Recent Standards Measurements That Impacted The Standards Evaluation and the Results of the 2017 Standards Evaluation.

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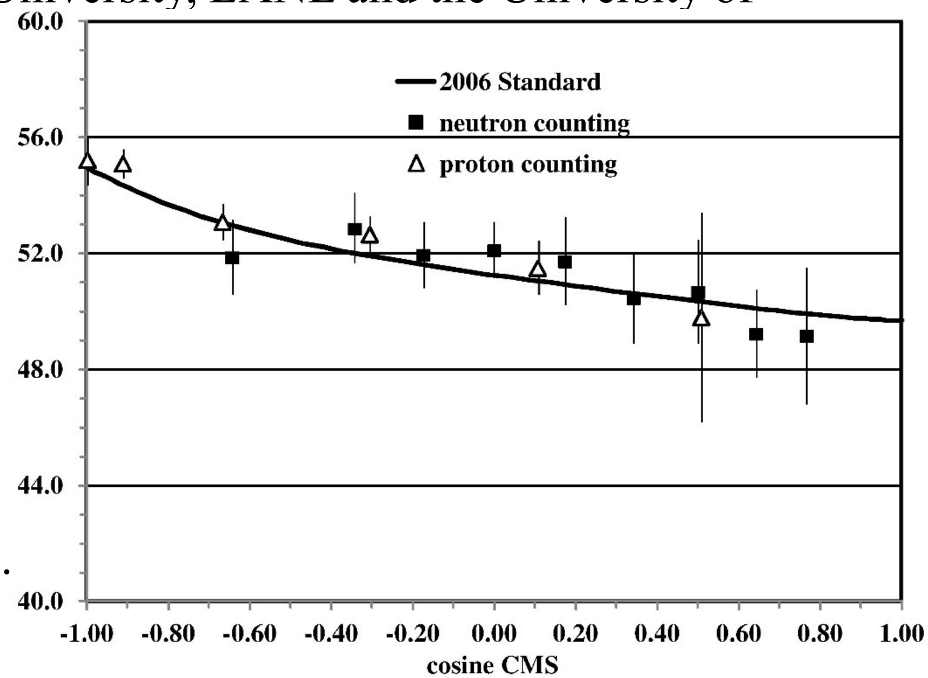
Presented at
The CSEWG Meeting
BNL
November 8, 2017

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.
- The neutron detector efficiency was determined relative to the ^{252}Cf spontaneous fission neutron spectrum with a neutron-fission fragment coincidence.
- (collaboration of NIST with Ohio University, LANL and the University of Guelma)

Data shown here compare results obtained using detection of the recoil proton with that obtained detecting the recoil neutron. There is excellent agreement with the ENDF/B-VII (2006 standards) evaluation within the uncertainties but there is a trend toward lower values at small CMS angles for both experiments.



Nuclear Reaction Activities: Standards Measurements

$^{6}Li(n,t)$ Cross Section

- At the NIST Neutron Center for Neutron Research a measurement was made of the $^{6}Li(n,t)$ cross section standard. This is the first direct and absolute measurements of this cross section in this neutron energy range using monoenergetic neutrons.
  - A primary effort was focused on measuring the neutron fluence accurately. It was determined with an uncertainty of 0.06%.
  - The total uncertainty of less than 0.3% was expected from this measurement however an unexpected uncertainty of 1% in mass was found. A better determination of the mass must be made to improve the uncertainty of this measurement. We are seeking support to do that work.

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

NBS-I Source Strength Determination Work

- Work continues on improvements in the determination of the source strength for NBS-I, 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.
  - Measurements have been made relative to a ^{252}Cf neutron source, based on its accurately known nu-bar. They are being analyzed
  - Plans are being made to absolutely calibrate using a technique where the neutron fluence is determined by employing an α-γ coincidence with the $^{10}B(n,\alpha_1\gamma)$ reaction.

Evaluation of the Neutron Data Standards

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(Dated: November 3, 2017; Received 31 August 2017; revised received xx September 2017; accepted xx October 2017)

With the need for improving existing nuclear data evaluations, (e.g., ENDF/B-VIII.0 and JEFF-3.3 releases) the first step was to evaluate the standards for use in such a library. This new standards evaluation made use of improved experimental data and some developments in the methodology of analysis and evaluation. In addition to the work on the traditional standards, this work produced the extension of some energy ranges and includes new reactions that are called reference cross sections. Since the effort extends beyond the traditional standards, it is called the neutron data standards evaluation. This international effort has produced evaluations of the following cross section standards: the H(n,n), ^{6}Li(n,t), ^{10}B(n,α), ^{10}B(n,$\alpha_1\gamma$), ^{nat}C(n,n), Au(n,γ), ^{235}U(n,f) and ^{238}U(n,f). Also in the evaluation process the ^{238}U(n,γ) and ^{239}Pu(n,f) cross sections that are not standards were evaluated. Evaluations were also obtained for data that are not traditional standards: the Maxwellian spectrum averaged cross section for the Au(n,γ) cross section at 30 keV; reference cross sections for prompt γ-ray production in fast neutron-induced reactions; reference cross sections for very high energy fission cross sections; the ^{252}Cf spontaneous fission neutron spectrum and the ^{235}U prompt fission neutron spectrum induced by thermal incident neutrons; and the thermal constants. The data and covariance matrices of the uncertainties were obtained directly from the evaluation procedure.

The 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

Additional Data Evaluated

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

The 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 Impact of Measurements

- Selected measurements made after the last evaluation of the standards will be shown.

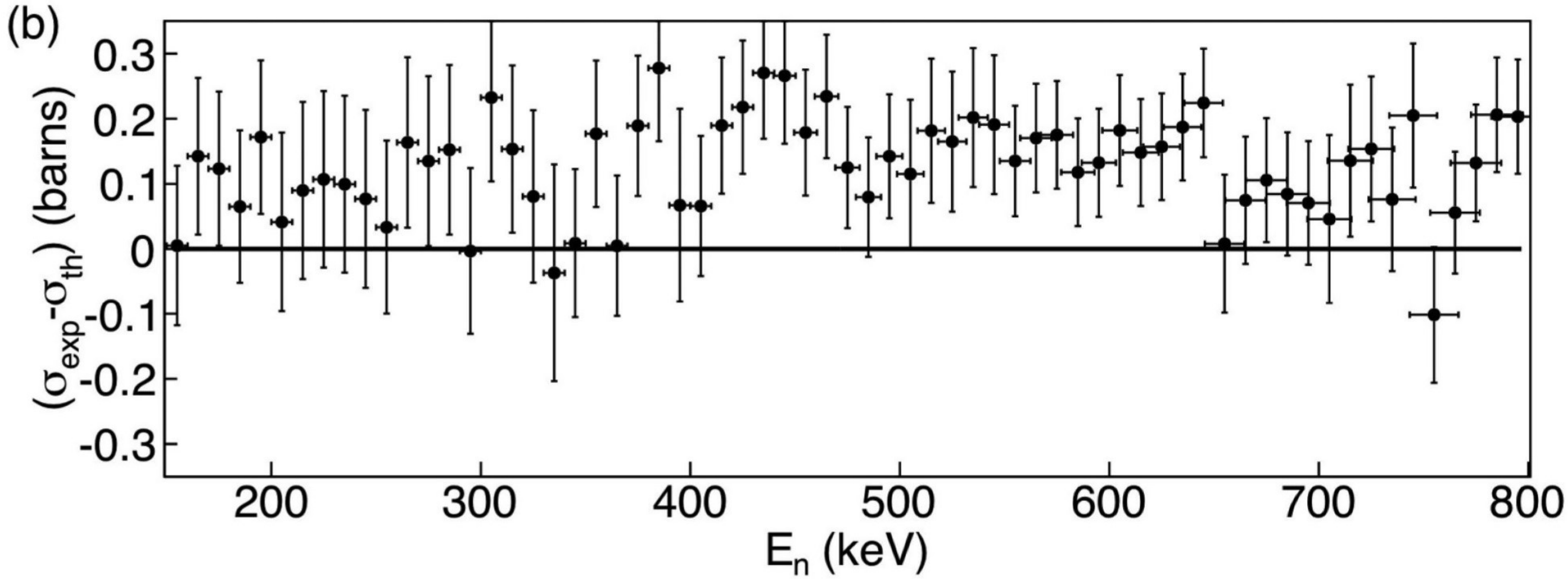
- The impact of new measurements on the new evaluations will be given in specific cases

Recent H(n,n)H Standard Measurements

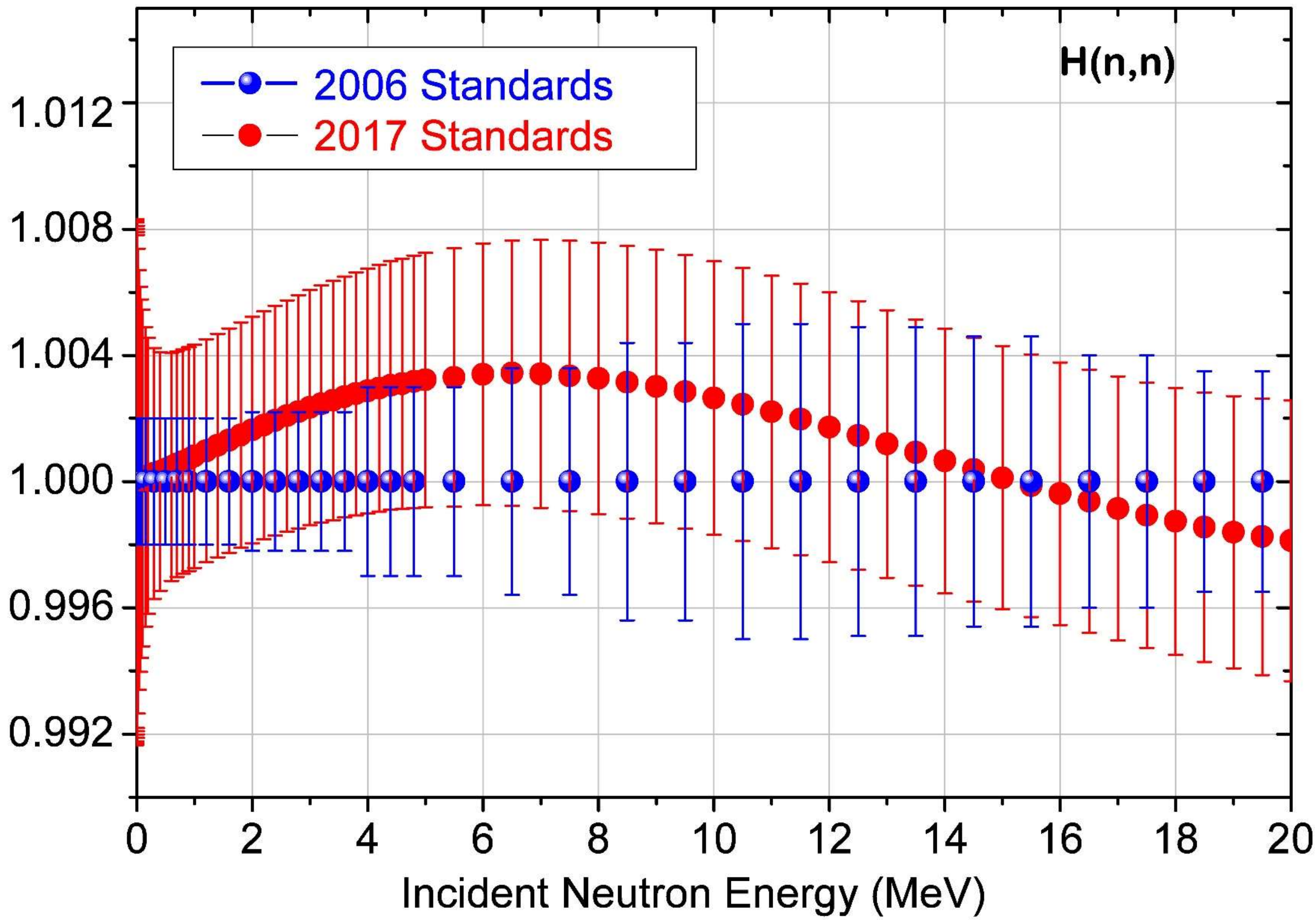
- Concerns about the hydrogen total scattering cross section at low neutron energies led to University of Kentucky Van de Graaff work by Daub *et al.* from 150 keV to 800 keV. The results are systematically slightly larger than the ENDF/B-VII (2006 Standards) values but generally within their uncertainties of 1.1 to 2%. Including these data in the new hydrogen being done by Hale and Paris will cause a slight increase in the evaluated cross section. This would then lead to a somewhat better agreement with the Arndt evaluation. The Arndt evaluation is larger than ENDF/B-VII by about 0.1% at low energies and about 1% at about 12 MeV.

