Recent Work on Neutron Standards Data Since the Completion of the Standards Evaluation

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

- Measurements of Neutron Cross Section Standards Completed and underway

- Work on Source Strength Determination related to Fluence and Cross Section Determination

The Neutron Cross Section Standards

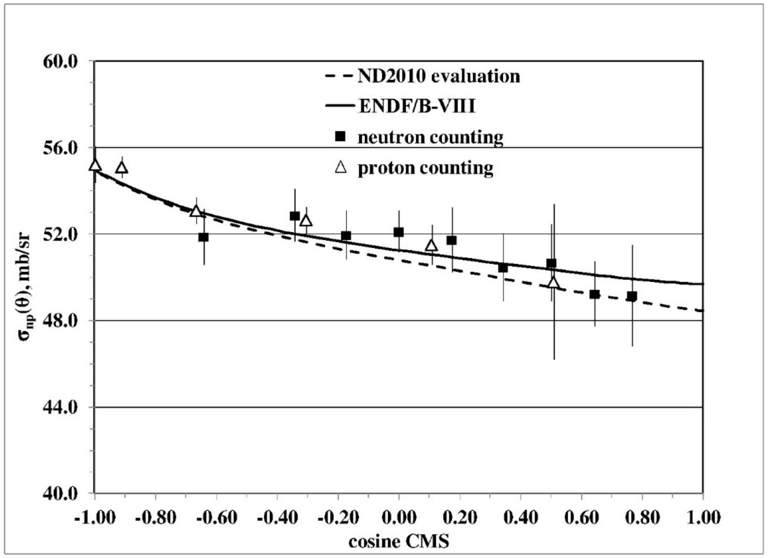
Reaction	Energy Range
H(n,n)	1 keV to 20 MeV
^{3}He(n,p)	0.0253 eV to 50 keV
^{6}Li(n,t)	0.0253 eV to 1 MeV
^{10}B(n,α)	0.0253 eV to 1 MeV
^{10}B(n,$\alpha_1\gamma$)	0.0253 eV to 1 MeV
C(n,n)	10 eV to 1.8 MeV
Au(n,γ)	0.0253 eV, 0.2 to 2.5 MeV, 30 keV MACS
^{235}U(n,f)	0.0253 eV, 7.8-11 eV, 0.15 MeV to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

Nuclear Reaction Activities: H(n,n)H Standard Angular Distribution Work

This work was initiated to resolve problems with the hydrogen database.

- We previously made measurements at 10 and 14.9 MeV at the Ohio University accelerator facility. The data were obtained by detecting the recoil proton.
- New 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 data were obtained at the Ohio University accelerator facility.
- (collaboration of NIST with Ohio University, LANL and the University of Guelma)

This work has been completed. A paper has been submitted for publication on this work. Present results shown here are compared with data obtained using detection of the recoil proton. There is excellent agreement with the ENDF/B-VIII standards evaluation within the uncertainties but there is a trend toward lower values at small CMS angles for both experiments.



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

- Simulations have been conducted to determine optimum positions for the detectors, neutron energy range possible as well as durations for the event and background measurements.

- Experiments are underway using E-ΔE detector arrays in a vacuum chamber viewing a polyethlene sample bombarded by white source neutrons from 1.6 GeV protons on a target.

- It is possible that angles from 10 to 55 degrees in the laboratory system may be possible with neutron energies considerably above 20 MeV.

- It is important to extend the hydrogen standard to higher neutron energies. It is now limited to 20 MeV.

- R-matrix analyses are underway by Paris and Hale at LANL to extend the energy range to 150 MeV and possibly 200 MeV.

$^{6}Li(n,t)$ 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. The uncertainty is mainly from the uncertainty in the ^{6}Li mass. The deposits were obtained from IRMM. The initial value obtained was in excellent agreement with the ENDF/B-VIII standards evaluation. It was recently found at IRMM that the mass reported was in error. Using the new mass value produces a cross section value with an uncertainty of 0.3% that is 1% lower than the ENDF/B-VIII value. **Last month samples were sent for evaluation by Isotope Dilution Mass Spectrometry to obtain a very accurate value for the mass.**

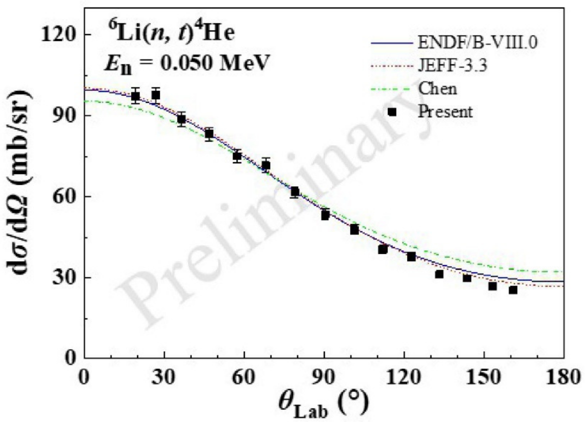
- **The low energy (thermal) ENDF/B-VII cross section value is largely determined by three measurements made in 1970-1971.**
  - It is not clear how well they determined their ^{6}Li masses.

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

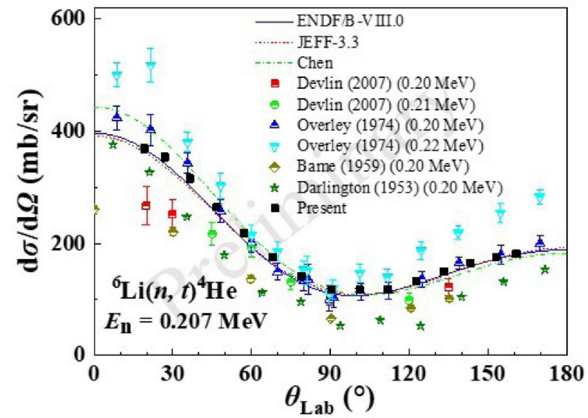
$^{6}Li(n,t)$ Measurements at the China Spallation Source by Bai et al.

