NIST Measurements and Standards Related Work at Other Facilities

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Presented at
The Measurements Committee Meeting
of
The CSEWG meeting
Santa Fe, NM
November 2, 2010

THE NEUTRON CROSS SECTION STANDARDS

Reaction	Energy Range
H(n,n)	1 keV to 20 MeV
^{3}He(n,p)	thermal to 50 keV
^{6}Li(n,t)	thermal to 1 MeV
^{10}B(n,α)	thermal to 1 MeV
^{10}B(n,$\alpha_1\gamma$)	thermal to 1 MeV
C(n,n)	thermal to 1.8 MeV
^{197}Au(n,γ)	thermal, 0.2 to 2.5 MeV
^{235}U(n,f)	thermal, 0.15 to 200 MeV
^{238}U(n,f)	2 to 200 MeV

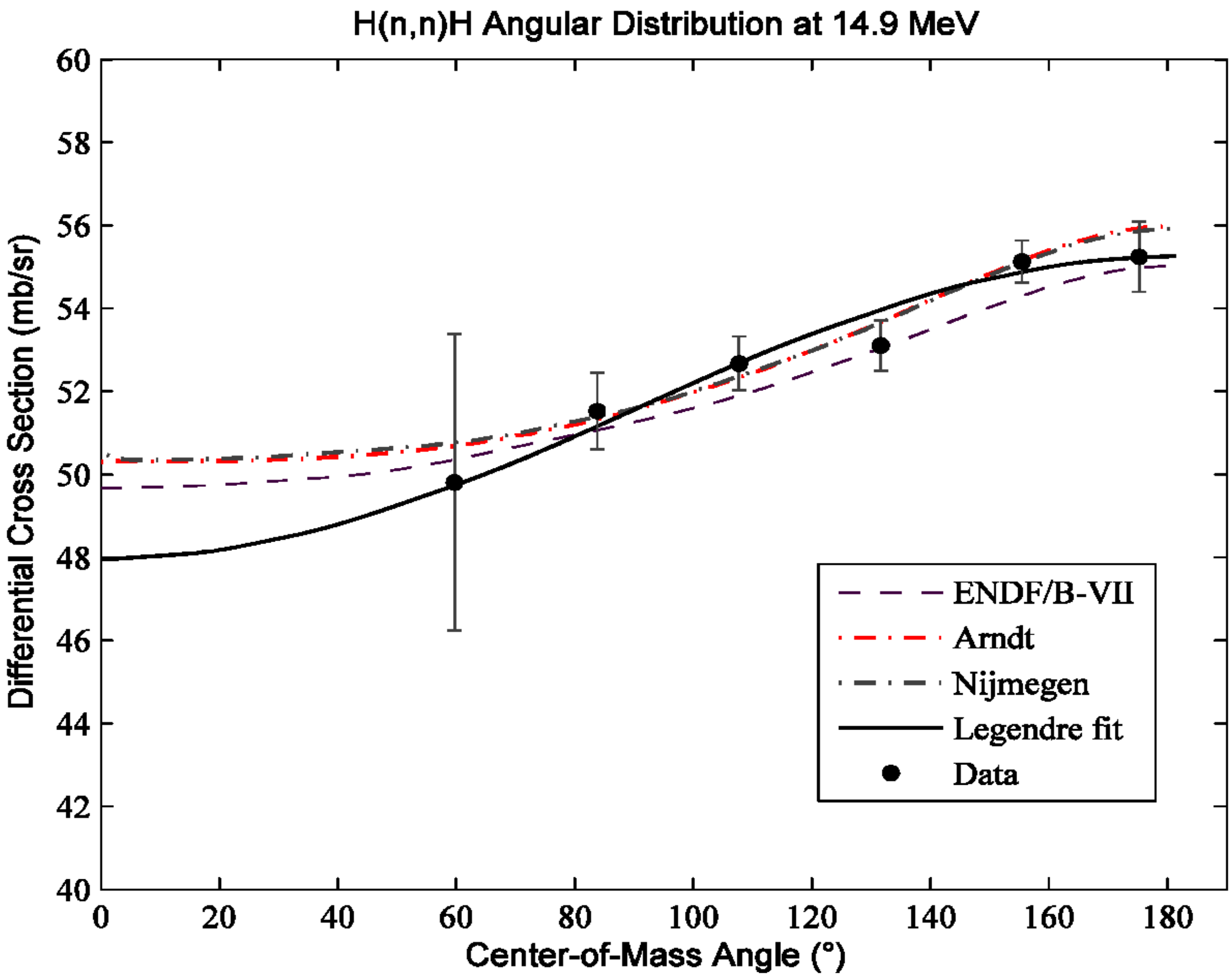
H(n,n)H Angular Distribution Measurements

• The measurements of Boukharouba *et al.* at 14.9 MeV have been completed and published in Phys. Rev. This work was initiated to resolve problems with the hydrogen database used for the ENDF/B-VI hydrogen evaluation. To improve that database, measurements were made at laboratory proton recoil angles of 0 degrees, ± 12 degrees (one on each side of the beam direction), ± 24 degrees, ± 36 degrees, ± 48 and ± 60 degrees at the Ohio University accelerator facility.