- Additional total cross section work at Kentucky has been done by Yang. The focus was on lower neutron energies than those obtained by Daub *et al*. Data were Obtained from 90 keV to 1.8 MeV with uncertainties of 1-2%. No data were available for use in this evaluation.

Daub *et al.* Hydrogen Total Cross Section-ENDF/B-VII Evaluation



Comparison of H(n,n) Total Cross Section Standards Evaluations



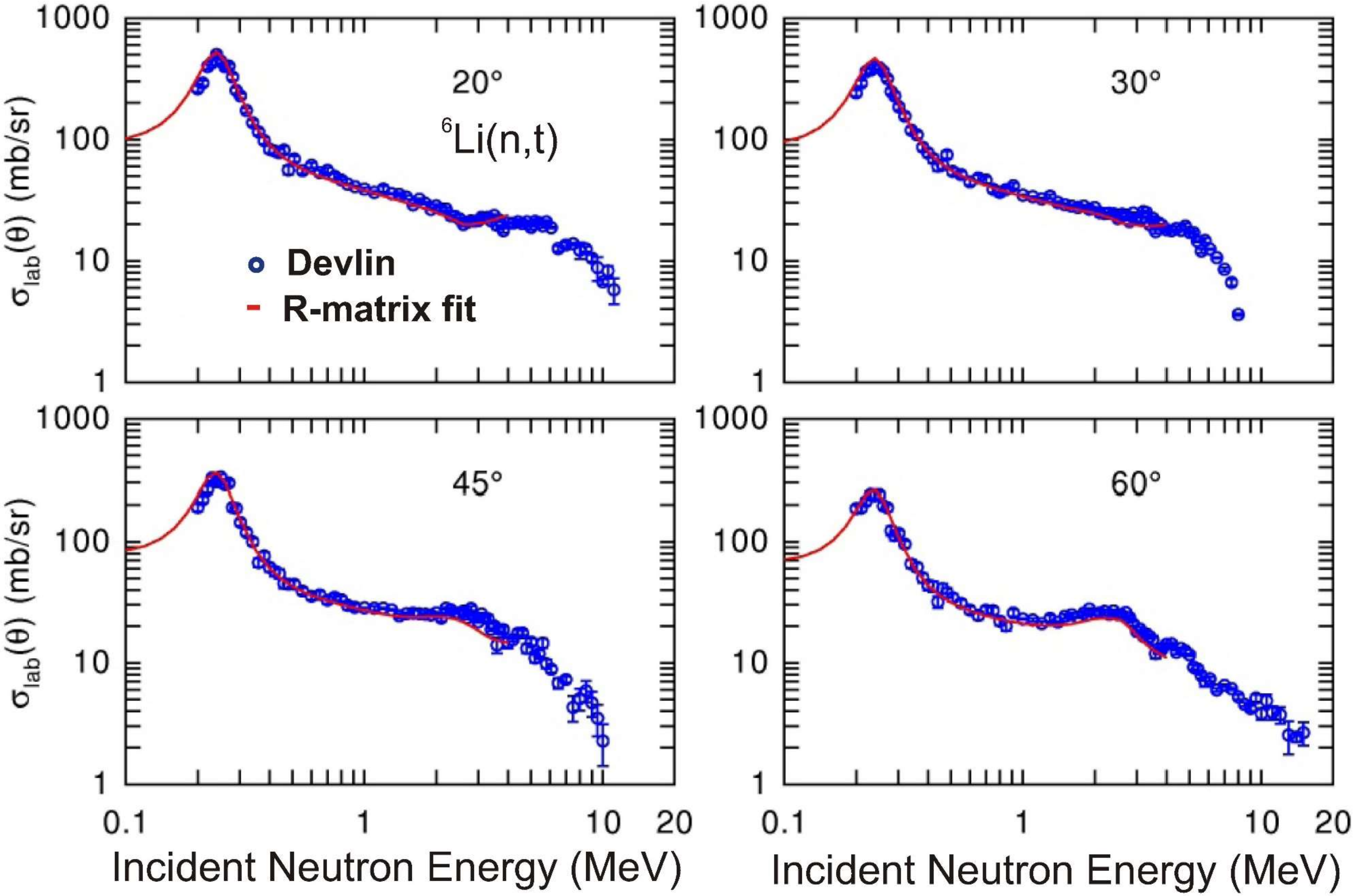
Recent ^{6}Li(n,t) Measurements

- Measurements have been made of the ^{6}Li(n,t) cross section by Devlin et al. at LANL. This work includes angular distribution data obtained from 0.2 to 10 MeV at eight laboratory angles using four E-ΔE telescopes. These data are absolute ratios to the ^{235}U(n,f) cross section and also the hydrogen scattering cross section. An R-matrix analysis using these data led to larger cross sections particularly about 1 MeV and above.

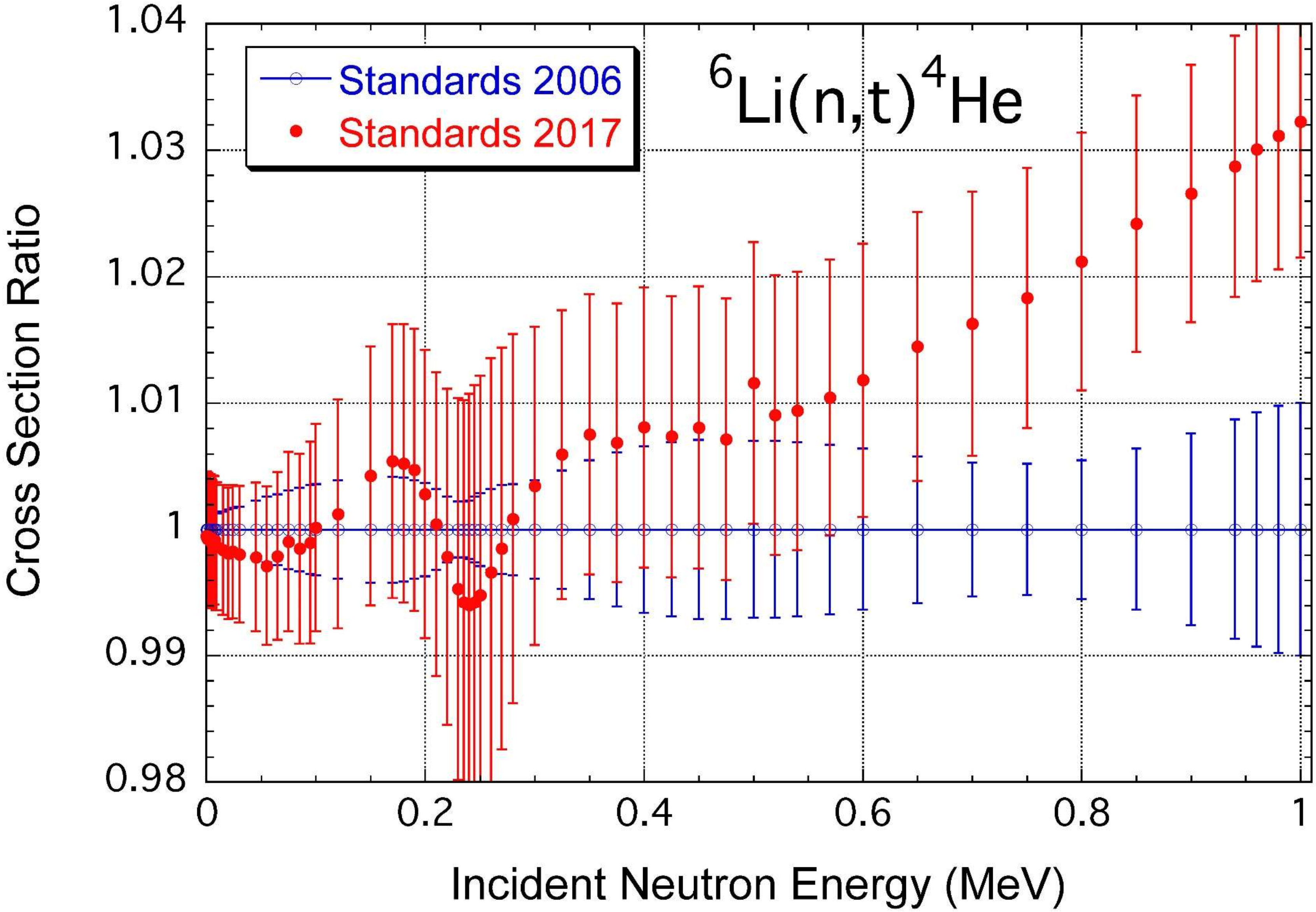
- Measurements by Giorginis and Bencardino at IRMM were made in the 2 MeV energy region. The data agreed with the ENDF/B-VII (2006 standards) evaluation at 1.9 MeV but was 2.6% higher at 2.0 MeV and 1.8% higher at 2.1 MeV

- Zhang at Peking University made angular distribution measurements at 1.05 MeV and 1.54 MeV relative to the ^{10}B(n,α) standard; and at 1.85, 2.25, and 2.67 relative to the ^{238}U(n,f) standard. Data not finalized

^{6}Li(n,t) Angular Distribution Measurements by Devlin



Comparison of the ^{6}Li(n,t) Standards Evaluations



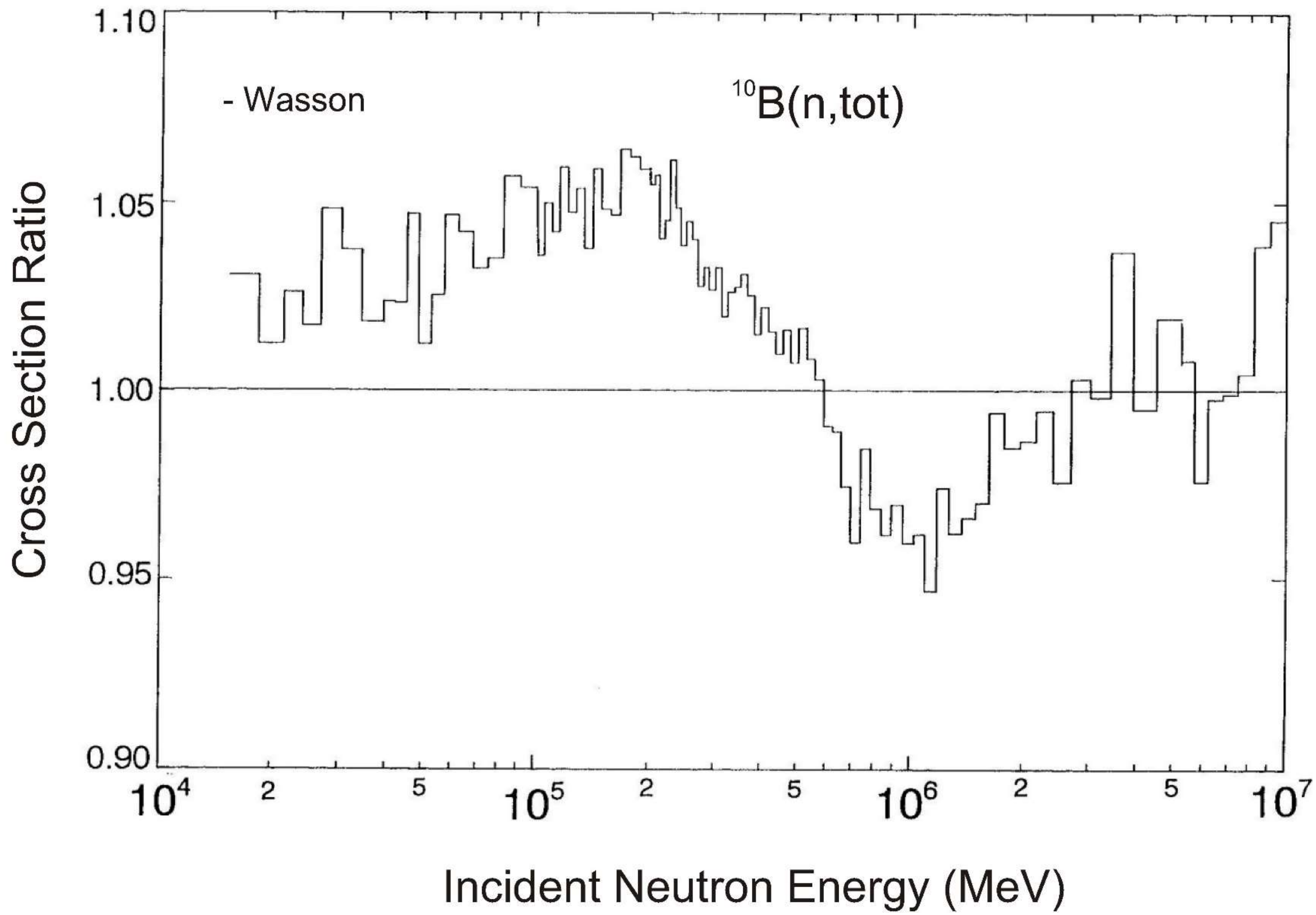
$^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1\gamma)$ Measurements