- Angular distributions were measured at 15 angles in the experiment with the white source.
  - The work extends from 1 eV to 3 MeV (80 energy groups)
    - The differential results were analyzed to obtain integrated cross section data
    - **Preliminary results were shown at the ND2019 conference**
    - This work could provide the data necessary for a smooth transition from the H(n,n) standard to the $^{6}Li(n,t)$ standard with sufficient overlap

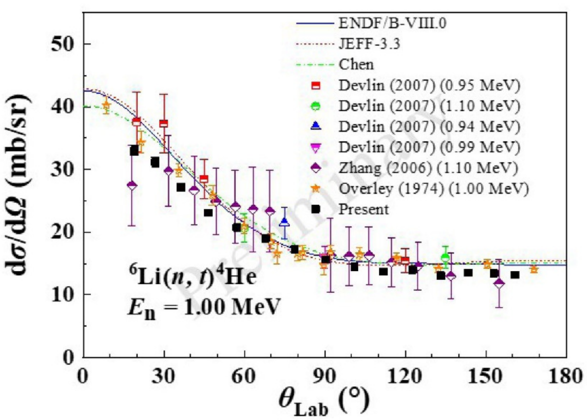
^{6}Li(n,t) Angular Distributions Measurements by Bai *et al.*



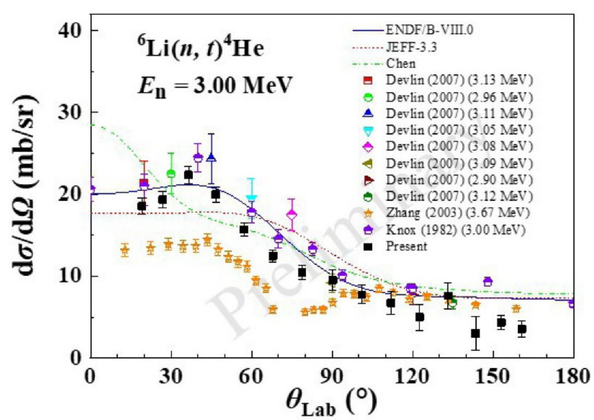
(c) E_n = 0.050 MeV



(d) E_n = 0.207 MeV

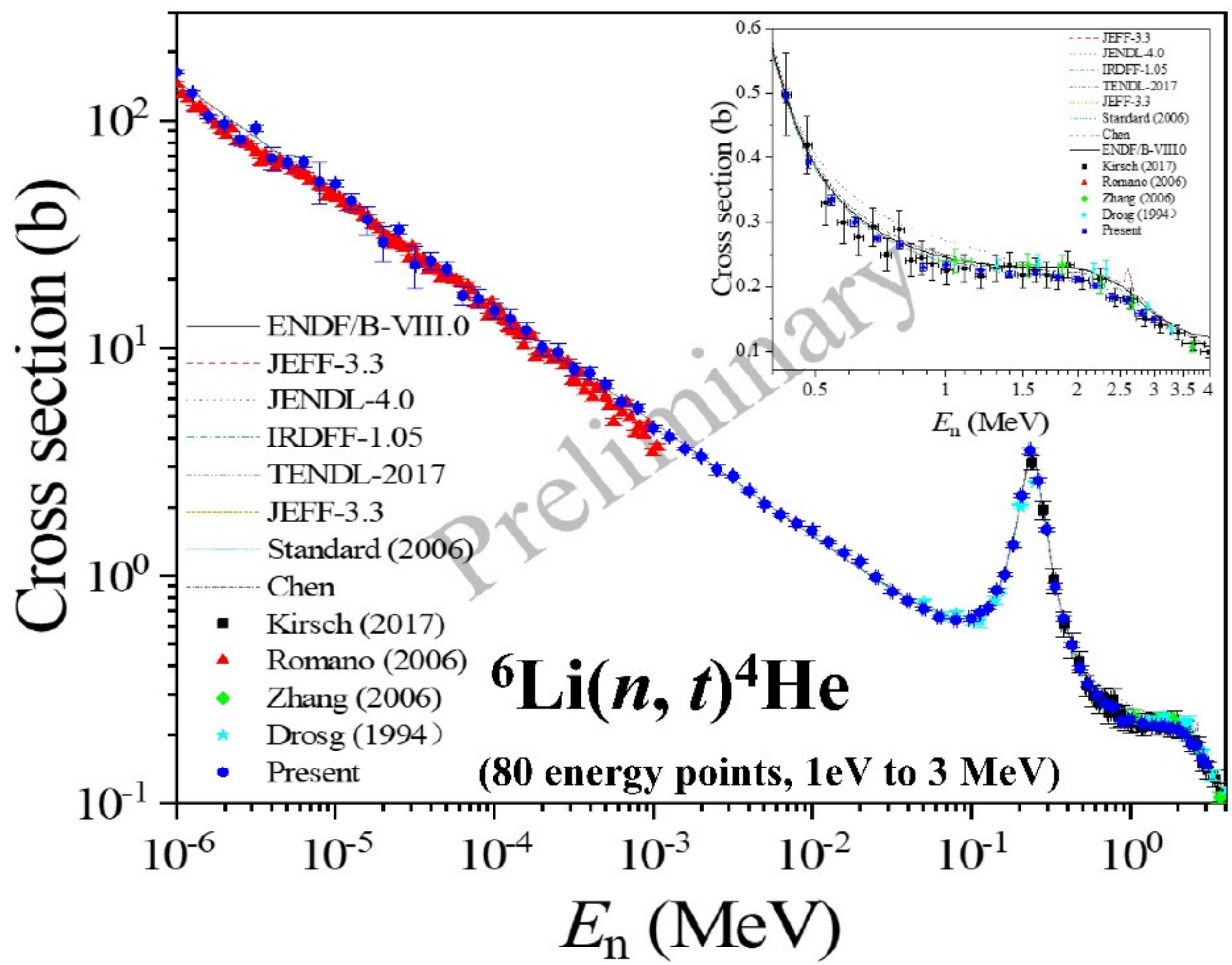


(e) E_n = 1.00 MeV



(f) E_n = 3.00 MeV

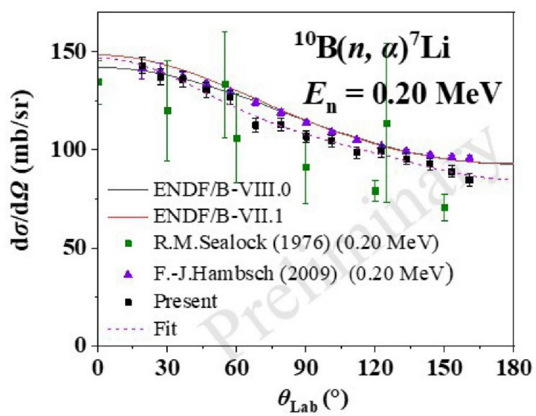
^{6}Li(n,t) Cross Section Measurements by Bai *et al.*



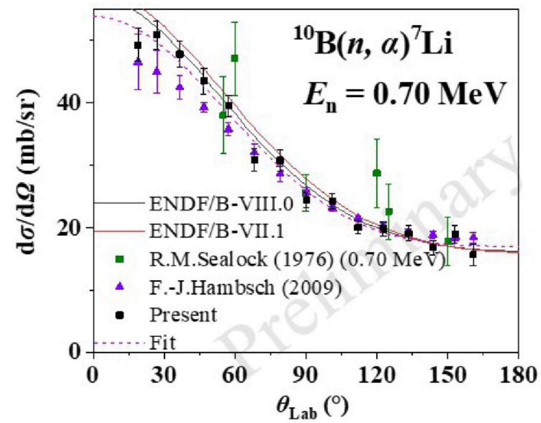
$^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1)$ Measurements at the China Spallation Source by Jiang et al.