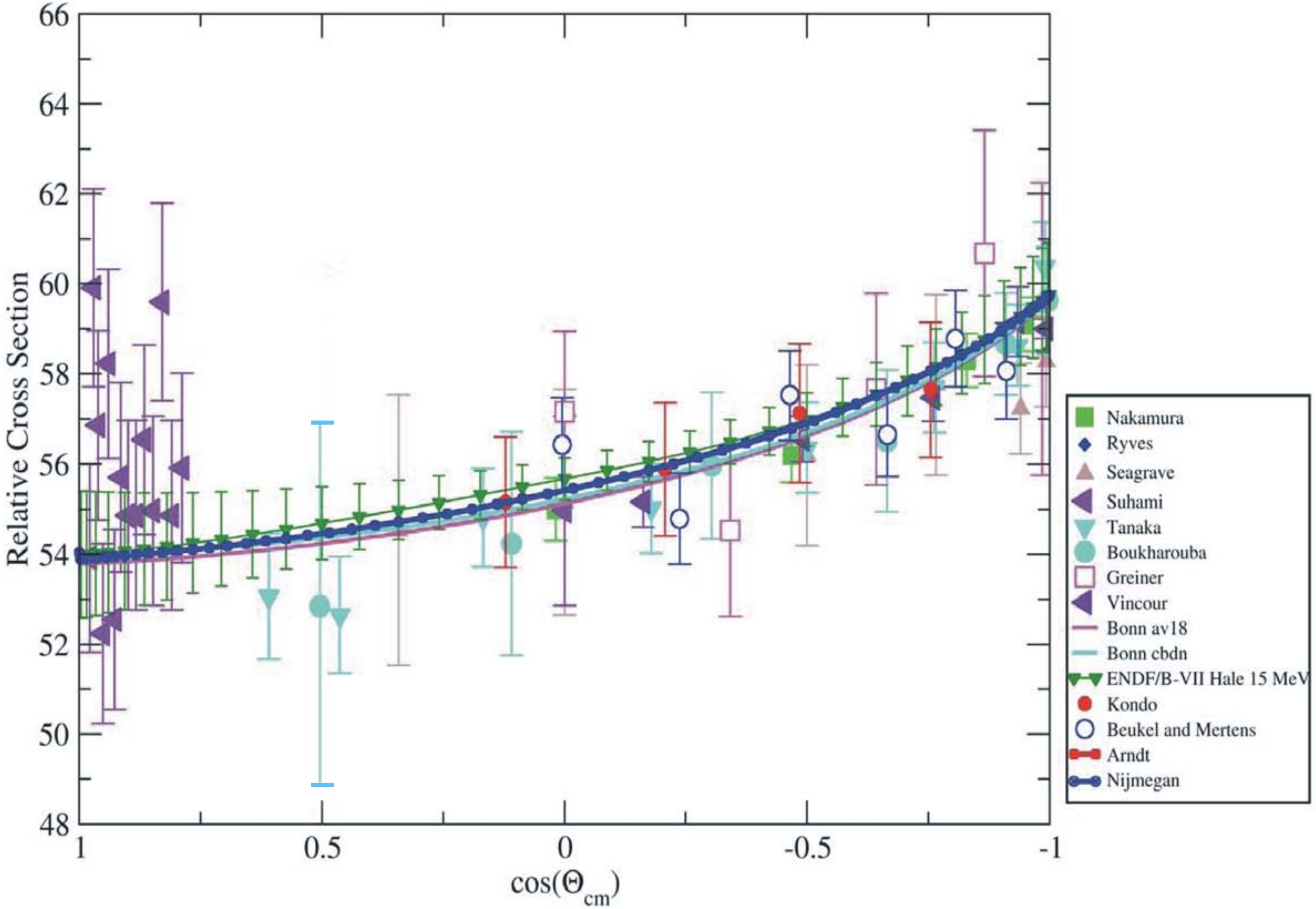
• Also improvements were made to earlier measurements made by this collaboration at 10 MeV. This included providing the mean angles since the central angles were given in the publication and also the normalization was converted to the ENDF/B-VII total elastic cross section.

(collaboration of Ohio University, NIST, LANL and the University of Guelma)

Measurements by Boukharouba *et al.*(shown as Data) compared with Evaluations and Calculations (detecting recoil protons)



14 MeV Angular Distribution Data



Note problem near zero degrees

All data have been converted to 14 MeV

H(n,n)H Angular Distribution Measurements (cont.)

• In order to make measurements at smaller scattering angles an experiment has been designed where the primary objective is detection of the scattered neutron instead of the scattered proton.

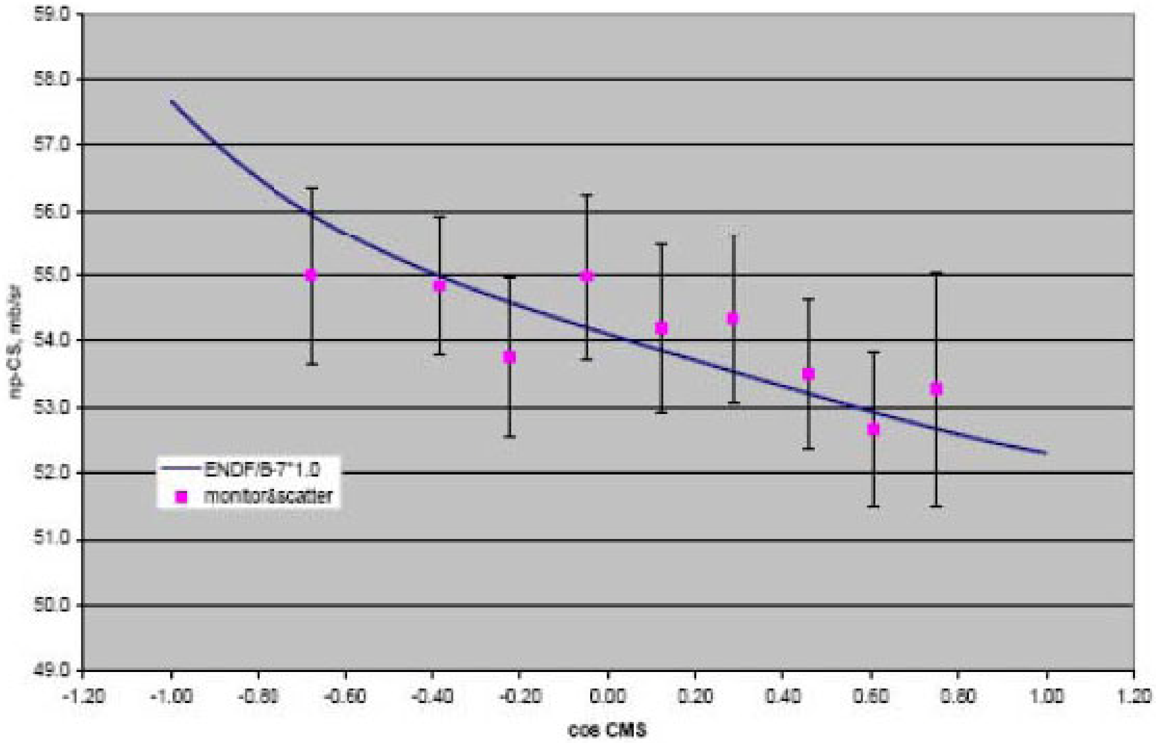
• The work is being done at the Ohio University accelerator facility. Preliminary measurements have been made at laboratory neutron scattering angles from 20 degrees to 65 degrees in 5 degree steps for 14.9 MeV incident neutrons. The plan is to increase the accuracy of the measurements and extend the angular range so that data are obtained from 15 to 70 degrees.

• To obtain the accuracy needed for this work, the neutron detector efficiency must be determined accurately. At lower energies ^{252}Cf spectra will be used. At the higher energies, several methods are under investigation including the use of a well characterized ^{235}U fission chamber to implement the ^{235}U(n,f) standard

• Following the completion of this work, measurements will be made at 10 MeV incident neutron energy, where measurements were made earlier by this collaboration, to help fill in the gap at small angles at that energy.