- Bevvilacqua *et al.* has measurements of the branching ratio, the angular distribution and the $^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1\gamma)$ cross sections relative to the $^{235}U(n,f)$ standard up to 1 MeV. The data were obtained at the 60m station of GELINA at IRMM. They have good statistics but there appear to be some systematic problems. The branching ratio measurements look high at the highest energies and the $^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1\gamma)$ cross sections used to make that ratio are high below about 0.5 MeV. It could something in common such as the fluence determination.

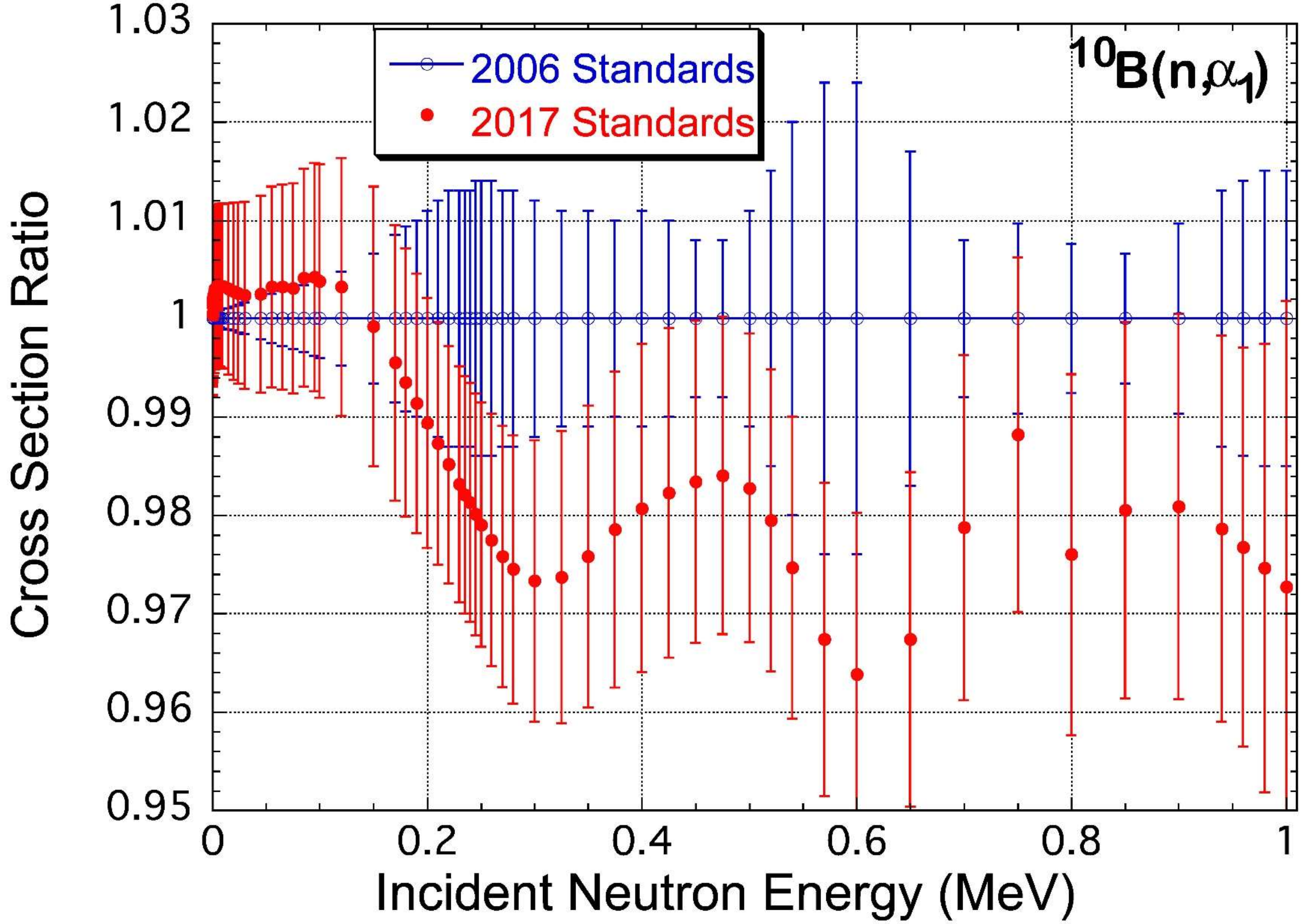
- Zhang *et al.* made measurements with a Frisch gridded ionization chamber of the $^{10}B(n,\alpha)$ angular distribution relative to the $^{238}U(n,f)$ standard at 4 and 5 MeV . These data are in very good agreement with the 2006 data of Giorginis and Khryachkov. Data not finalized

- Wasson *et al.* made measurements of the ^{10}B total cross section from 20 keV to 20 MeV. They showed a significant difference compared with the ENDF/B-VI Standards evaluation

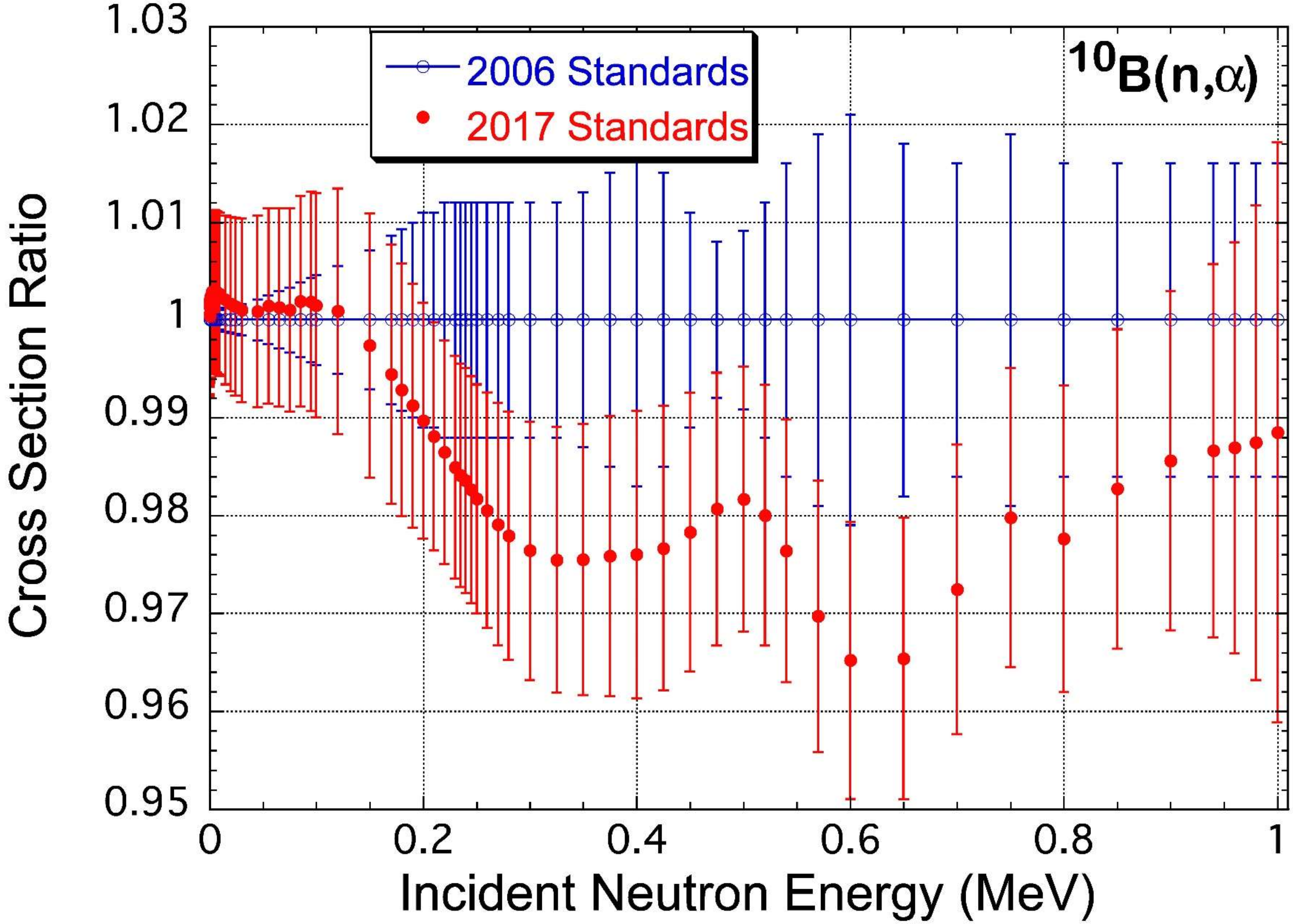
Measurements of the ^{10}B total Cross Section by Wasson compared with ENDF/B-VI