- Angular distributions were measured at 15 angles with the white source.
  - The work extends from 1 eV to 3 MeV (67 energy groups)
    - The differential data were analyzed to obtain integrated cross section results
    - **Preliminary results were shown at the ND2019 conference**
    - This work could provide the data necessary for a smooth transition from the H(n,n) standard to the $^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1)$ standards with sufficient overlap.

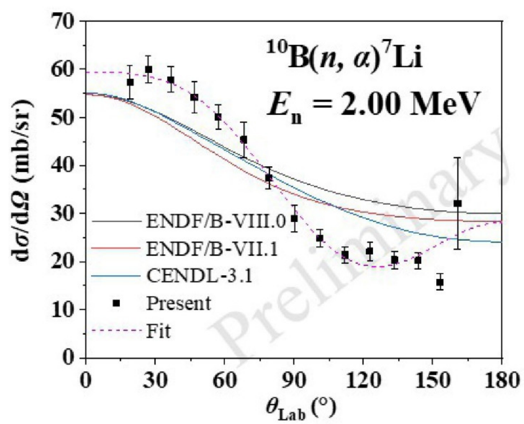
$^{10}B(n,\alpha)$ Angular Distribution Measurements by Jiang *et al*.



(c) $E_n = 0.20$ MeV

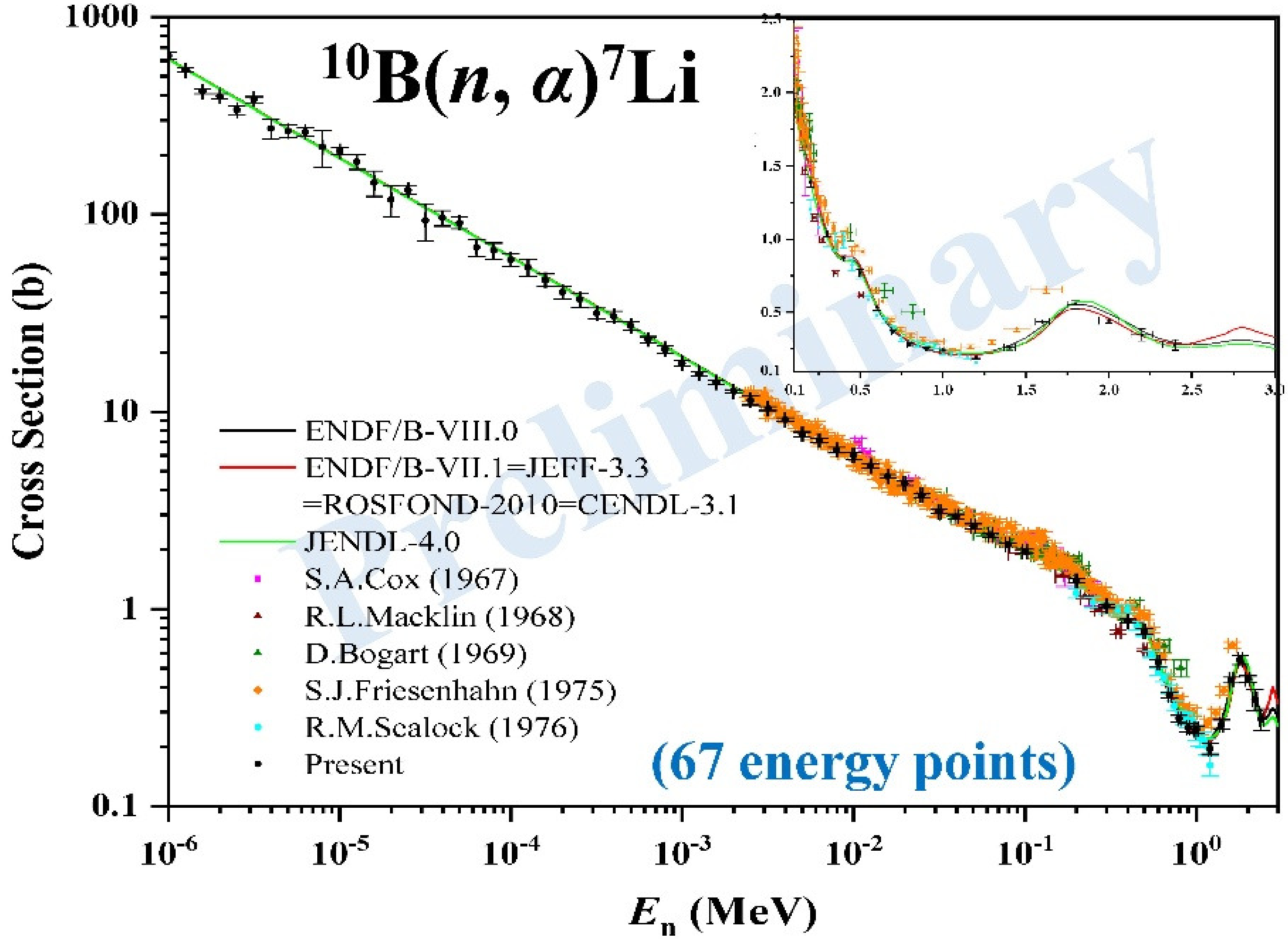


(d) $E_n = 0.70$ MeV

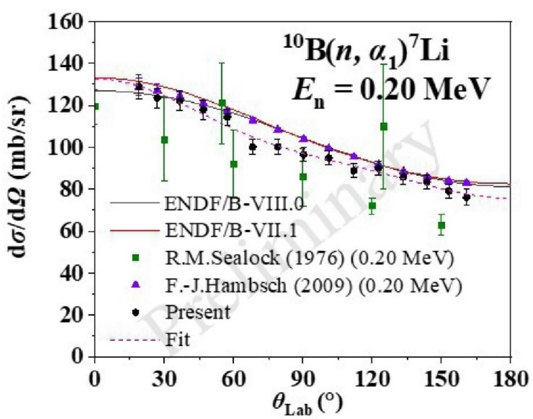


(e) $E_n = 2.00$ MeV

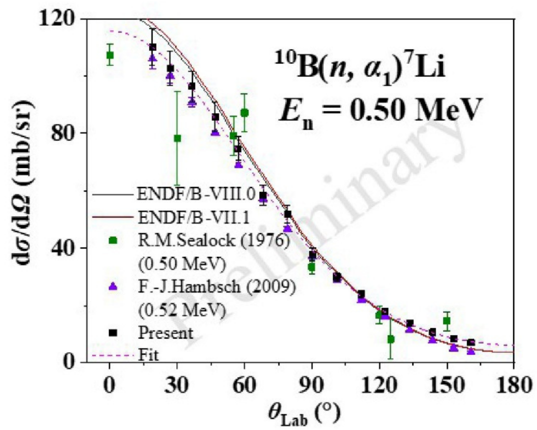
$^{10}B(n,\alpha)$ Cross Section Measurements by Jiang *et al*.