(collaboration of NIST, Ohio University, LANL and the University of Guelma)

Preliminary Data for the Ohio U. Experiment at 14.9 MeV (detecting recoil neutrons)



Average results from this work compared with the latest ENDF/B evaluation. The uncertainties shown are due to statistics only. The data are shape measurements and were normalized to the ENDF/B results.

H(n,n)H Angular Distribution Measurements (cont.)

•Plans are being made to continue hydrogen angular distribution measurements using a Time Projection Chamber which will provide higher counting rates than are possible with the other methods.

(collaboration of NIST, Ohio University, LANL and the University of Guelma)

Hydrogen Angular Distribution at High Neutron Energies

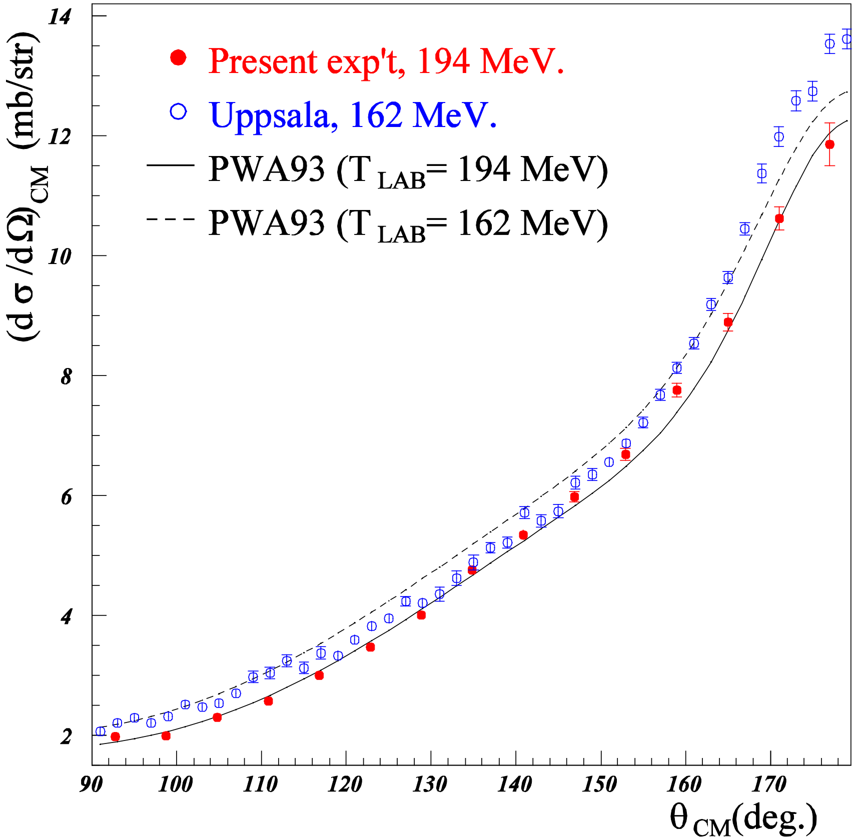
• The most recent measurements of the hydrogen angular distribution in the 100 MeV energy region are not consistent at back angles. Larger cross sections were measured at Uppsala (96 and 162 MeV) and PSI (many energies from about 280 MeV to 580 MeV), both using pseudo-monoenergetic sources. The work at Indiana University at 194 MeV, using neutrons tagged by detection of the associated protons from the D(p,n)2p reaction, indicate lower cross sections and they agree with PWA calculations.

• The Uppsala group has investigated the sources of error in their experiment and can not find any problems that would resolve the discrepancy but they suggest that the Indiana experiment may be preferred due to the smaller total uncertainties.

• The PSI group indicates they have done all they can with their experiment and its analyses. Nothing further can be expected from that group to resolve the discrepancy.

H(n,n)H Angular Distribution Work at ~200 MeV

• There is a discrepancy between the results of the Uppsala University and Indiana University measurements (shown here as Present exp’t).



Hydrogen Angular Distribution at High Neutron Energies (cont.)

• Though there is an indication that the discrepancy may be resolved at about 160 MeV - 200 MeV, the PSI data which cover a very large energy range (200-580 MeV) still stand as measured. Further work should be done to understand this problem.

• Also more work should be done on angular distribution measurements in the intermediate energy region from about 30 MeV to 150 MeV. Little data are now available and the angular interval is very limited.

• The standards should be at the forefront, producing high accuracy cross sections in energy regions that may shortly require improved standards. It is short sighted to not have quality standards in the intermediate and high energy regions.

^{3}He(n,p) Measurements

• The NIST collaborative work on the measurement of the spin-dependent portion of the n- ^{3}He coherent scattering length using a polarized neutron beam and a polarized ^{3}He target has been published. The data from this measurement will allow separation of the real part of the two spin channels of this interaction. These data are complementary to NIST published measurements made of the n- ^{3}He coherent scattering length. These data and NIST collaborative measurements of the total cross section by Keith *et al.* from 0.1 to 500 eV with uncertainties less than 1% are being used in an R-matrix evaluation of the ^{3}He(n,p) standard cross section by Hale.

• There appears to be some inconsistency for the data in the evaluation. The very small uncertainties for the total cross section have led to problems with convergence for the R-matrix analysis.

(collaboration of NIST with Indiana University and the University of North Carolina)

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

• Measurements are now underway at the NIST of the $^{6}Li(n,t)$ cross section standard at ~ 4 meV neutron energy. These are the first direct and absolute measurements of this cross sections in this neutron energy range using monoenergetic neutrons. A primary effort has been focused on measuring the fluence accurately. The fluence (efficiency) has now been determined with an uncertainty of less than 0.1%. The solid angle uncertainty is about 0.1%.

• The limitation on the accuracy of the $^{6}Li(n,t)$ cross section measurement is the mass uncertainty of the ^{6}Li target. The present mass uncertainty is about 0.25%. Further studies will be made to compare the mass with the value obtained when it was characterized a number of years ago. It is expected that a total uncertainty less than 0.3% for the cross section can be obtained from this experiment.

(collaboration of NIST, LANL, the University of Tennessee and Tulane University)

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

• Hambsch plans angular distribution and cross section measurements for the $^{6}Li(n,t)$ Reaction. The cross section data will be relative to the $^{235}U(n,f)$ standard. Both LINAC and Van De Graaff facilities will be used. The work on the LINAC will extend from a few keV to about 3 MeV so the resonances in that region can be covered. The Van De Graaff work will cover higher energies but should overlap the LINAC data from 1 to 3 MeV. Some setup work has been done for the Van De Graaff work. The ^{6}Li deposits are being made at IRMM.