Comparison of $^{10}B(n,\alpha_1\gamma)$ Standards Evaluations



Comparison of $^{10}B(n,\alpha)$ Standards Evaluations



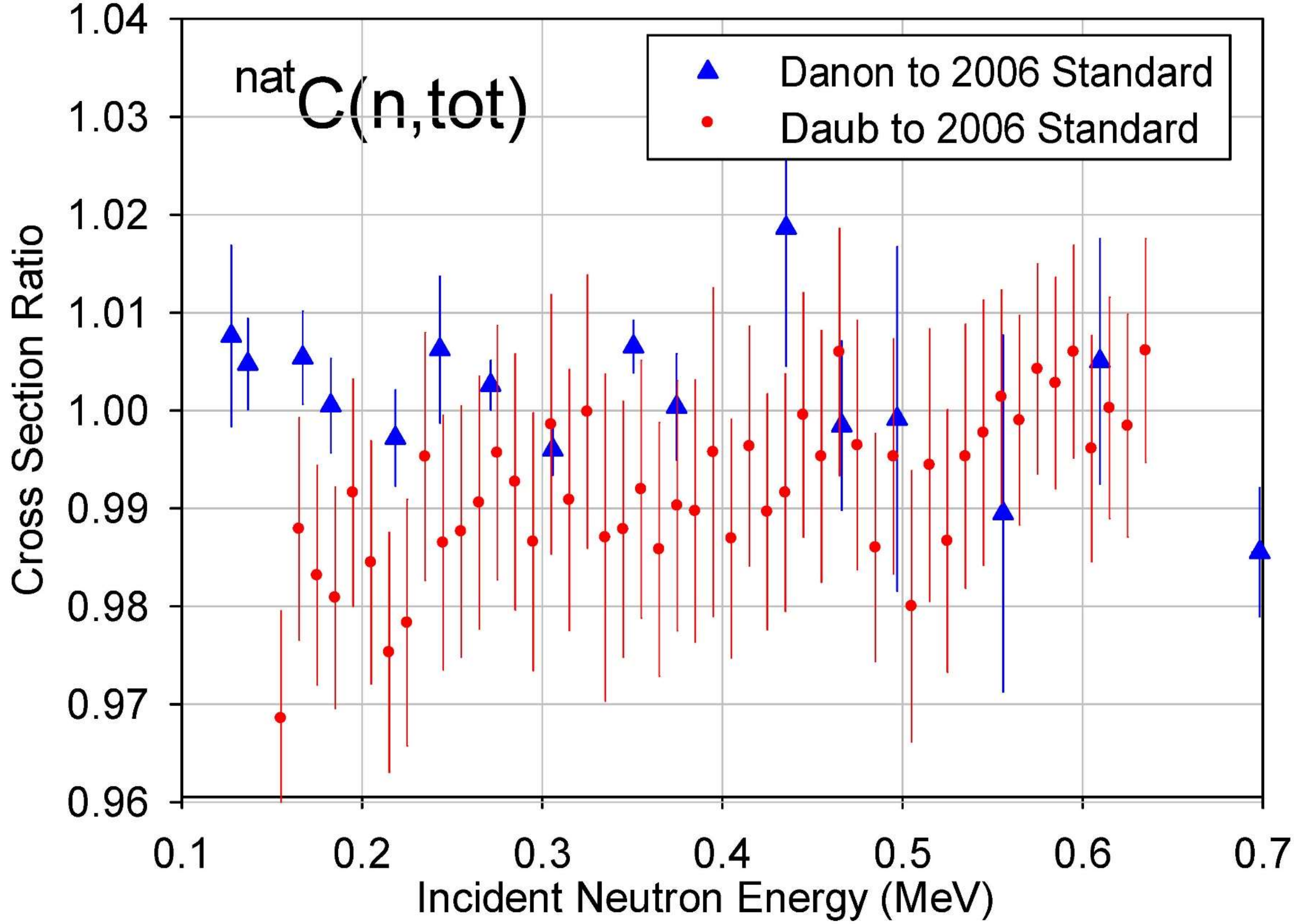
C(n,n) Data

- Daub *et al.* also made very accurate measurements of the carbon total cross section from 150 keV to 800 keV. The results were systematically very slightly lower than the ENDF/B-VII (2006 Standards) evaluation values but generally within their uncertainties of 1.1 to 2%.

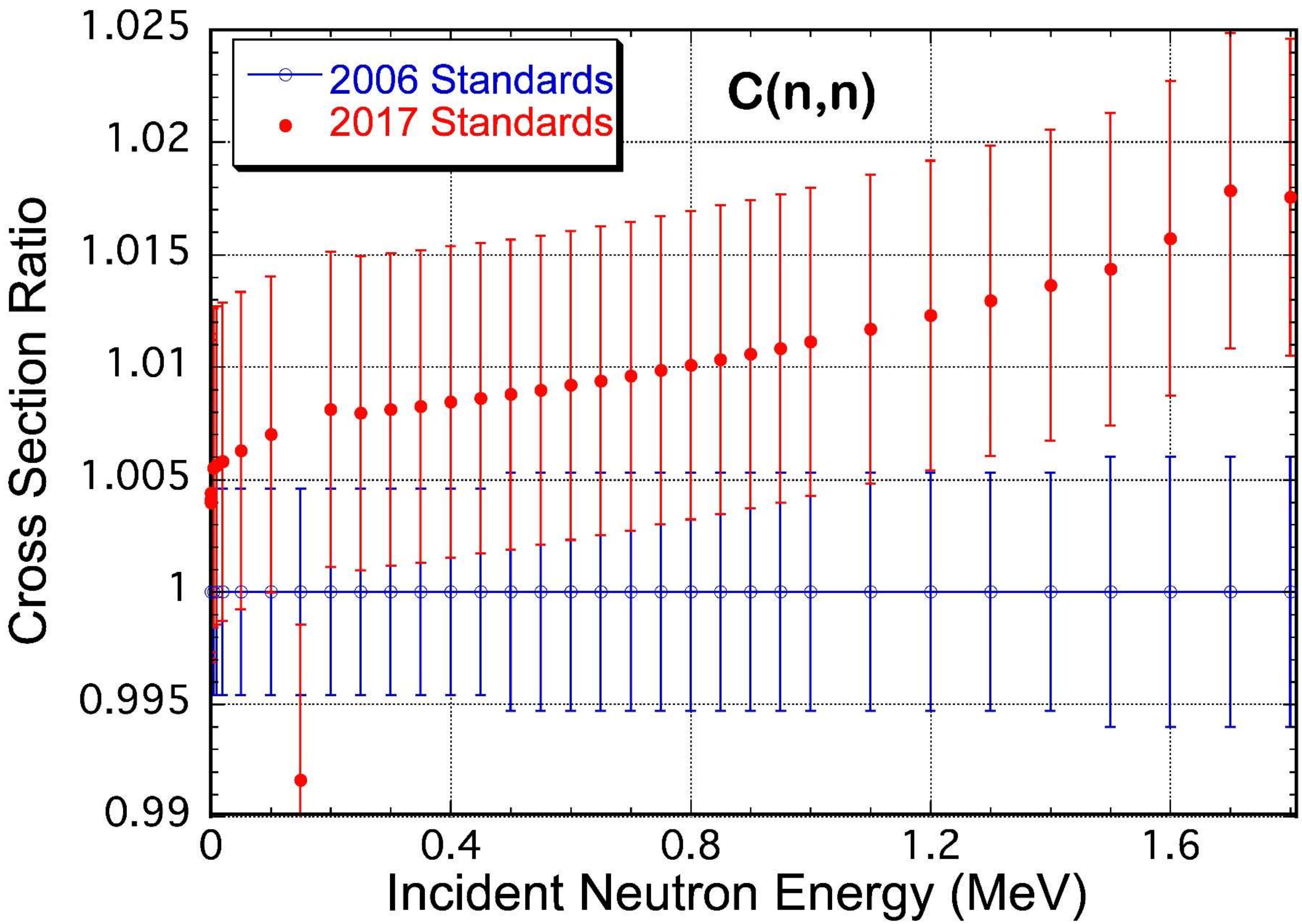
- Danon *et al.* made very accurate measurements of the carbon total cross section using an iron filtered linac neutron beam. The data were obtained for 19 peaks from 24.3 to 945 keV. This method provided very low backgrounds. The results obtained with an accuracy of better than 1% were in excellent agreement with the ENDF/B-VII (2006 Standards) evaluation.

- Gritzay *et al.* reported at the ND2007 conference carbon total cross section data taken at the Kyiv reactor using filtered beams with energies of 2, 3.5, 12, 24, 55, 59, 133 and 148 keV. They are generally in good agreement with the ENDF/B-VII (2006 Standards) evaluation. However, with 1-2% uncertainties, at the lower energies their results are somewhat low and at 148 keV their result is about 5 standard deviations higher. However these data are considered preliminary

Danon *et al.* and Daub *et al.* Carbon Total Cross Section Measurements Compared with the 2006 Standards Evaluation



Comparison of Natural Carbon Total Cross Section Evaluations



Au(n,γ) and ^{238}U(n,γ) Measurements

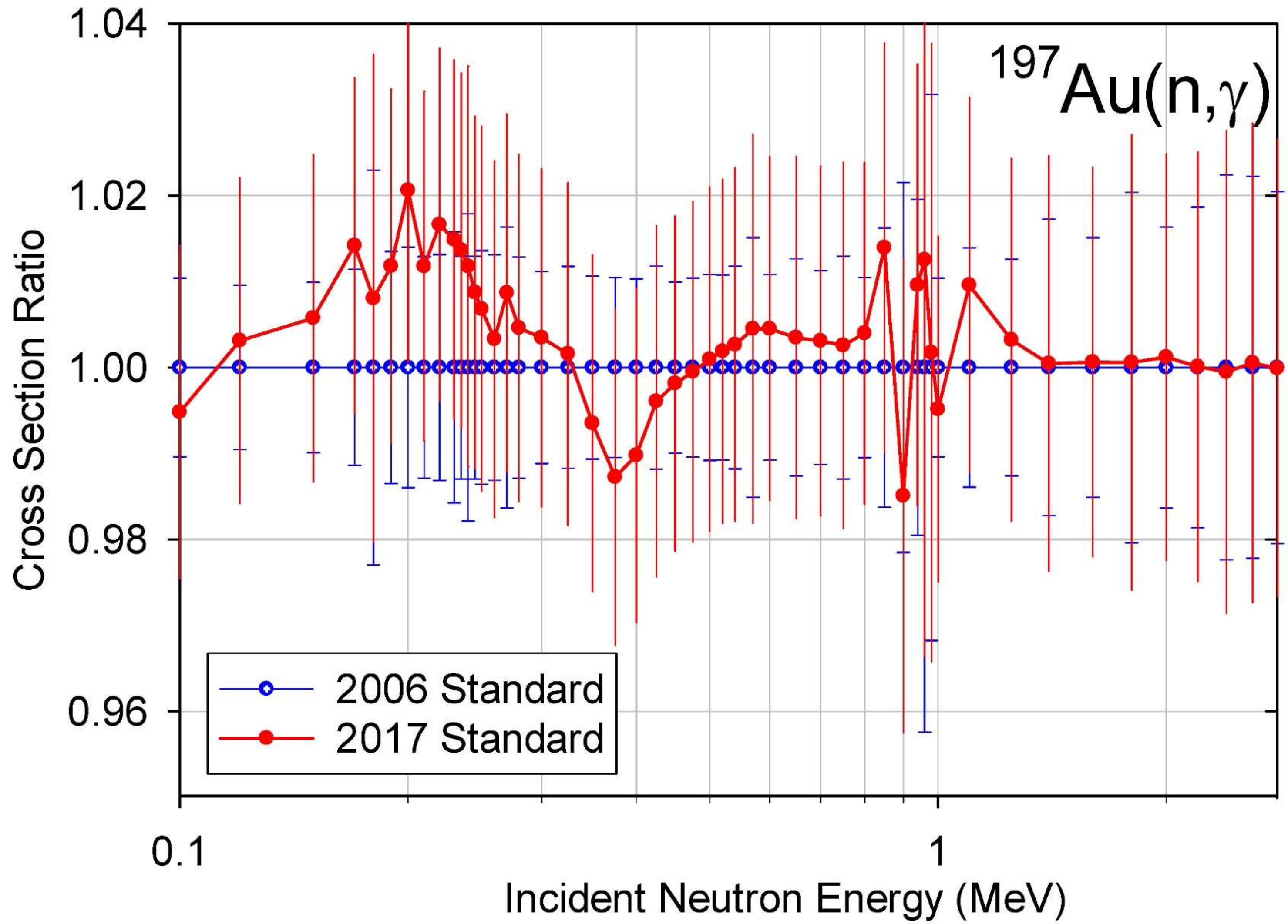
- Wallner (U. of Vienna) made measurements of the ^{238}U(n,γ)/^{197}Au(n,γ) cross section ratio at 426 keV. Accelerator mass spectrometry was used to measure the ^{239}Pu resulting from the ^{239}U. Activation was used for the gold measurements. The measurement has a large (150 - 200 keV FWHM) energy spread. That ratio, 0.99± 0.04, compared with the 2006 standards evaluation is in excellent agreement.

- Massimi made measurements of the ^{197}Au(n,γ) cross section relative to the ^{235}U(n,f) and ^{10}B(n,α) standards. These data extend to about 200 keV and generally support the ENDF/B-VII.0 (2006 Standards) evaluation results.