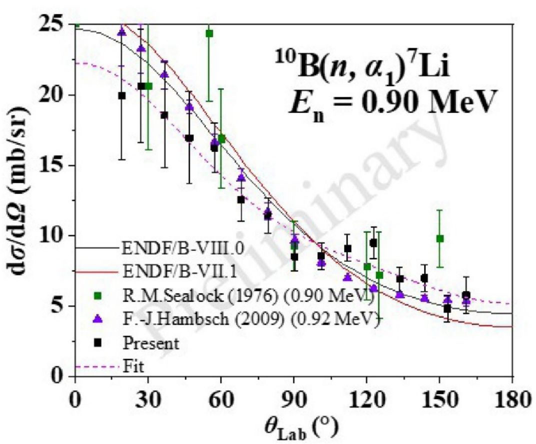
$^{10}B(n,\alpha_1)$ Angular Distribution Measurements by Jiang *et al*.



(c) E_n = 0.20 MeV

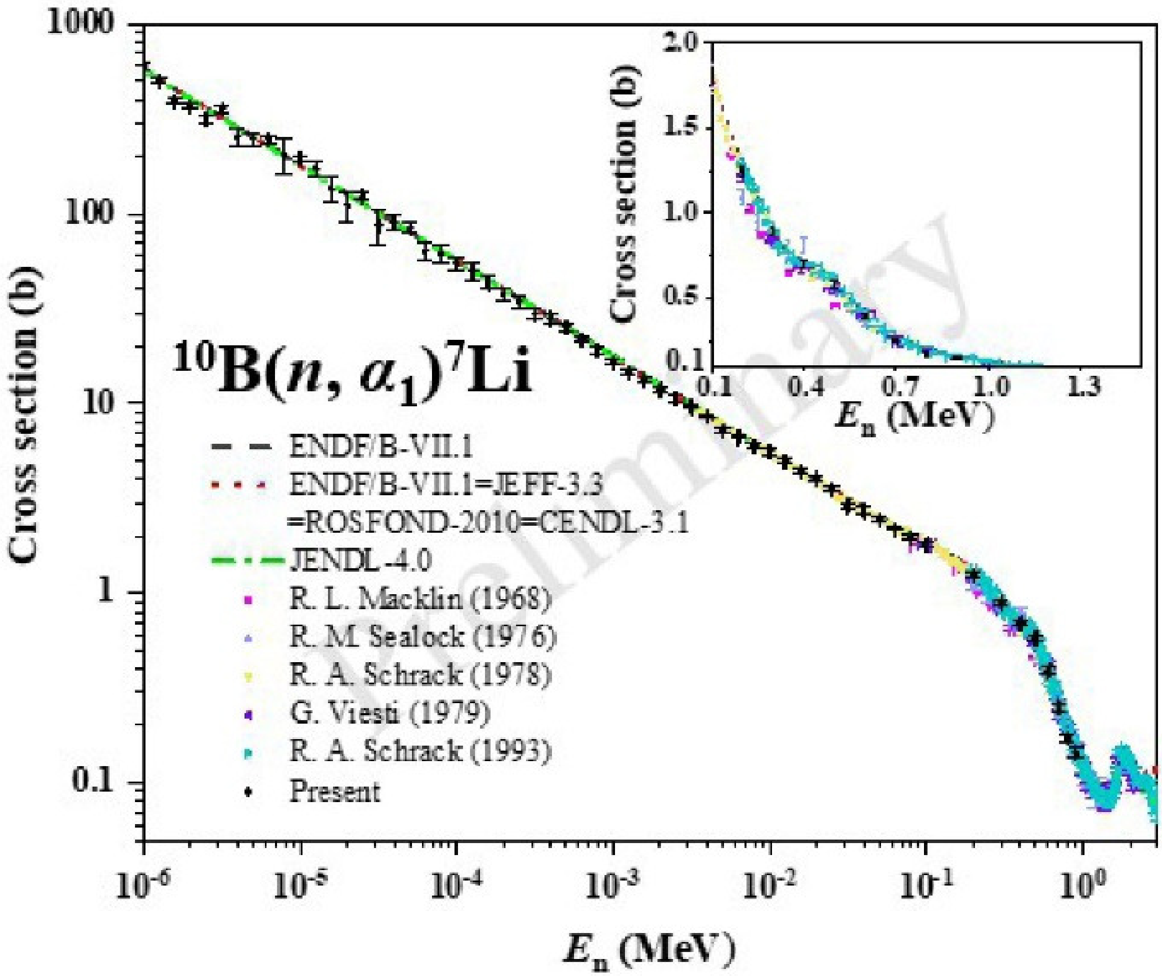


(d) E_n = 0.50 MeV

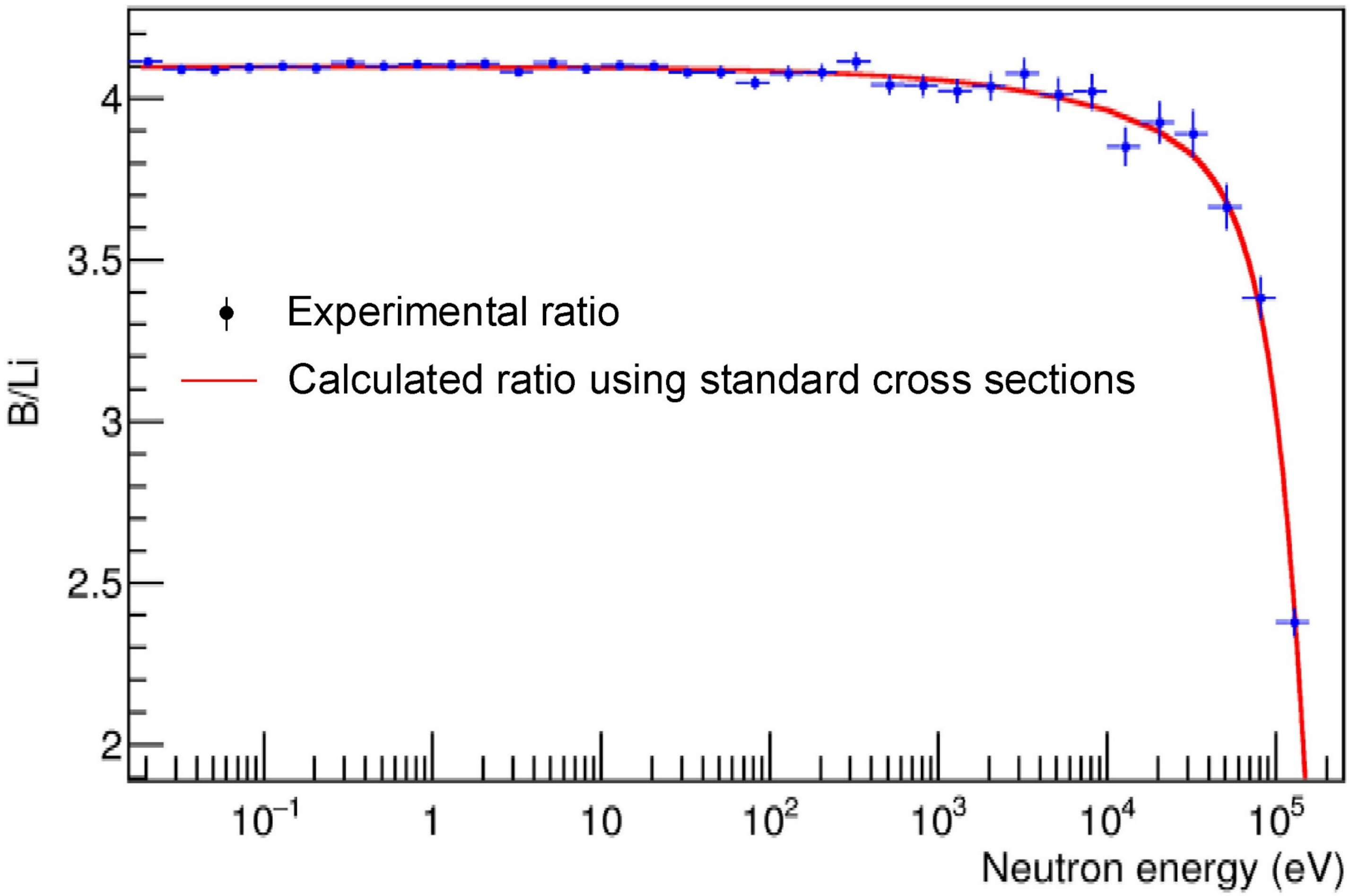