^{6}Li(n,t) Measurements (cont.)

• Zhang has recently communicated that his Frisch gridded ionization chamber data near 90 degrees are affected by “particle leaking effects.” at 3.67 MeV and 4.42 MeV.

• The angular distribution measurements at 1.05, 1.54, 1.85, 2.25, and 2.67 MeV are not affected. The data that are not affected were obtained 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.

• At the present time data at these higher energies are not used in the standards evaluation process. Eventually, as improved data become available, the ^{6}Li(n,t) standard may be extended to higher energies.

^{10}B(n,α) Measurements

• As a separate experiment, the same basic experimental setup being used for the NIST collaborative measurements of the ^{6}Li(n,t) cross section at ~ 4 meV will be used to measure the ^{10}B(n,α) cross section also. ^{10}B samples from previous work exist but an investigation must be done to ensure that the deposits have been stable. Those samples were produced at IRMM using very special evaporation techniques. If additional samples are needed, it may be difficult to get them fabricated at that facility.

• The angular distribution measurements of Hambsch have been published in Nuclear Science and Engineering. He continues to accumulate data on the branching ratio, the angular distribution and the ^{10}B(n,α) and ^{10}B(n,$\alpha_1\gamma$) cross sections relative to the ^{235}U(n,f) standard up to about 3 MeV. The data are being analyzed. He plans to have a post-doc to assist in analyzing the large amount of experimental data.

$^{10}B(n,\alpha)$ Measurements (cont.)

• The Frisch gridded ionization chamber work of Zhang et al. on the $^{10}B(n,\alpha)$ Angular distribution relative to the $^{238}U(n,f)$ standard at 4 and 5 MeV is not affected by "particle leaking". However they communicate that there is a problem with the data at 4.17, 5.02, 5.74, and 6.52 MeV, apart from "particle leaking". This is being investigated.

• They also have found that there appears to be a loss of ^{10}B from their samples as a function of time.

• As a result of these problems, they are doing a systematic study of their work.

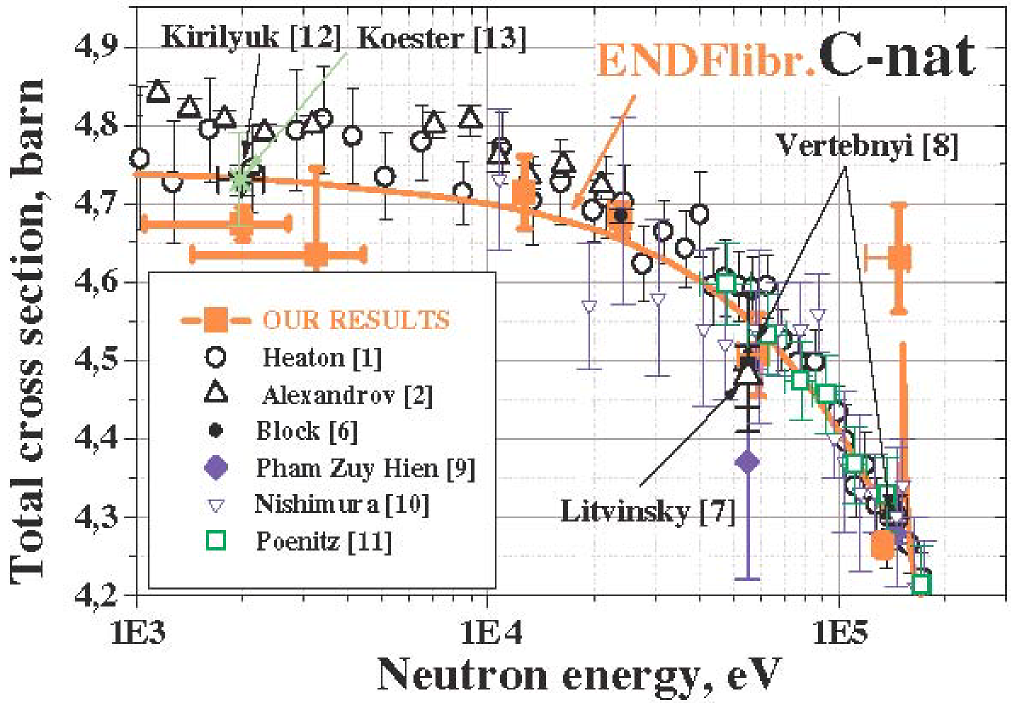
C(n,n) data

• Measurements have been made of the carbon total cross section at RPI by Danon et al. for the energy range from 24 to 940 keV. The data were obtained with a linac using an iron filtered beam. Uncertainties are a percent or less and are in excellent agreement with the ENDF/B-VII evaluation. The data were reported at the ND-2007 conference.

• 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 evaluation. However at the lower energies their results are somewhat low and at the highest energy the result is significantly higher. They suggest that the resonance in ^{13}C at 152.9 keV may cause this increase. For this to be the case, however, would require that its neutron width be greater than the reported 3.7 keV. At the ISRD-13 meeting in 2008, they showed angular distribution data for 2, 59 and 133 keV. The measurements were made at 30, 55, 90, 125 and 150 degrees. They were measured relative to lead scattering but the shape should still be relatively good anyway.