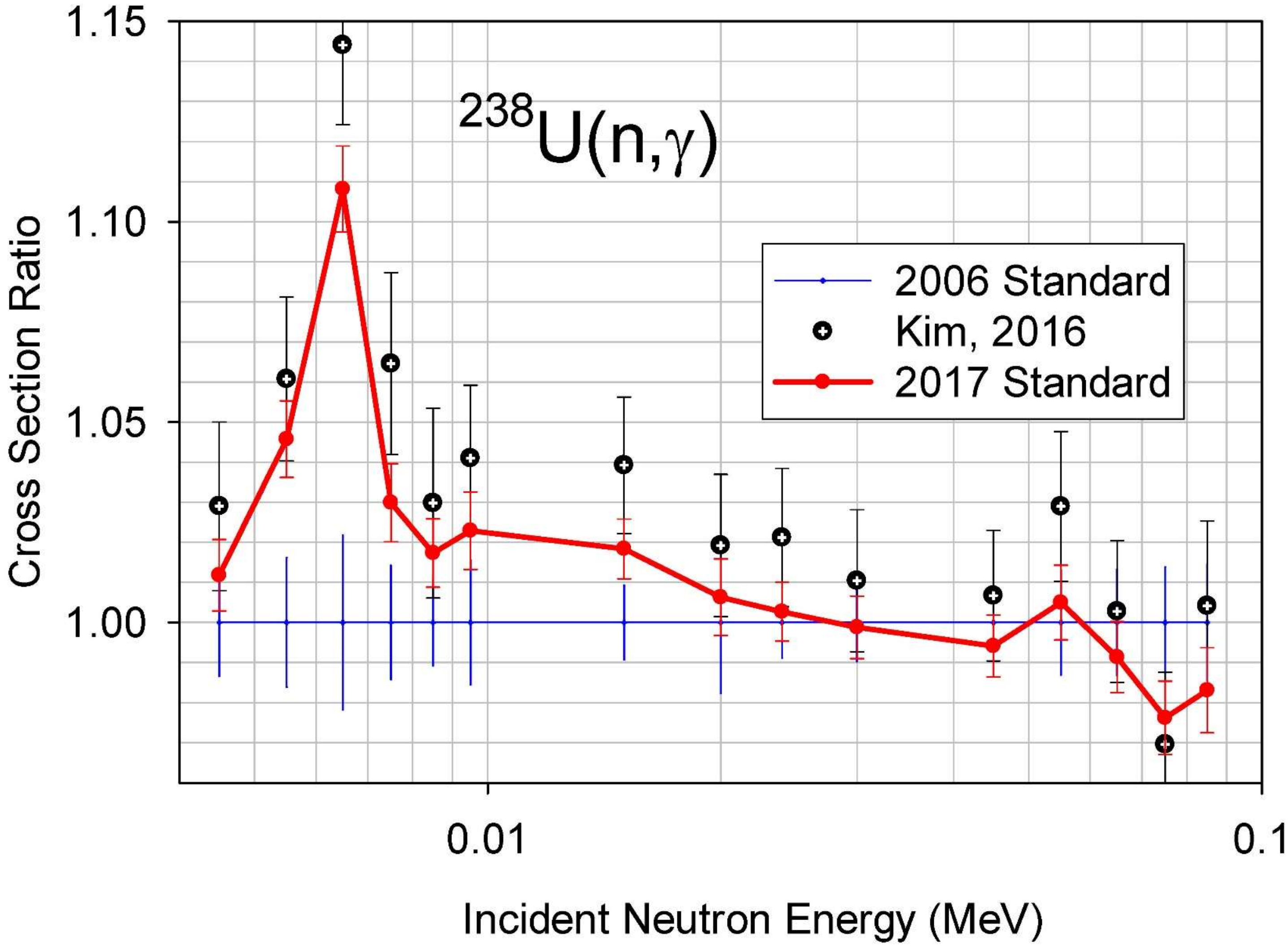
- Ullmann *et al.* made measurements of the ^{238}U(n,γ) cross sections using the DANCE. They state there is generally good agreement with the ENDF/B-VII (2006 Standards) evaluation. For the evaluation, it was decided that the data from 150 keV to 500 keV could be used in the evaluation, but the data from 10 keV to 150 keV could not be included due to structure in the data.

- At GELINA ^{238}U(n,γ) cross sections measurements were made by Kim *et al.* using a C_6D_6 detector with very high accuracy. They are slightly higher but agree very well with the (2017 Standards) data.

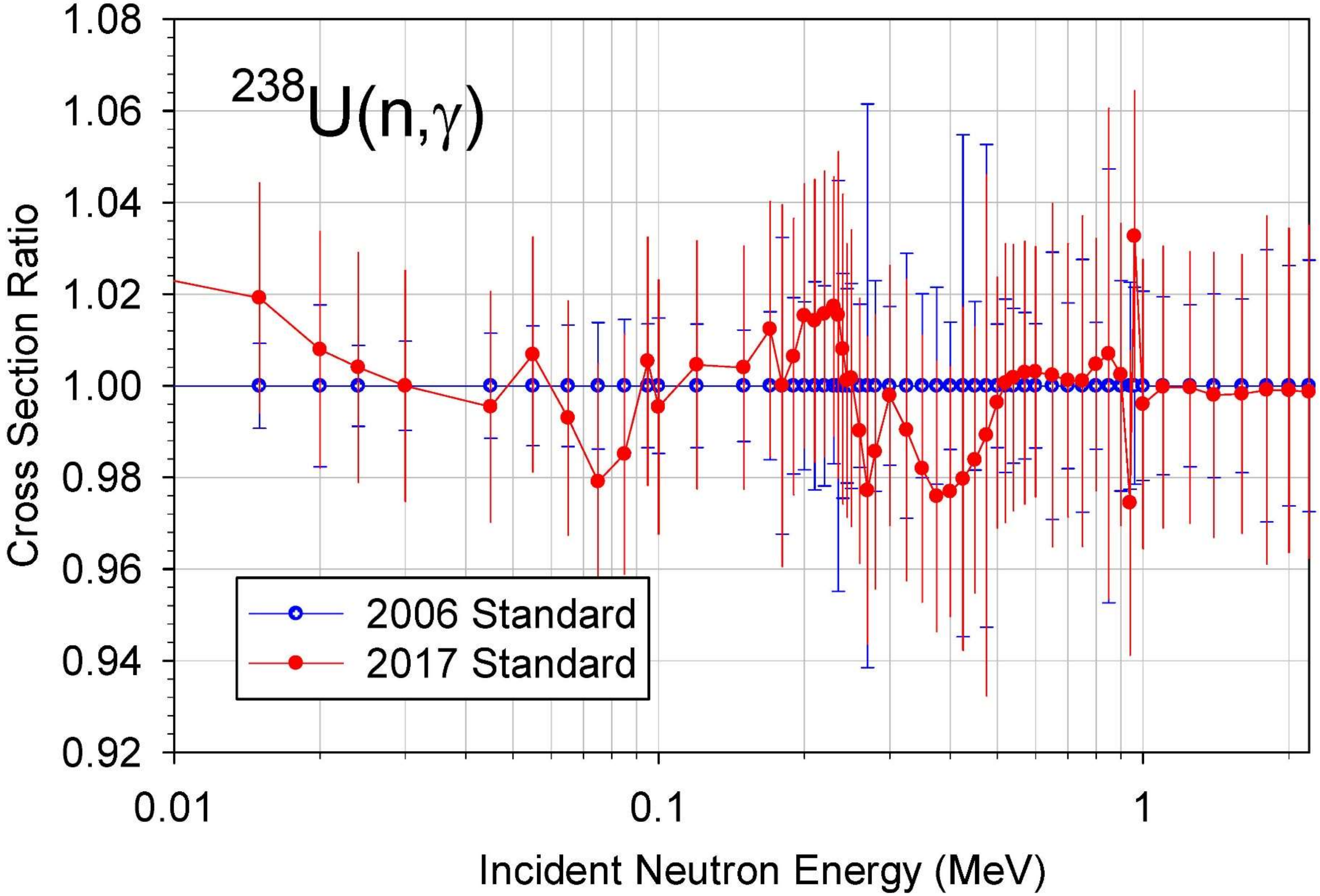
Comparison of Au(n, γ) Standards Evaluations



Measurements and Evaluations of the $^{238}U(n,\gamma)$ Cross Section



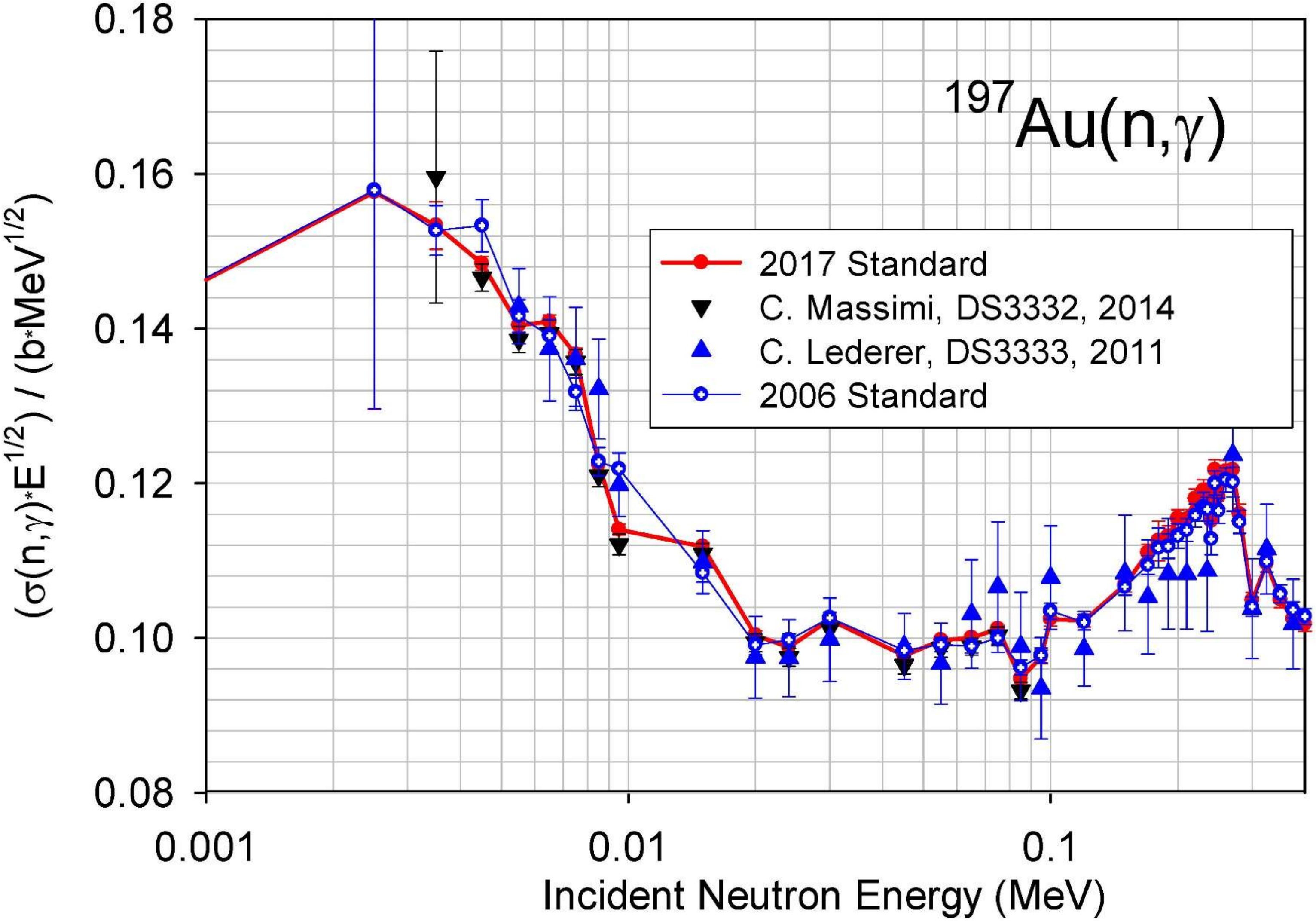
Comparison of $^{238}U(n,\gamma)$ Evaluations



Au(n,γ) Data at Low Neutron Energies

- Au(n,γ) reference cross section for capture cross section measurements for astrophysics (below the standards energy region)
  - The measurements cited below all support the results of the standards evaluation. They indicate the Ratynski and Käppeler results that are used as the astrophysics reference are low by about 5-7% from 15 to 25 keV.
    - Wallner using AMS with a simulated Maxwellian neutron source spectrum of 25 keV mean energy obtained a ratio to the standards evaluation for gold capture of 1.04 ± 0.05
    - Lederer reanalyzed n_TOF gold capture data of Massimi and folded a simulated Maxwellian neutron source spectrum of 25 keV mean energy into that data. The result was 564 ± 23 mb compared with the standards evaluation of 575 mb. That is a 2% difference with an uncertainty of 4%.
    - The 30 keV Maxwellian averaged cross section for gold 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 agrees with the 2017 standards evaluation within one standard deviation.