(e) E_n = 0.90 MeV

$^{10}B(n,\alpha_1)$ Cross Section Measurements by Jiang *et*



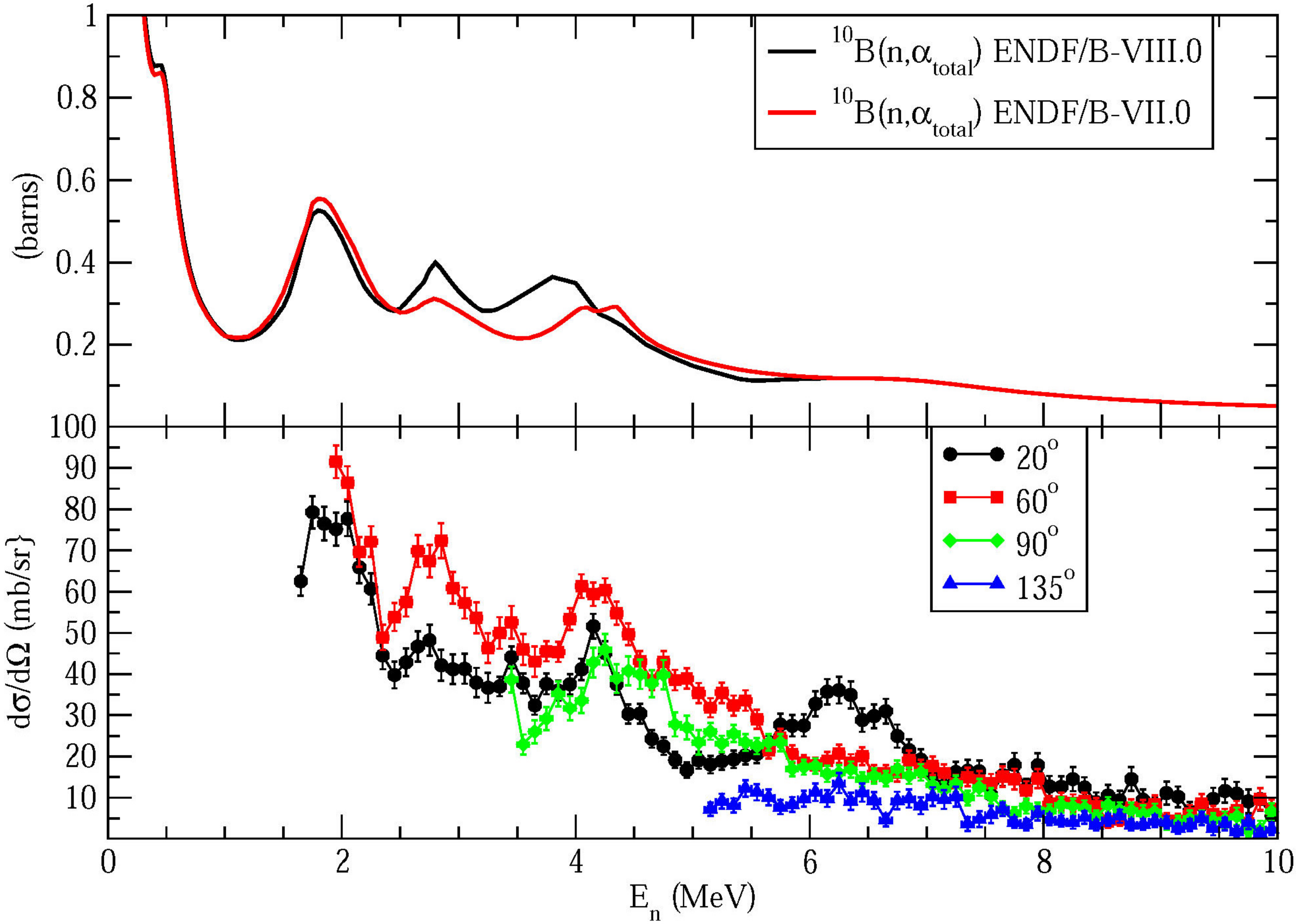
Amaducci *et al*. n_TOF Measurements of $^{10}B(n,\alpha)/^{6}Li(n,t)$ Cross Section Ratio Compared with the Calculated Result