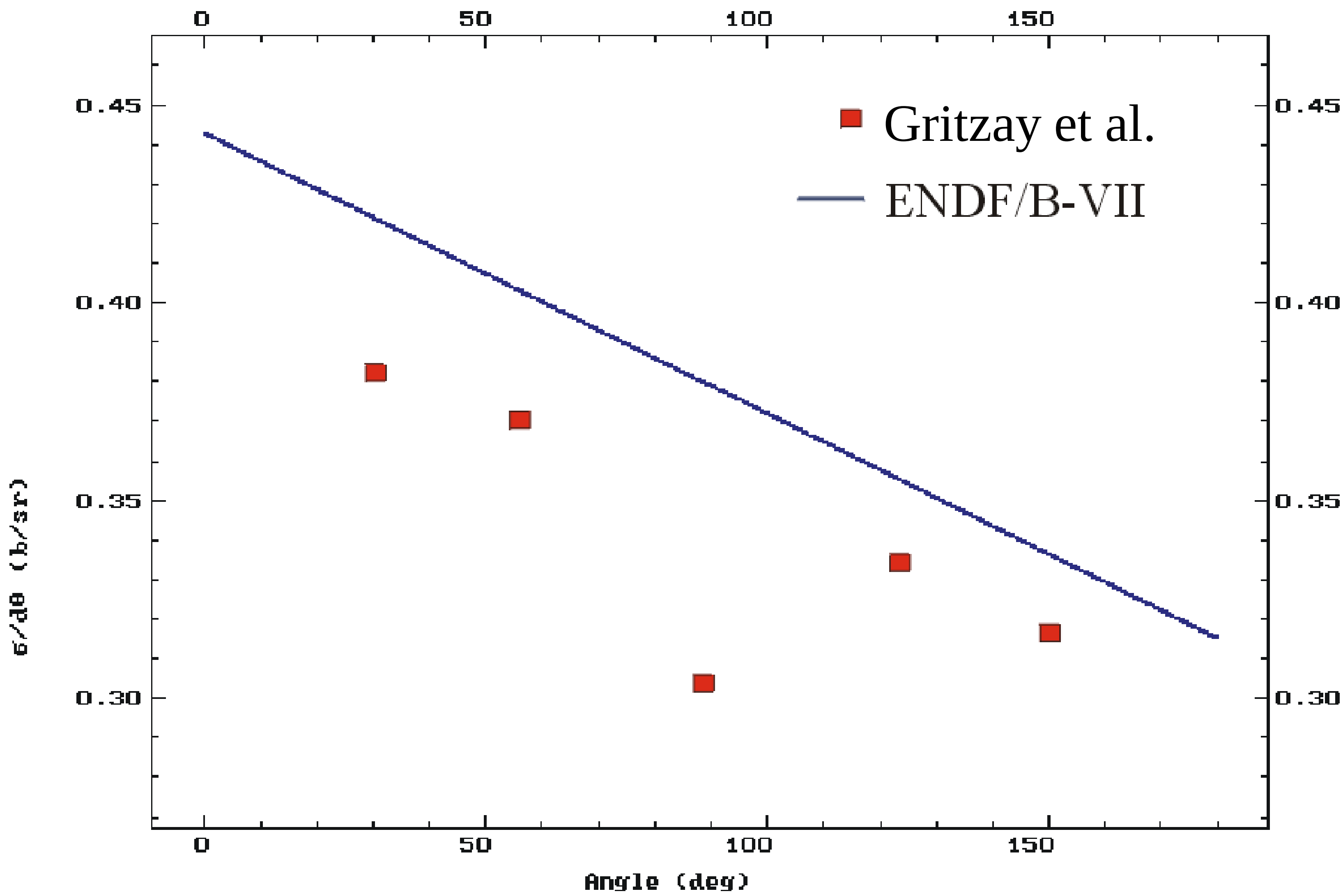
•The results differ from the carbon standard.

Measurements by Gritzay *et al.*(shown as "Our Results") Compared with Other Measurements and the ENDF/B-VII Evaluation



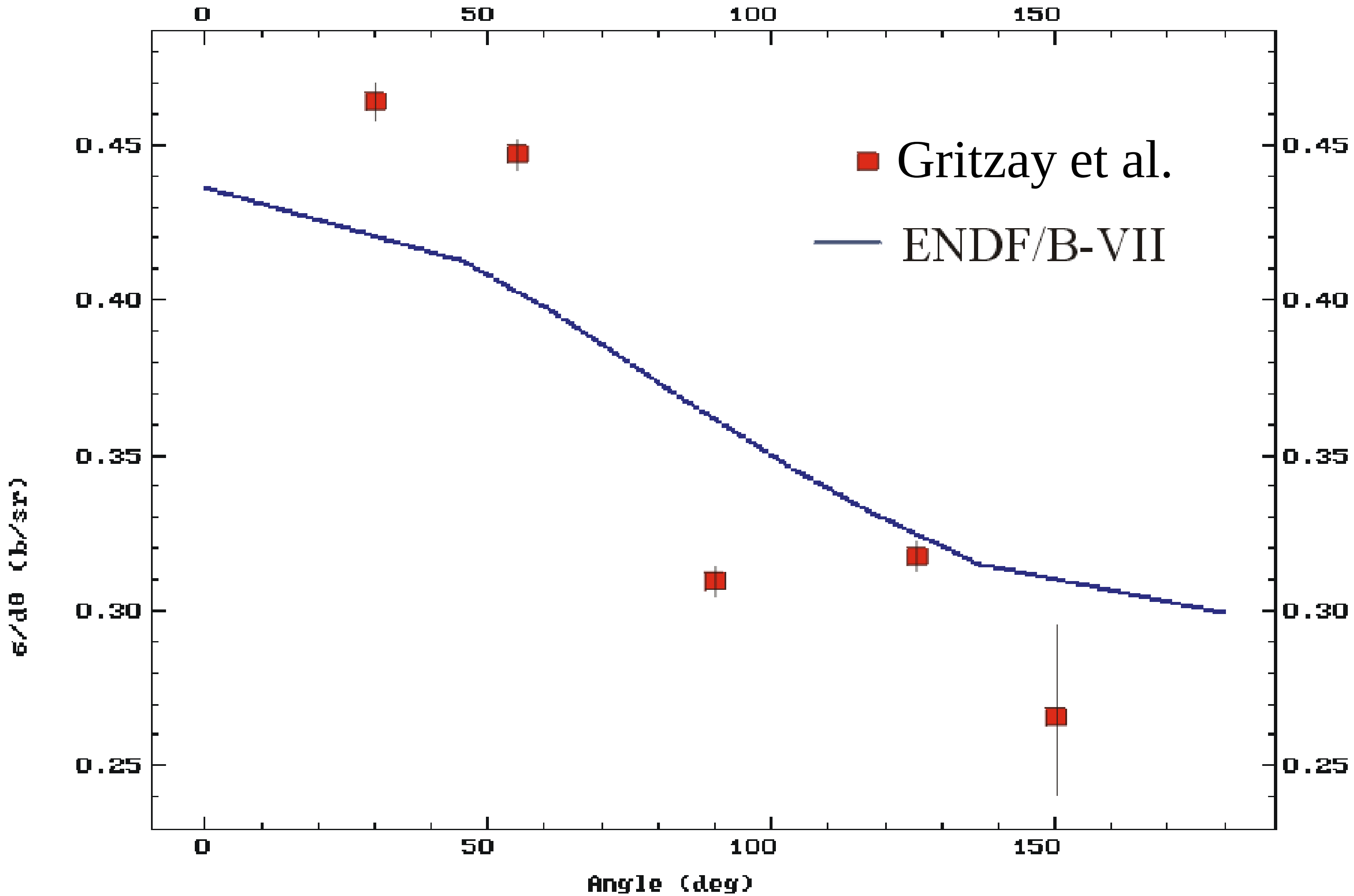
Our results for C-nat. total neutron cross sections, experimental data from database EXFOR/CSISRS and ENDF libraries.