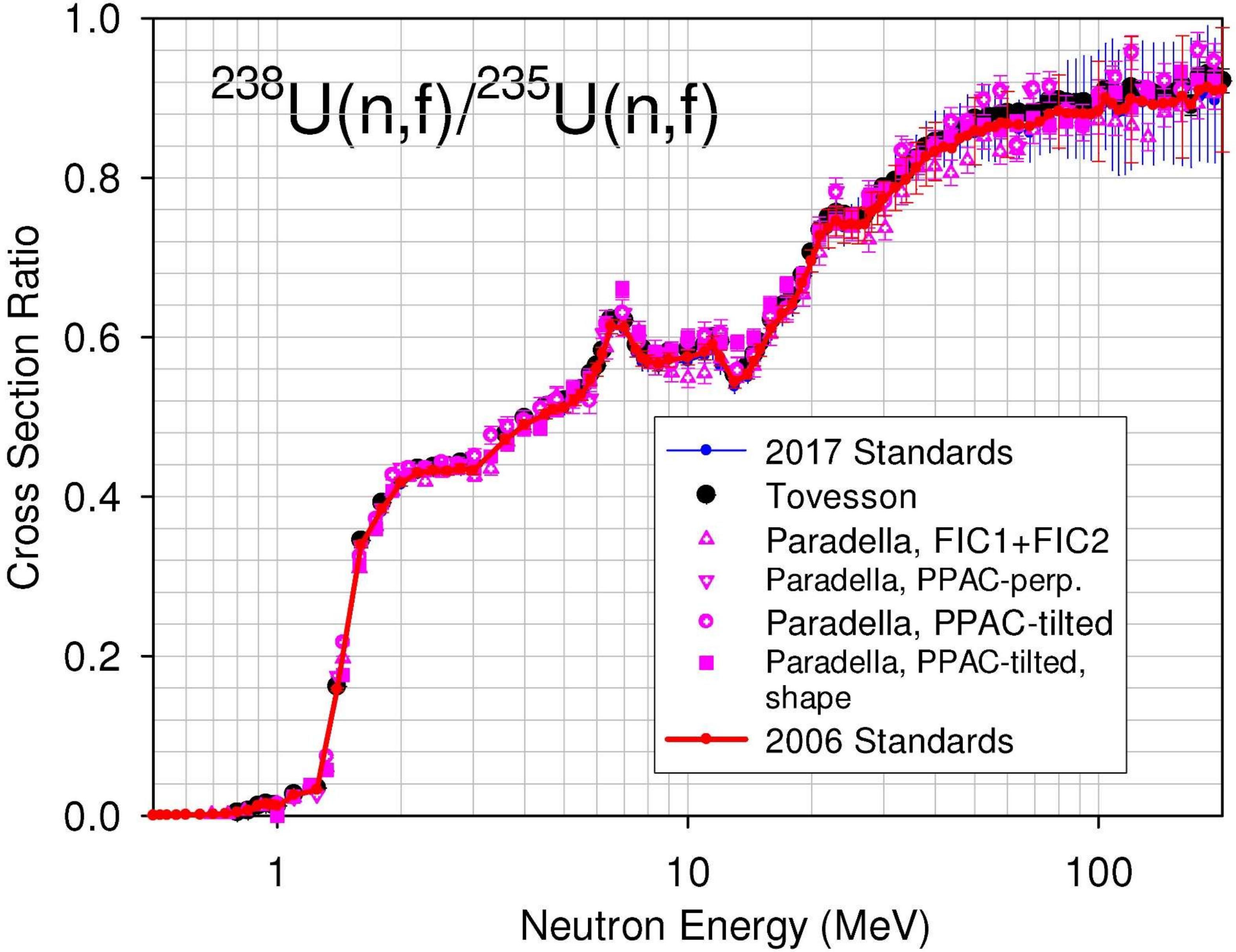
Au(n,γ) Cross Section Measurements and Evaluations



$^{235,\,238}$U(n,f) Measurements

- Four measurements of the ^{238}U(n,f)/^{235}U(n,f) cross section ratio were made at the n_TOF facility and reported by Paradela.
  - A Fission chamber measurement.
  - Parallel plate avalanche counters were used for 3 sets of measurements.
    - The same deposits were used for both the PPAC perpendicular and the PPAC tilted 1 measurements. The difference was that the perpendicular measurements were made with the deposits perpendicular to the beam direction whereas the tilted 1 measurements were made with the deposits at 45° to the beam direction.
    - The third setup for the PPAC detectors, PPAC tilted 2, again were made with the deposits at 45° to the beam direction, were not as well characterized as the other deposits so they were normalized to the ENDF/B-VII.1 (2006 standards) evaluation between 3 and 5 MeV.
- The PPAC sets are slightly higher than the fission chamber data but they agree within their uncertainties. They all agree reasonably well with the standards evaluation.
- Measurements were also made by Tovesson *et al.* of the ^{238}U(n,f)/^{235}U(n,f) cross section ratio at LANSCE up to 198 MeV. They are in fair agreement with the standards evaluation.

Recent $^{238}U(n,f)/^{238}U(n,f)$ Cross Section Measurements



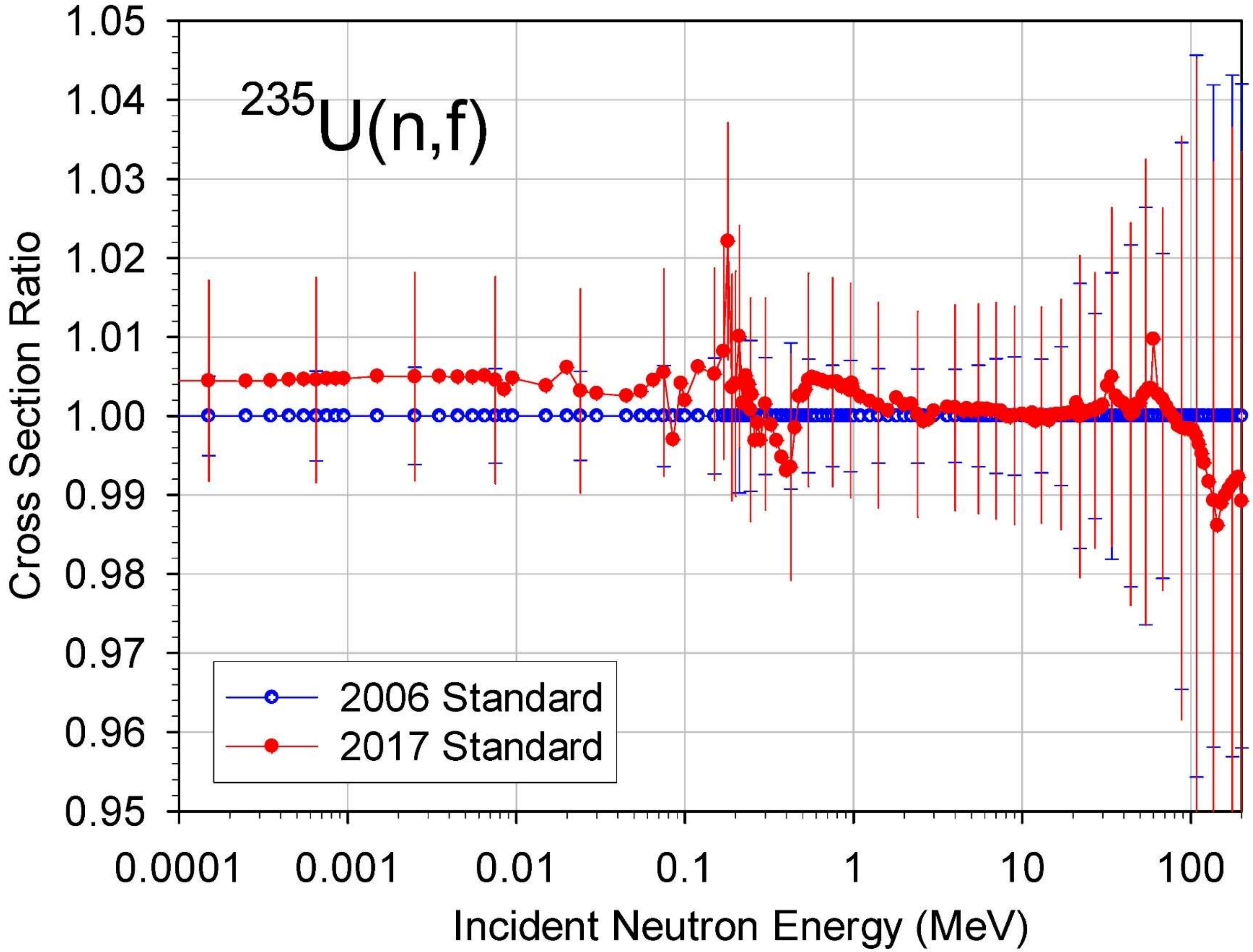
Thermal Constants

- An evaluation of the thermal constants has been completed.
- Due to concerns about how well temperatures are understood for Maxwellian data, only microscopic data were used.
- The GMA code was used for the evaluation.
- An improved evaluation was possible with additional measurements that include α data for ^{235}U at 0.0253 eV by Adamchuck with 2.1% uncertainty, and three results of measurements of the ratios of ^{233}U, ^{239}Pu and ^{241}Pu to ^{235}U at 0.0253 eV done at LANL and n_TOF with estimated uncertainties between 2 and 3%. Also α data by Lounsbury with an uncertainty of 1.7% were used in the evaluation. They are in excellent agreement with the work by Adamchuck.
- The data from this evaluation are v-bar, the cross sections for fission, capture and scattering for ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu.