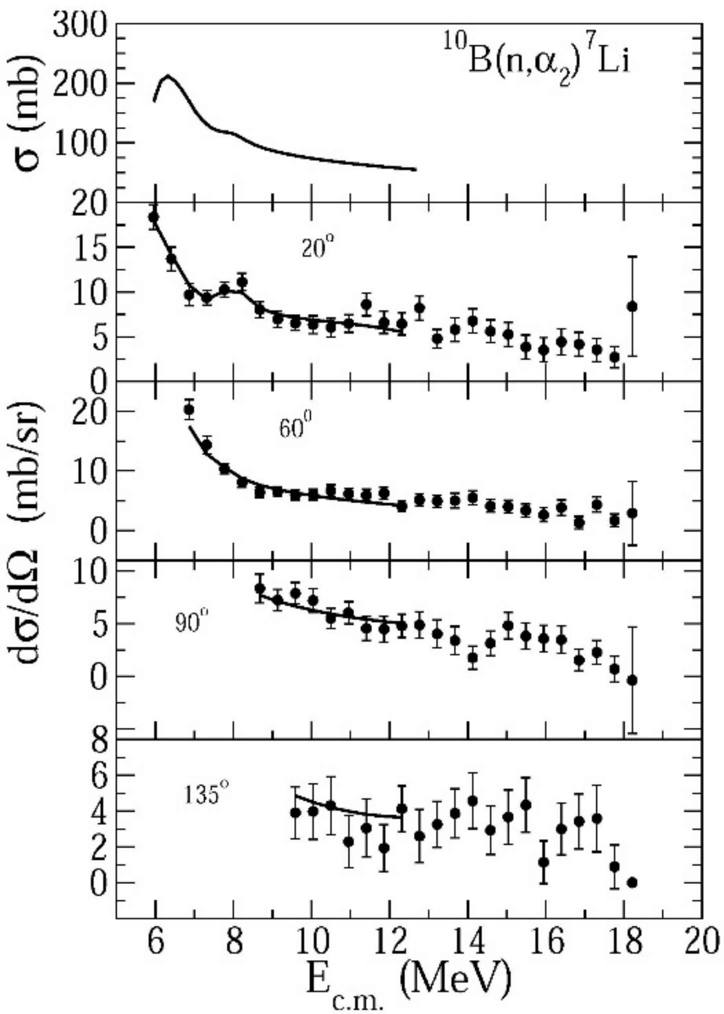
$^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1\gamma)$ Measurements

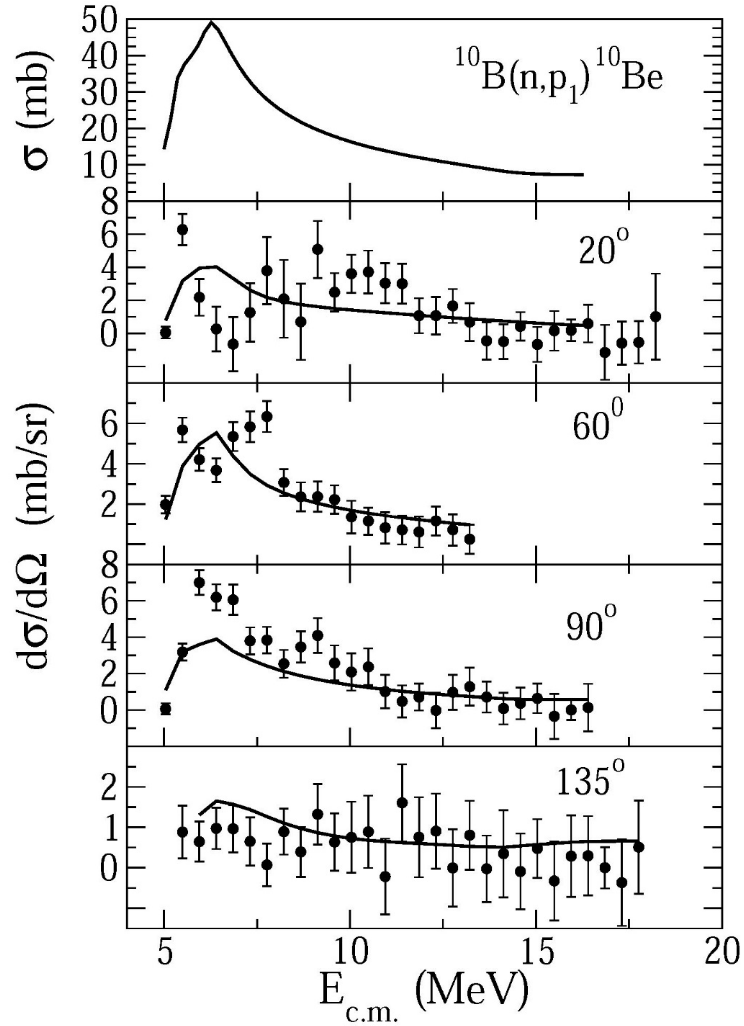
- Massey *et al.* have measured $^{10}B(n,Z)$ reactions for neutron energies from 2 to 20 MeV.
  - The work was done at the LANSCE WNR facility
  - Proton, triton and alpha particles were measured at four angles
  - Differential cross sections were obtained for the $^{10}B(n,p_0)^{10}Be$, $^{10}B(n,p_1)^{10}Be$, $^{10}B(n,t_0)^{8}Be$, $^{10}B(n,t_1)^{8}Be$, $^{10}B(n,\alpha_2)^{7}Li$, and $^{10}B(n,\alpha_3)^{7}Li$ cross sections
  - These data can be used in R-matrix fits to improve the standards

$^{10}B(n,\alpha)^{7}Li$ Measurements by Massey et al.



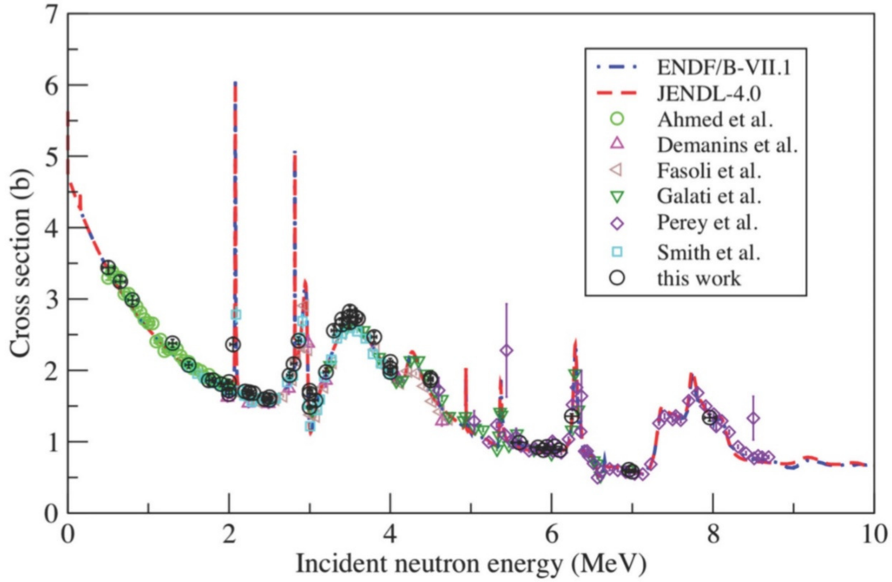
^{10}B(n,x) Measurements by Massey et al.