C(n,n) E_n =2 keV



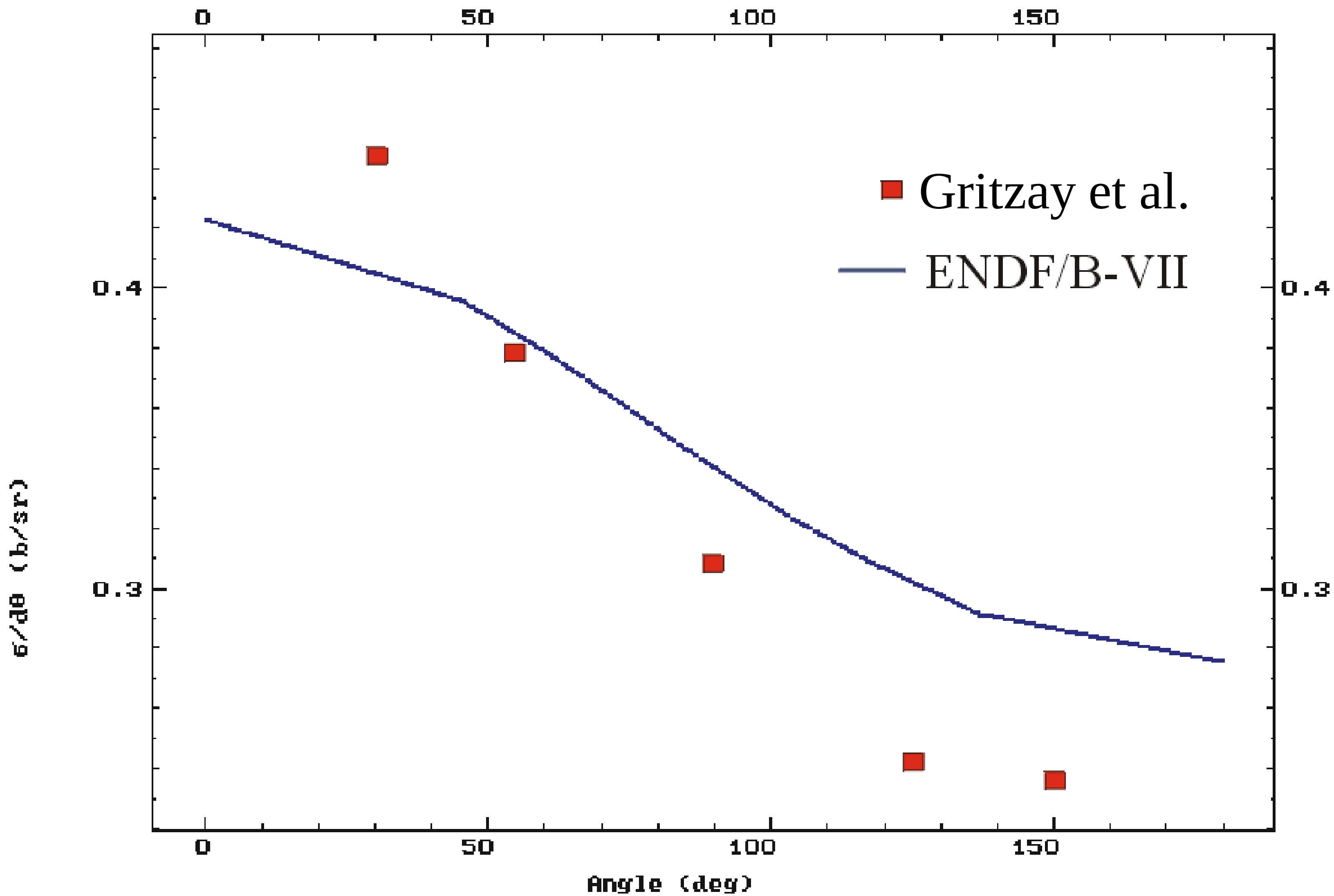
0
50
100
150
0.45
0.40
0.35
0.30
Gritzay et al.
ENDF/B-VII
σ/dθ (b/sr)
Angle (deg)

C(n,n) E_n = 59 keV



Gritzay et al.
ENDF/B-VII
0
50
100
150
0.45
0.40
0.35
0.30
0.25
σ/dΩ (b/sr)
Angle (deg)

C(n,n) E_n =133 keV



Au(n,γ) at low energies

• To support the needs of certain applications, such as astrophysics, the energy range below about 100 keV for gold capture will be added to the standards activities as a "reference" cross section.

• Due to the evaluation process used for the standards evaluation, data for the Au(n,γ) cross section were obtained for energies below 200 keV.

• These results are consistently higher than the Ratynski evaluation (by about 5-7% from 15 to 25 keV) which is used in astrophysics applications.

• The Ratynski evaluation relies on Macklin capture data and Ratynski-Käppeler Karlsruhe pseudo-Maxwellian capture data.

• The standards evaluation uses a large database of various types of data.

• The results of WPEC Subgroup 4 support the standards evaluation.

Au(n,γ) at low energies (cont.)

- Au(n,γ) reference cross section for capture cross section measurements for astrophysics (below the standards energy region) (cont.).