The Thermal Neutron Constants

Const.	^{233}U	^{235}U	^{239}Pu	^{241}Pu
σ_{nf}(b)	533.0 (2.2) (531.2)	587.3 (1.4) (584.3)	752.4 (2.2) (750.0)	1023.6 (10.8) (1014.0)
$\sigma_{n\gamma}$(b)	44.9 (0.9) (45.6)	99.5 (1.3) (99.4)	269.8 (2.5) (271.5)	362.3 (6.1) (361.8)
σ_{nn}(b)	12.2 (0.7) (12.1)	14.09 (0.22) (14.09)	7.8 (1.0) (7.8)	11.9 (2.6) (12.1)
$\overline{\nu}_{tot}$	2.487 (.011) (2.4968)	2.425 (.011) (2.4355)	2.878 (.013) (2.8836)	2.940 (.013) (2.9479)

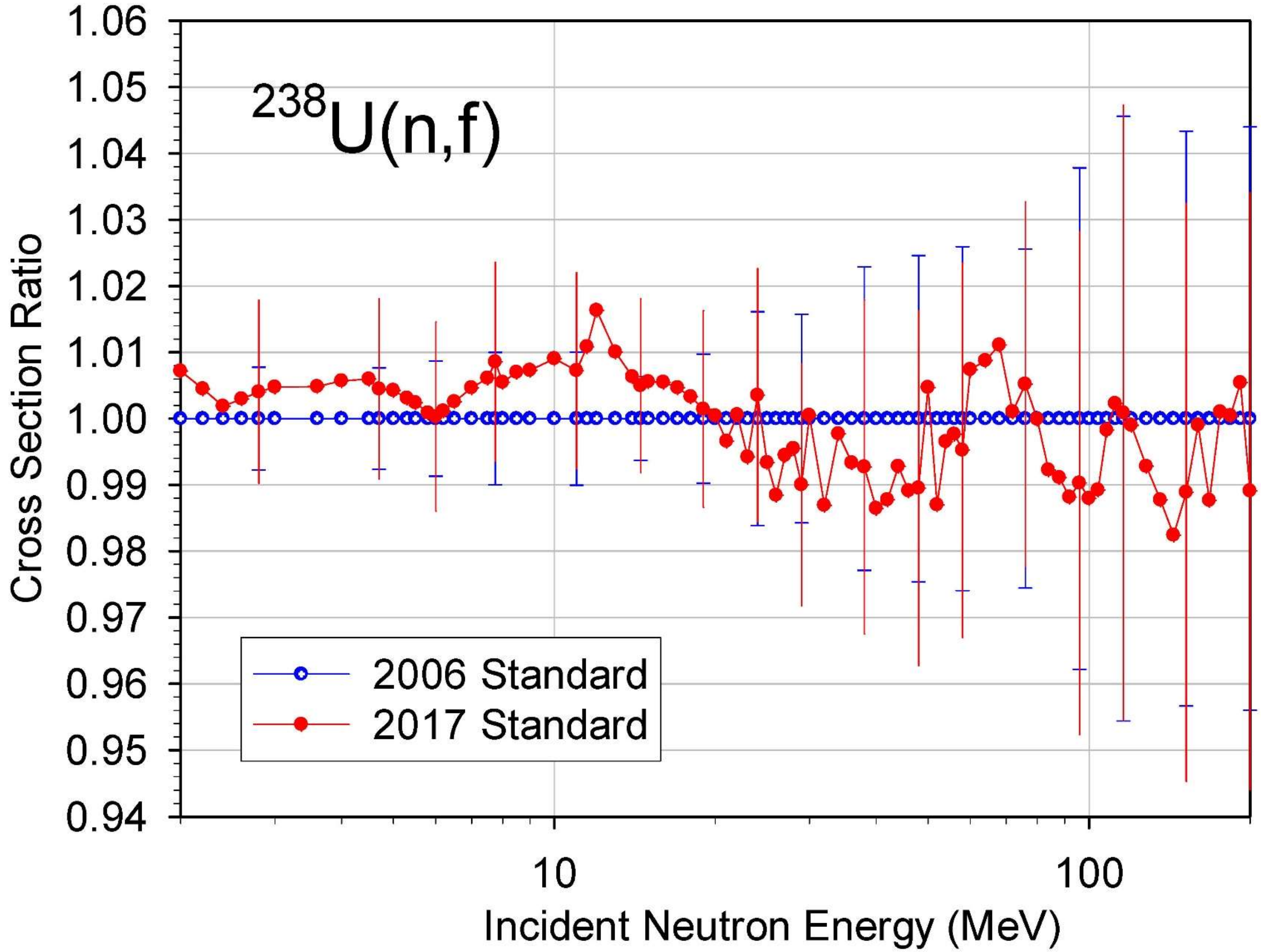
Comparison of $^{235}U(n, f)$ Standards Evaluations



$^{238}U(n,f)$ Measurements

- Re-analysis of an older experiment at LANSCE was done by Miller from the University of Kentucky. The measurement yielded a determination of the $^{238}U(n,f)$ cross section relative to hydrogen scattering. The data are shape measurements normalized to the 2006 Standards evaluation at 130 MeV. The data extend from 100 to 300 MeV. The data are in general agreement with The 2006 Standards evaluation.

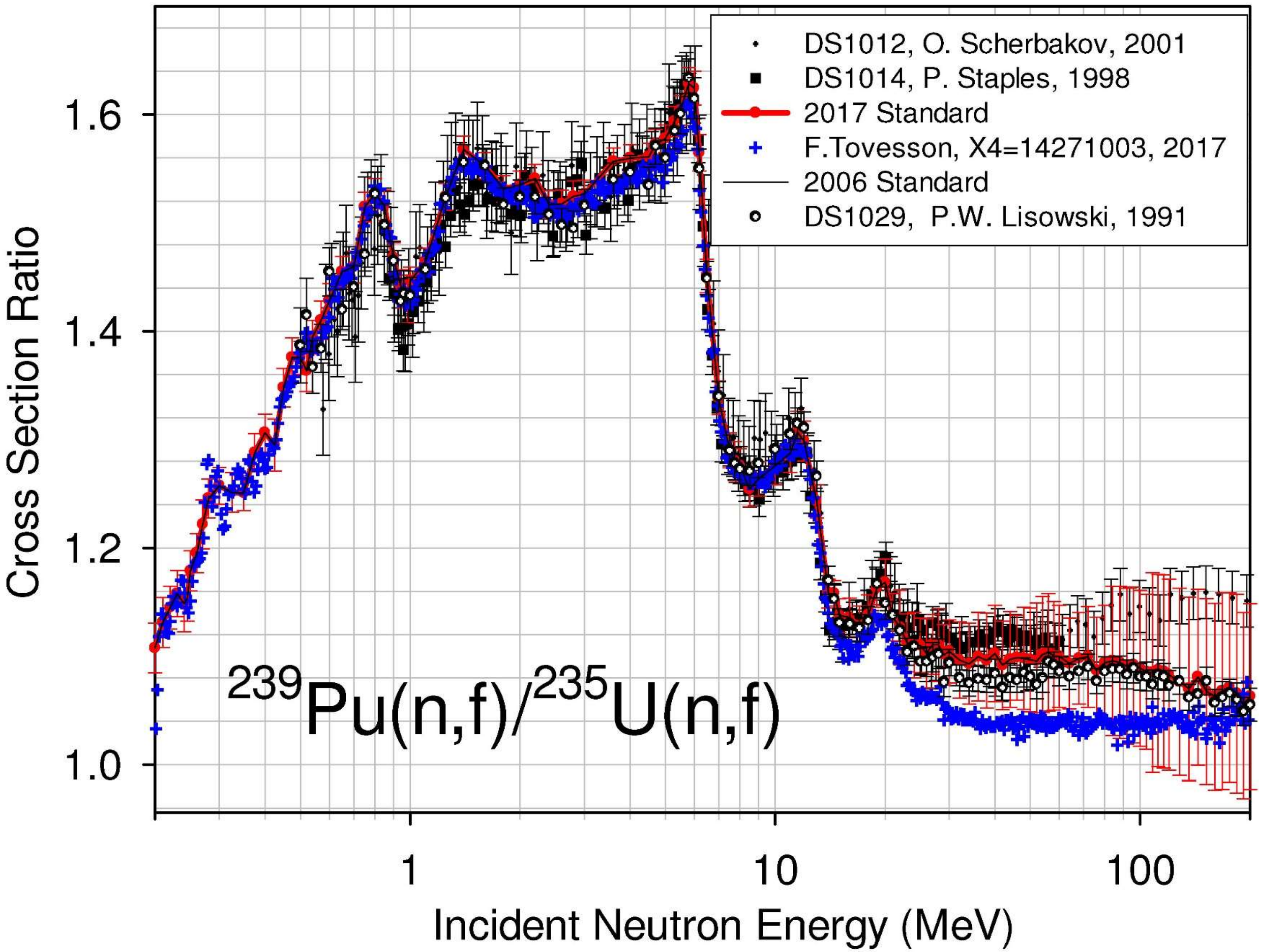
Comparison of ^{238}U(n, f) Standards Evaluations



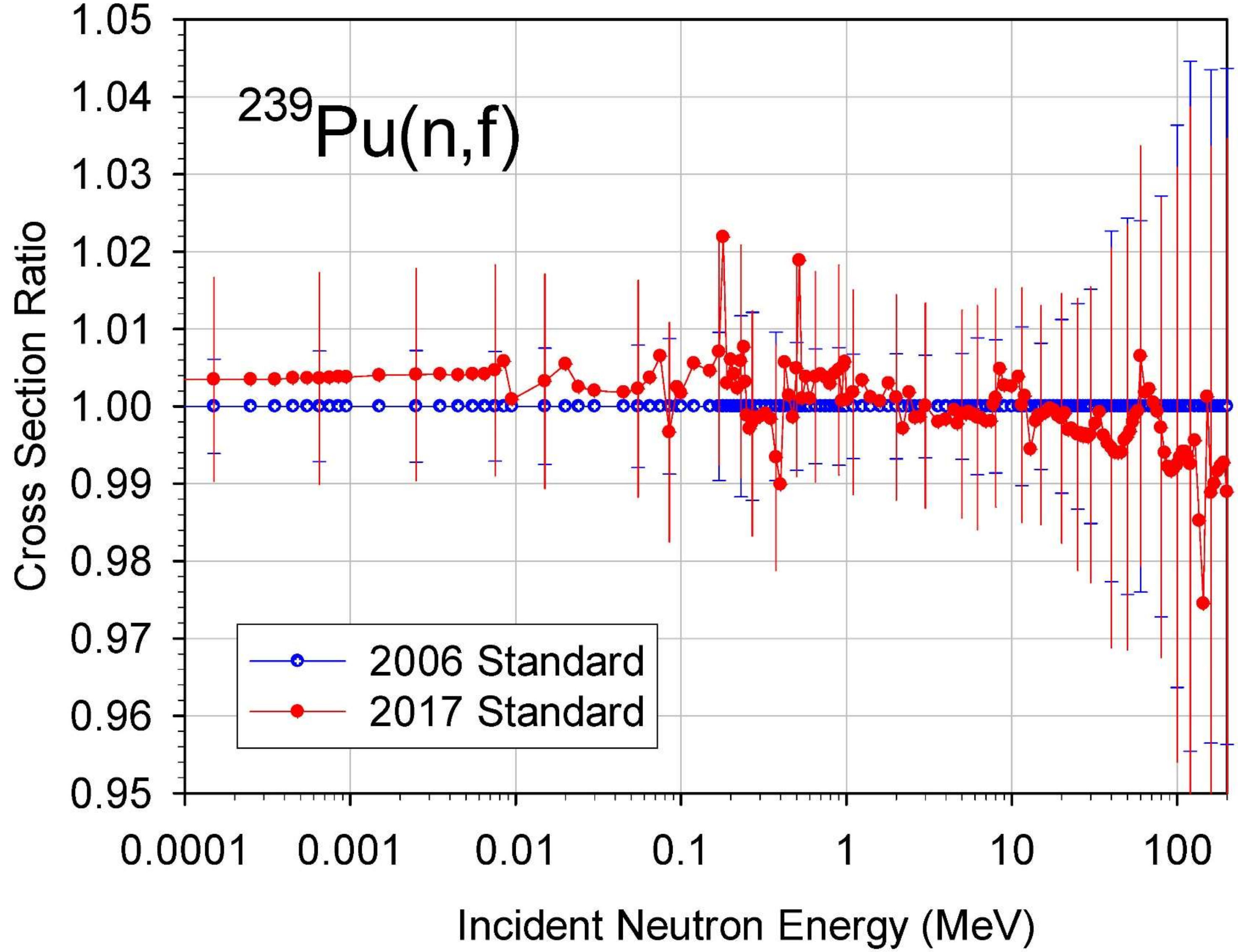
^{239}Pu(n,f) Measurements

- The most recent ^{239}Pu(n,f) cross section measurements were made by Tovesson and Hill at WNR-LANL. They agree reasonably well with the ENDF/B-VII standards evaluation and the Lisowski *et al.* and Shcherbakov *et al.* measurements up to about 10 MeV. The new measurements have somewhat smaller uncertainties than these other two data Sets. Above 10 MeV these new measurements fall somewhat lower than the ENDF/B-VII evaluation and the Lisowski et al. and Shcherbakov *et al.* measurements except above about 100 MeV where they agree with the Lisowski et al. data.