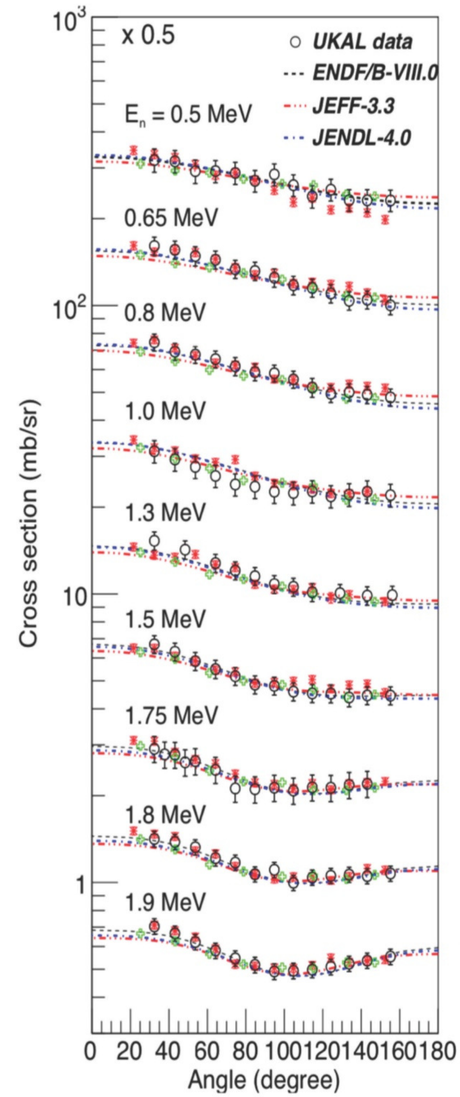




C(n,n) Data

- Measurements by Ramirez, Vanhoy have been made at the University of Kentucky of the carbon total cross section from 90 keV to 1.8 MeV.
  - 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 (shown below).





Au(n,γ) Data at Low Neutron Energies

- The 30 keV Au(n,γ) Maxwellian averaged cross section (MACS) is a reference cross section for the KADONIS 0.0 astrophysics database. The value of that reference was originally from the Ratynski-Käppeler evaluation based on the Ratynski and Käppeler measurements and the Macklin measurement. It is 582 ± 9 mb

  - Several Au(n,γ) cross section measurements have been made since the 2006 standards evaluation (ENDF/B-VII). They all agree within their uncertainties with the standards evaluation. They indicate the Ratynski and Käppeler results are low by about 5-7% near 30 keV.

    - The 30 keV MACS for gold capture using the 2017 standards evaluation (ENDF/B-VIII) has been accepted as a standard cross section. The astrophysical database, KADONIS 1.0, has changed the MACS for the Au(n,γ) cross section. Their new value, 611.6 ± 6.0, agrees with the 2017 standards evaluation of 620 ± 11 mb within one standard deviation.

New work on the 30 keV MACS problem with gold capture

- Reifarth *et al.* have recently 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.

  - In the Reifarth paper (Käppeler is a coauthor), a new evaluation is done of that MACS. They obtain 612 ± 6 mb. The standards value is 620 ± 11 mb. The two now agree within their uncertainties.

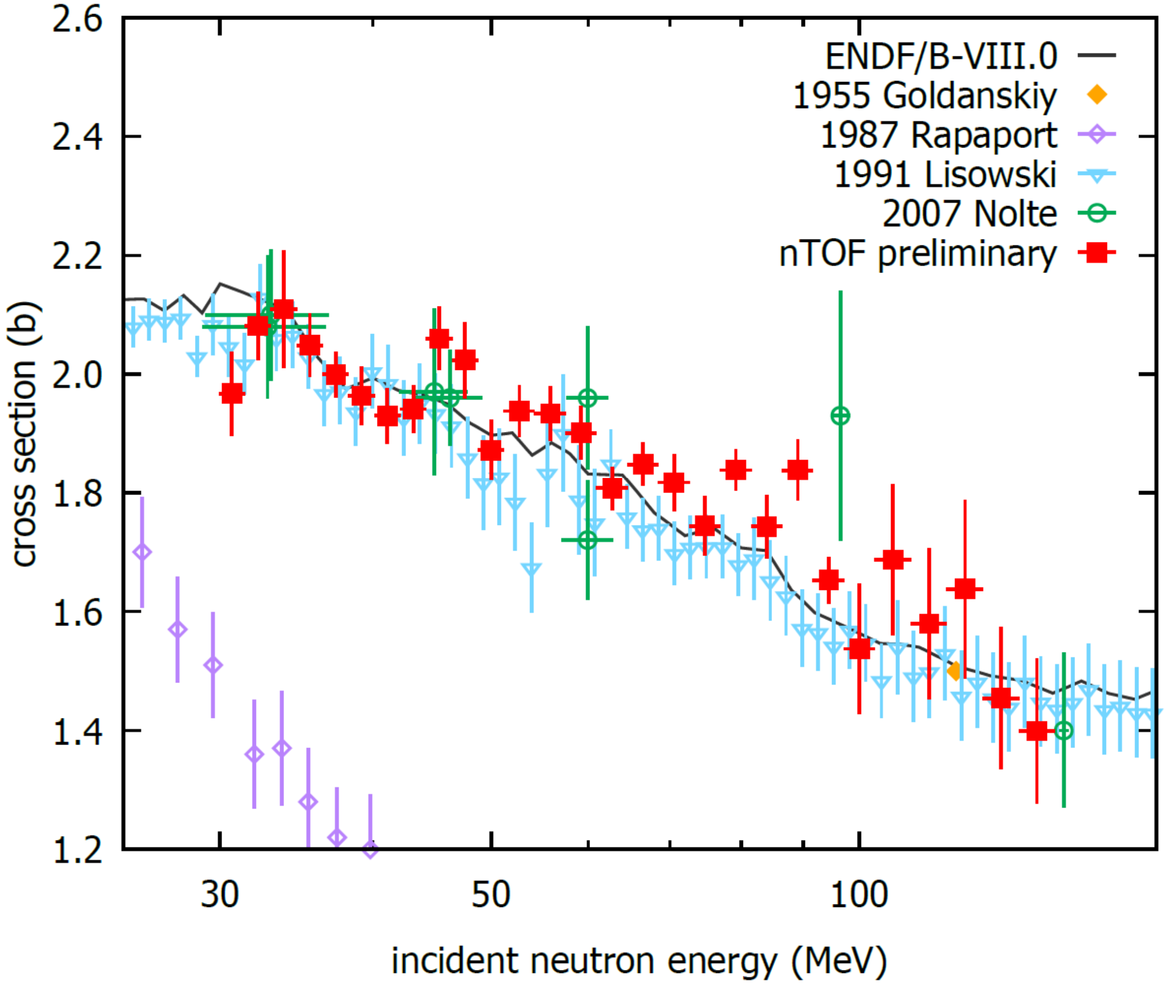
- An improvement to the Reifarth correctione was done by Praena and Jiménez-Bonilla with an improved representation of the Maxwellian. They obtained in two different experiments, 626 ± 15 mb and 612 ± 12 mb, both in agreement with the standards value

- A paper by Guido Martín-Hernández *et al.* published in 2019 finds their measured spectrum-averaged cross section agrees with the value calculated from the ENDF/B-VIII.0 library.