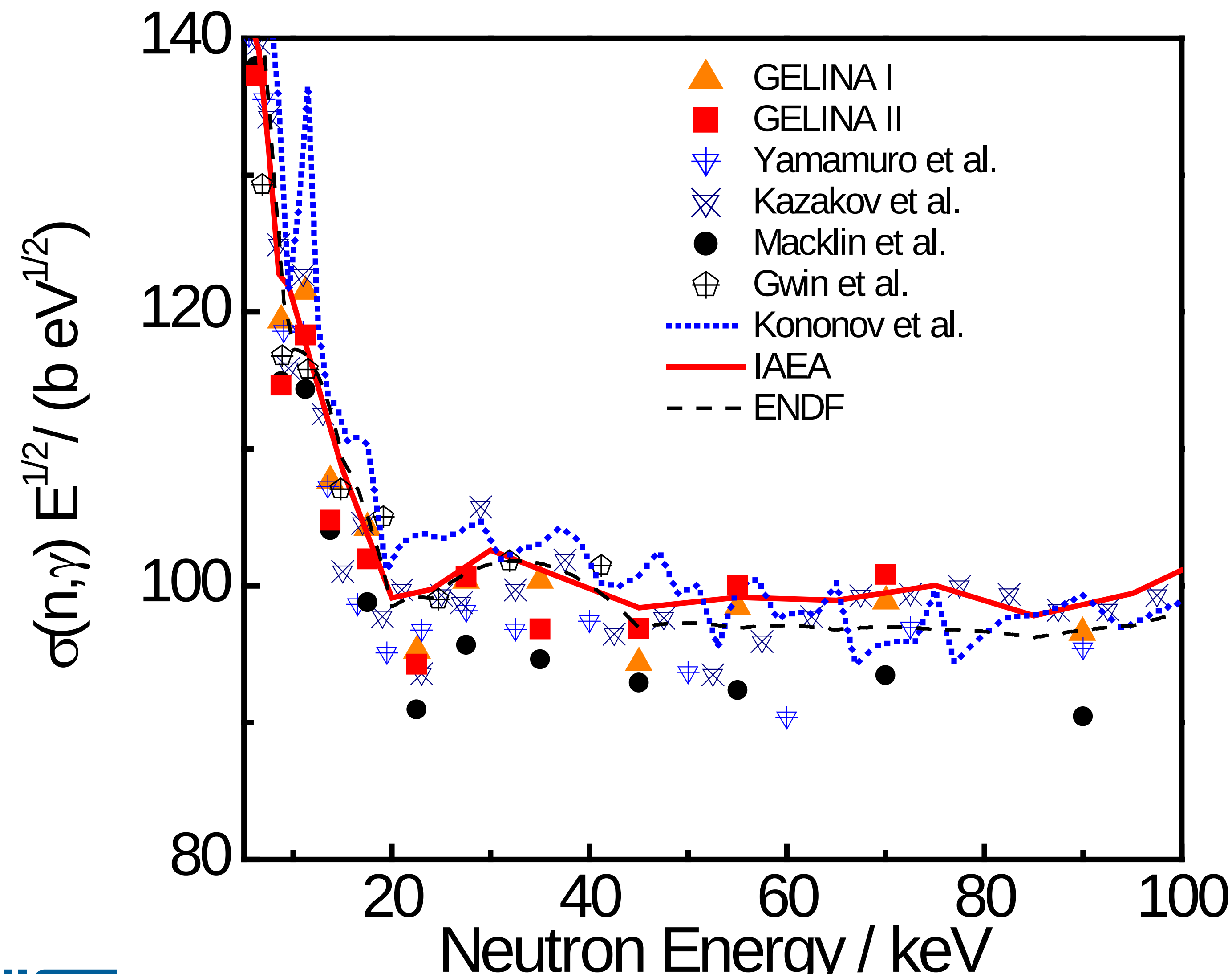
  - New experiments were reported at the Consultants' Meeting

    - 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 (obtained using his ^{238}U(n,γ)/^{197}Au(n,γ) cross section ratio and the ^{238}U(n,γ) cross section from the standards evaluation)

    - 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 Au(n,γ) cross section measurements of Borella et al. support the standards evaluation. Schillebeeckx repeated that experiment of Borella et al. with considerable concern about corrections to the data. The new results support the standards results and the Borella et al. data.

Gold Capture Measurements and Evaluations, GELINA I = Borella et al., GELINA II= Schillebeeckx, IAEA=the Standards Evaluation



Au(n,γ) and ^{238}U(n,γ) Measurements

• In addition to the measurements at 25 keV by Wallner (U. of Vienna) of the ^{238}U(n,γ)/^{197}Au(n,γ) cross section ratio, data were obtained for this ratio at 500 keV, at thermal energy and with cold neutrons. Accelerator mass spectrometry was used to measure the resulting ^{239}Pu resulting from the ^{239}U. Activation was used for the gold measurements. The 500 keV measurement has a large (150 keV FWHM) energy spread.

• At 500 keV the ^{238}U(n,γ) value obtained is 109 ± 2 mb which agrees exactly with the standards evaluation. (obtained using his ^{238}U(n,γ)/^{197}Au(n,γ) cross section ratio and the gold capture cross section from the standards evaluation)

• The thermal and cold neutron measurements are still being analyzed.

Au(n,γ) and ^{238}U(n,γ) Measurements (cont.)

• Comparison of measurements to the ENDF/B-VII.0 evaluations of the ratio of the ^{238}U(n,γ)/^{197}Au(n,γ) cross sections has caused some concern. The observation is that most of the measurements are larger than the evaluated values. It appears that the problem is the measurements. An examination of the all measurements that relate to the ^{238}U(n,γ) cross section indicates general agreement with the ENDF/B-VII.0 evaluation. Also the absolute measurements of the Au(n,γ) cross section are in good agreement with the ENDF/B-VII.0 evaluation.

• The Wallner measurements of the ^{238}U(n,γ)/^{197}Au(n,γ) cross section ratio referred to previously are in excellent agreement with the standards evaluation.

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

• Ullmann et al. made measurements of the $^{238}U(n,\gamma)$ cross sections using the DANCE (160 BaF_2 crystals) detector at LANSCE. The results were reported at the ND2010 conference. The neutron beam was monitored with a ^{235}U fission chamber, a BF_3 counter, a ^{6}Li F detector and a ^{3}He detector. Small ^{238}U samples could be used due to the high neutron intensity at DANCE. This reduces the uncertainty due to multiple scattering. Though the data could be made absolute, they normalized to capture in the 80 and 145 eV resonances. They associate a 2 percent uncertainty to this normalization. They state there is generally good agreement with the ENDF/B-VII evaluation. The data are not available yet since they are still working on a final normalization.