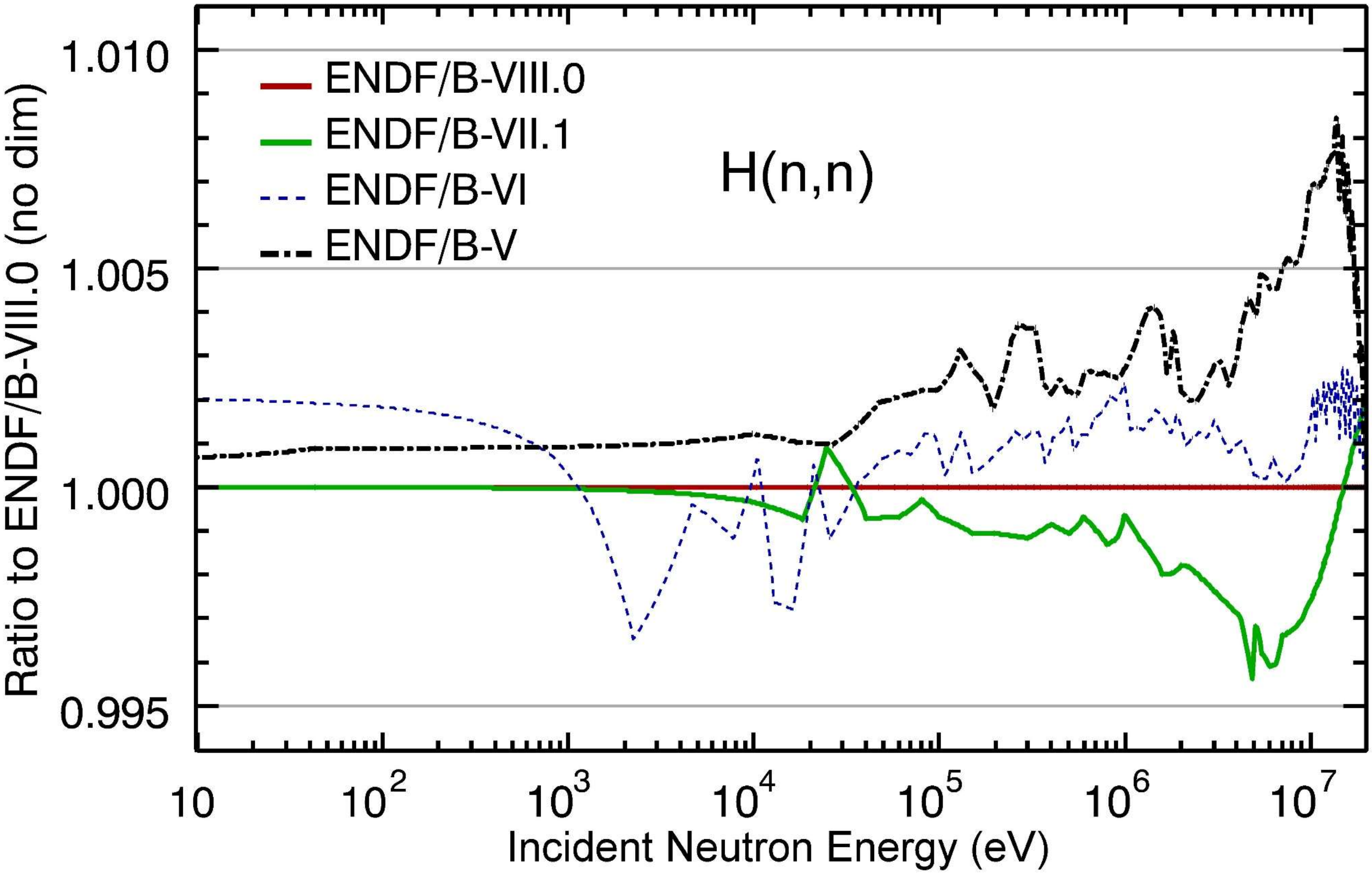
Recent measurements of the ^{239}Pu(n,f)/ ^{235}U(n,f) Cross Section



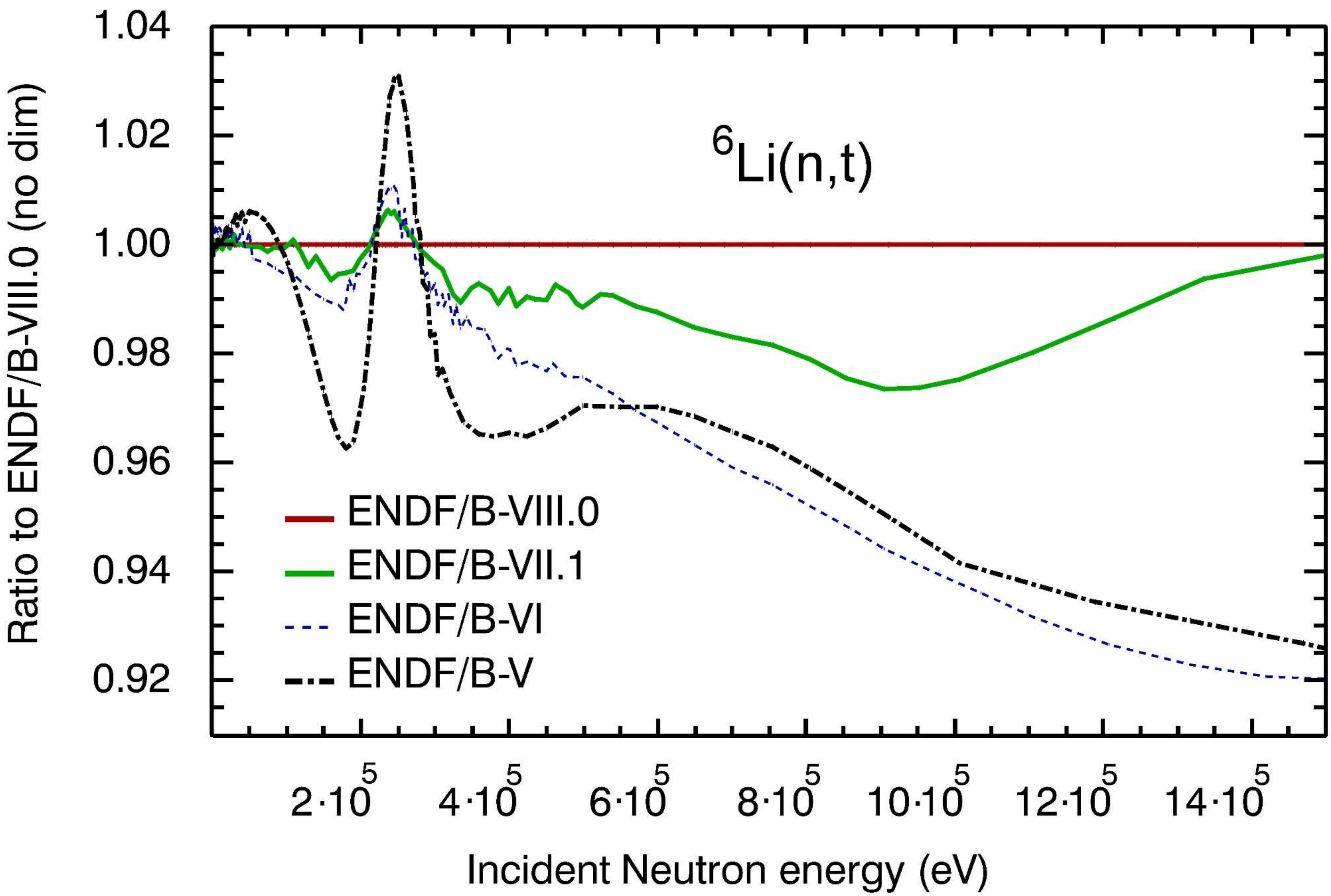
Comparison of ^{239}Pu(n,f) Evaluations



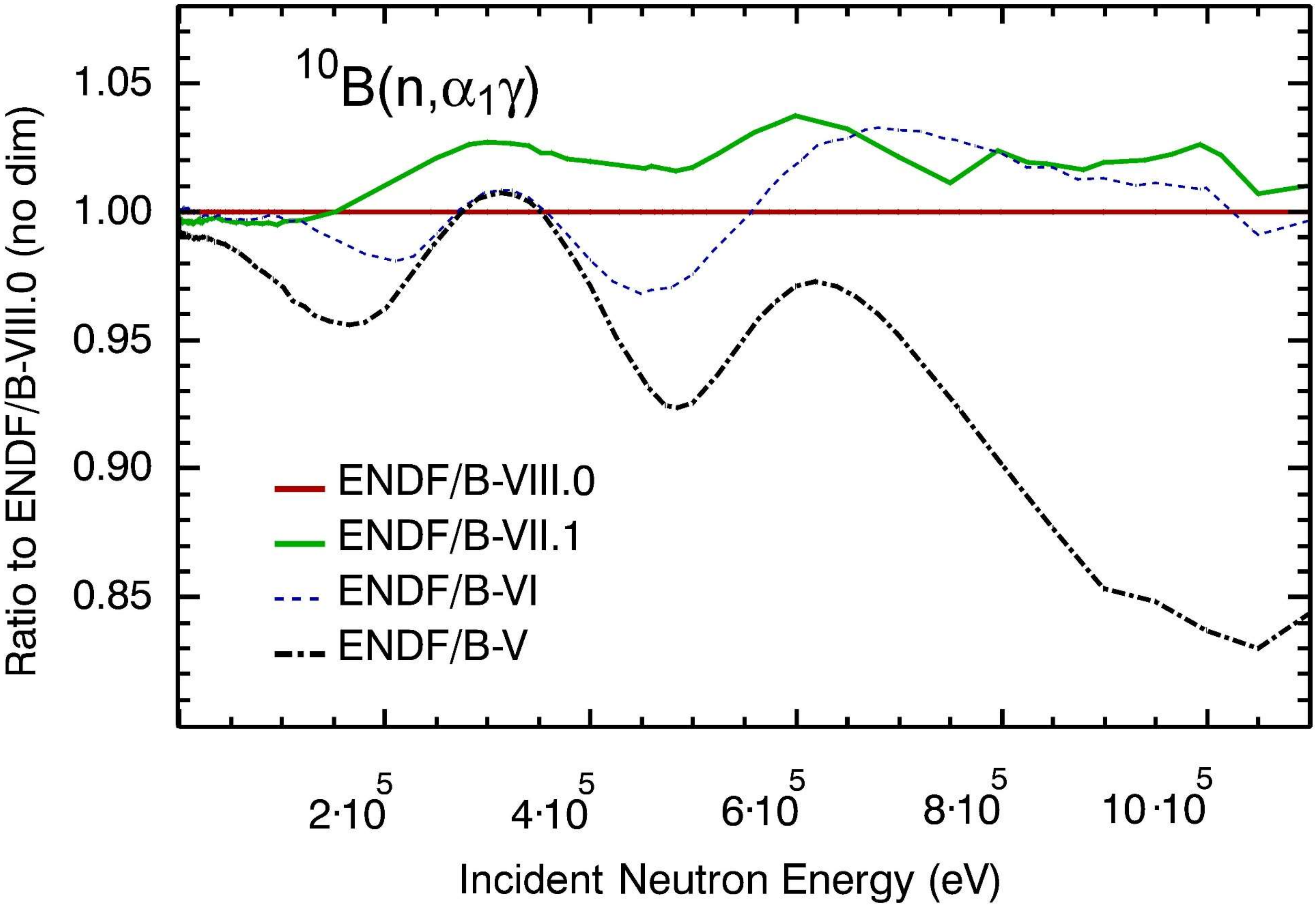
Comparison of Standards Evaluations of the H(n,n) Total Cross Section



Comparison of Standards Evaluations of the $^{6}Li(n,t)$ Cross Section



Comparison of Standards Evaluations of the $^{10}B(n,\alpha_1\gamma)$ Cross Section



Conclusions and Recommendations

- The new international standards evaluation is an improvement over previous evaluations of the standards in terms of the scope of the work and the quality of the data.

- The standards evaluation has not been completed, there are still important activities that need to be continued.

  - Extension of the H(n,n) standard to 200 MeV.
    - Re-evaluation of the standards based on the new hydrogen standard at these higher energies.

- These activities will continue to be done under an approved IAEA nuclear data development project. This project will continually update the standards so they are available for new versions of a library. New experiments will be encouraged and experimental results will be investigated for use in new evaluations. Also standards evaluation codes will be maintained and improved.