measurement was made with a large bank of ^{6}Li loaded liquid scintillation detectors. There were 154 individual segments (detectors) with a total of 4 tons of ^{6}Li.

  - Differs from the scintillation tank type measurements since gamma-rays from a ^{252}Cf source near the detector start the detection process vs neutrons. Detection of fission fragments in a fission chamber is not used. Then neutrons are detected using the ^{6}Li(n,t) reaction.

  - In concept this different design could provide information on systematic uncertainties for other nubar experiments.

  - High efficiency for neutron detection, about 70%. Unfortunately the uncertainty in the efficiency (2.2%) is large. A small loss of lithium with time was noted.

  The ^{252}Cf nubar obtained is 3.805 ± 1.4% not including the uncertainty in the neutron efficiency. The uncertainties are not final. The present standards value is 3.764 ± 0.42% including the correction for USU.

  - This work is not final. More runs may be possible.

ORNL Nubar Proposed Measurements

- A study is underway at ORNL that should lead to an improved measurement of nubar for ^{252}Cf.
- The measurement will be similar to the scintillator tank measurements done by Spencer
  - However a large bank of ^{3}He proportional counters will be used instead.
  - This will provide a much higher efficiency for neutron detection, about 87%
  - A much lower bias can be used on these detectors since they do not have the high sensitivity to gamma rays that scintillators have. Less modelling is required.
  - This experiment may help to resolve the Mn-bath scintillator tank nubar differences
  - This method is new and independent of some systematic measurement biases that may be present in experiments using scintillation tanks, Mn-baths and the graphite pile.

Summary-What is Needed to Improve the Standards

- Improved experimental work is necessary for all the standards
  - Especially the boron and lithium standards so the upper energy bound can be increased
  - Accurate hydrogen scattering measurements at high energies are needed

- Extending the hydrogen standard evaluation 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

- Additional work beyond the $^{239}Pu(n,f)$ work of Neudecker for inspection of uncertainty sources for standards measurements should be done
  - All data in the GMA database should be used and correlations should be taken into account for this investigation

- Further work on unrecognized sources of uncertainty
  - Inspection of data sets for unrecognized sources of uncertainty and correlations in data
  - Investigation of the energy dependence of USU for each standard

- Consider improved evaluation techniques for the standard cross sections