^{235}U(n,f) Cross Section Measurement

- A measurement was made of the ^{235}U(n,f) cross section from thermal to 170 keV by Amaducci *et al*.
  - The data are relative to the ^{6}Li(n,t) and ^{10}B(n,α) cross section standards.
  - They are 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
- ^{239}Pu(n,f)/^{235}U(n,f) cross section ratio measurements made at LANSCE by the NIFFTE collaboration are being analyzed.
- Work on the ^{235}U(n,f) cross section relative to hydrogen scattering from 10 MeV to 1 GeV was discussed by Manna *et al.* (n_TOF collaboration) at the ND2019 meeting. Very preliminary results are available.

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



$^{235}U(n,f)$ Cross Section Measurements (At Thermal – No Maxwellian Data)

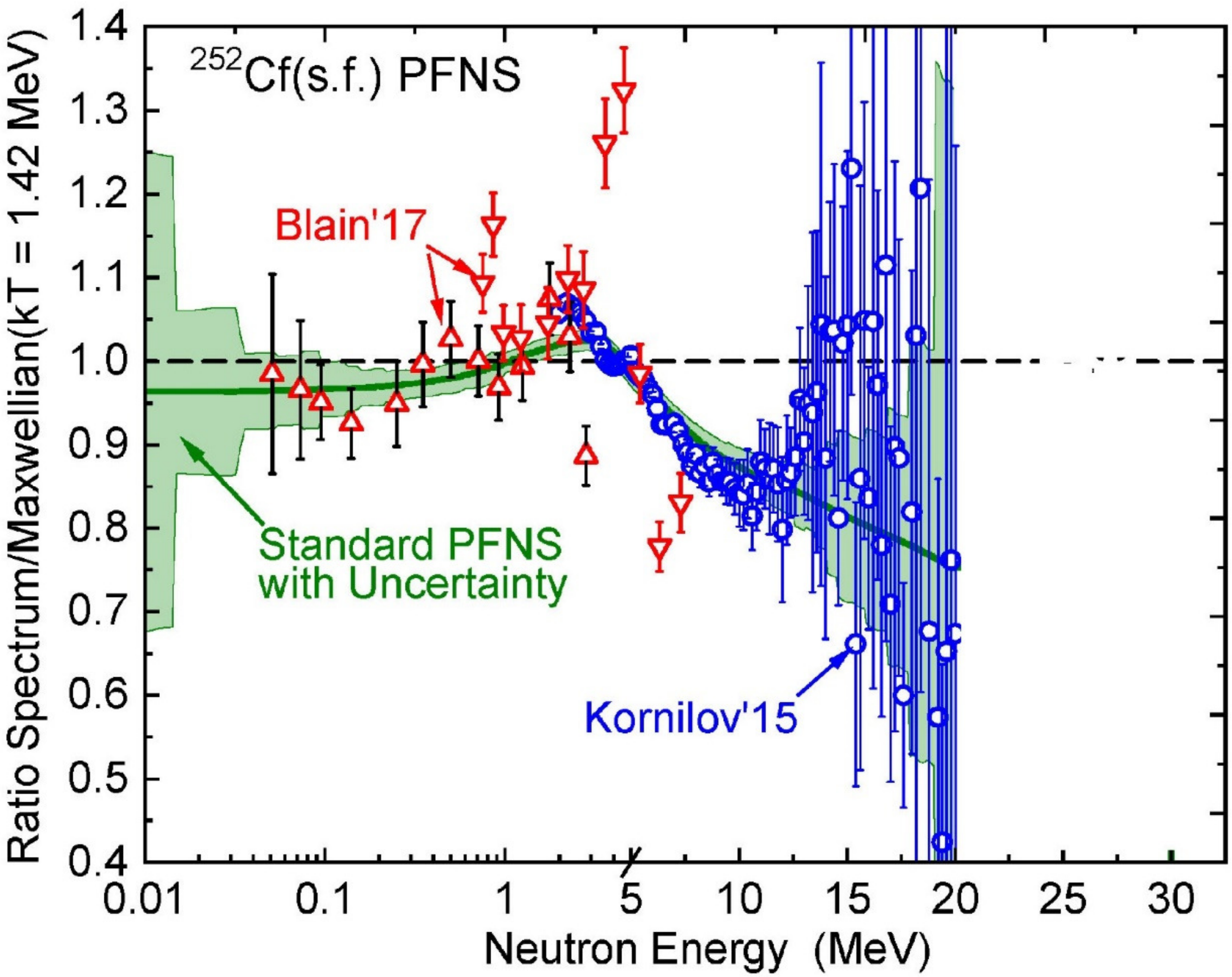
Author	Date	CS (b)	DCS (%)	Reference
Saplakoglu	1959	593.17	2.2	*2nd Geneva Conf.* ***4,*** *157*
Raffle	1959	581.97	3.1	*AERE/R-2998*
Deruytter	1961	589.37	1.3	*J. Nucl. Energy* ***15****, 165*
Maslin	1965	583.71	1.4	*Phys. Rev.* ***139****, 852*

- A new measurement is planned at NIST of the $^{235}U(n,f)$ cross section using the same basic setup used for the $^{6}Li(n,t)$ measurement but replacing the ^{6}Li deposit with a well characterized ^{235}U deposit. The deposit has been obtained and paperwork submitted to allow the ^{235}U sample to be put in the reactor.

Work on Source Strength Determinations related to Fluence and Cross Section Determination

- NBS-I Source Strength Determination Work
  - Work is ongoing to improve its neutron source intensity-it is the U.S. national fast-neutron source standard.
  - This work will have an impact on many cross section measurements that have used this source as a standard and any future measurements made using this source.
    - The work requires that a $MnSO_4$ bath be calibrated using a very accurate measurement method for neutron fluence. Then calibration of the NBS-I source can be done by putting it into the calibrated bath.
- ^{252}Cf Prompt Fission Neutron Spectrum Measurements
  - Used for detector efficiency measurements, many spectra are relative to it, dosimetry applications
  - Measurements by Kornilov relative to hydrogen scattering and detector efficiency calculations
    - Fission chamber used for the start signal for ToF measurements
  - Measurements by Blain et al. relative to the ^{235}U(n,f) cross section
    - multiple γ tagging used for the start signal for ToF measurements

Recent ^{252}Cf Prompt Fission Neutron Spectrum Measurements



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
- Additional work beyond the ^{239}Pu(n,f) work of Neudecker for inspection of uncertainty sources for standards measurements. All standards should be investigated in this way.
- Further work on unrecognized sources of uncertainty
  - Inspection of data sets for unrecognized sources of uncertainty and correlations in data
- Consider improved evaluation techniques for the standard cross sections