Recent Measurements of the ^{238}U Capture Cross Section by Ullmann

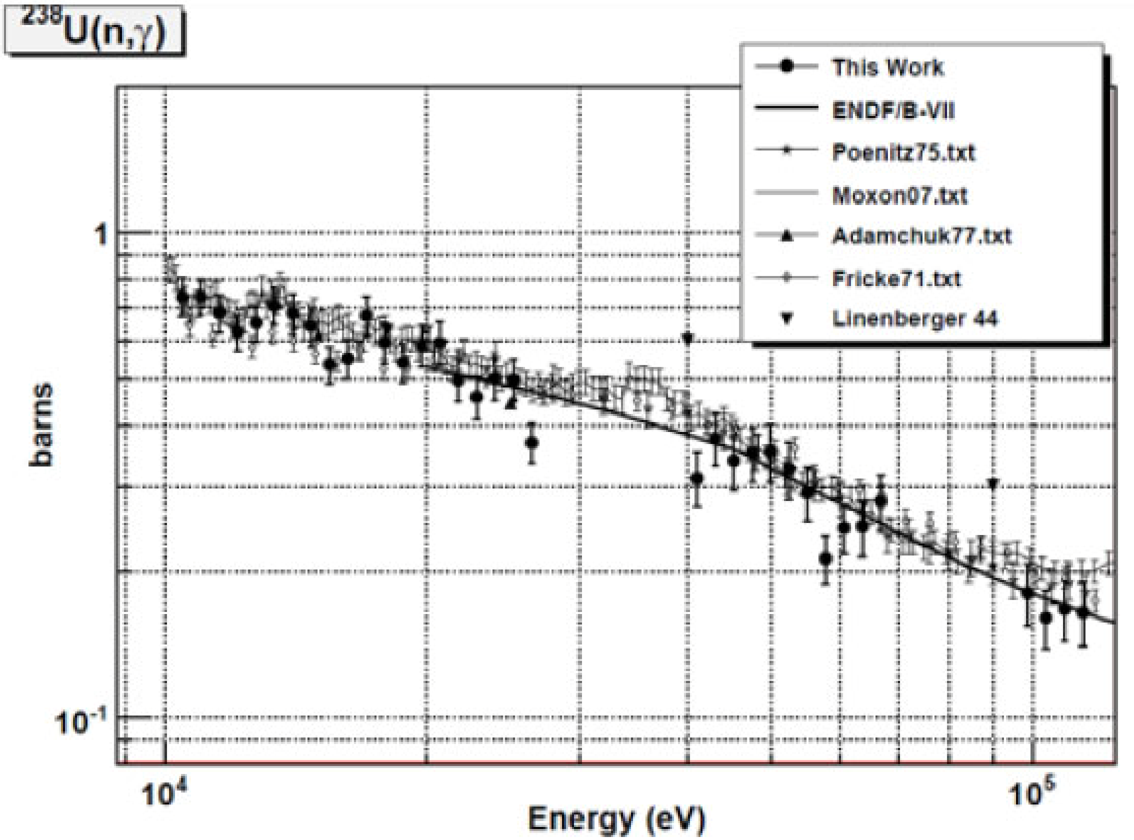


Fig. 3. Measured cross section in the 10 to 100 keV range compared with previous measurements[4] and the ENDF/B-VII evaluation.

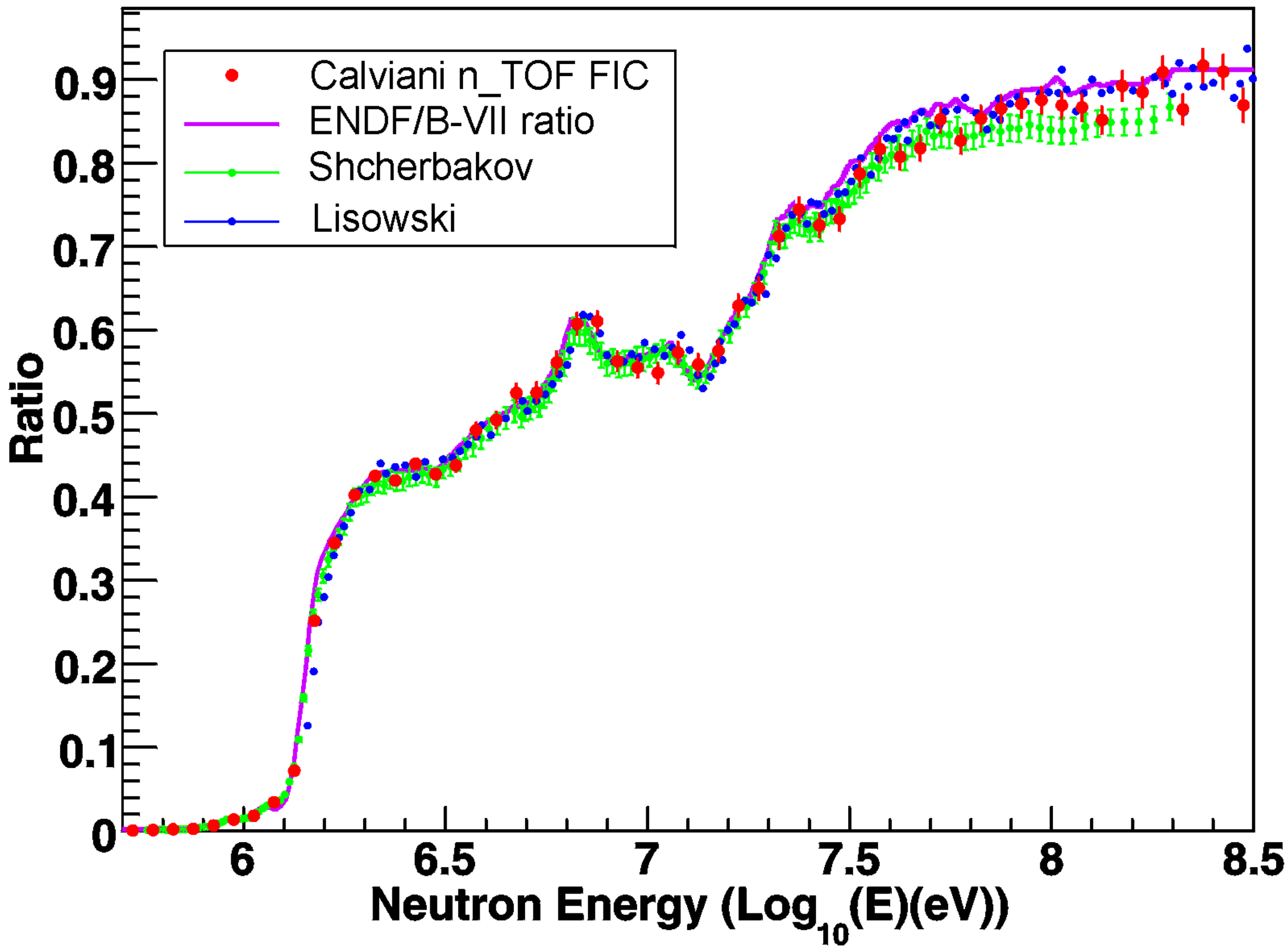
$^{235,\,238}$U(n,f) Measurements

•There has been no new measurement activity since the last CSEWG meeting for these fission cross sections. Analysis of the two independent measurements of the ^{238}U(n,f)/^{235}U(n,f) cross section ratio made at the n_TOF facility is underway. Both sets of measurements tend to support the Lisowski *et al.* data somewhat better rather than the Shcherbakov *et al.* data. Additional measurements are planned.

•Data from the Calviani et al. n_TOF experiment were obtained with fission ionization chambers. Preliminary results of the data analysis are available to about 300 MeV.

•The n_TOF measurements by Audouin et al. used coincidences between fission fragments in Parallel Plate Avalanche Counters. The data extend to about 1 GeV. The data are preliminary.

Comparison of Recent Measurements of the $^{238}U/^{235}U$ Fission Cross Section Ratio

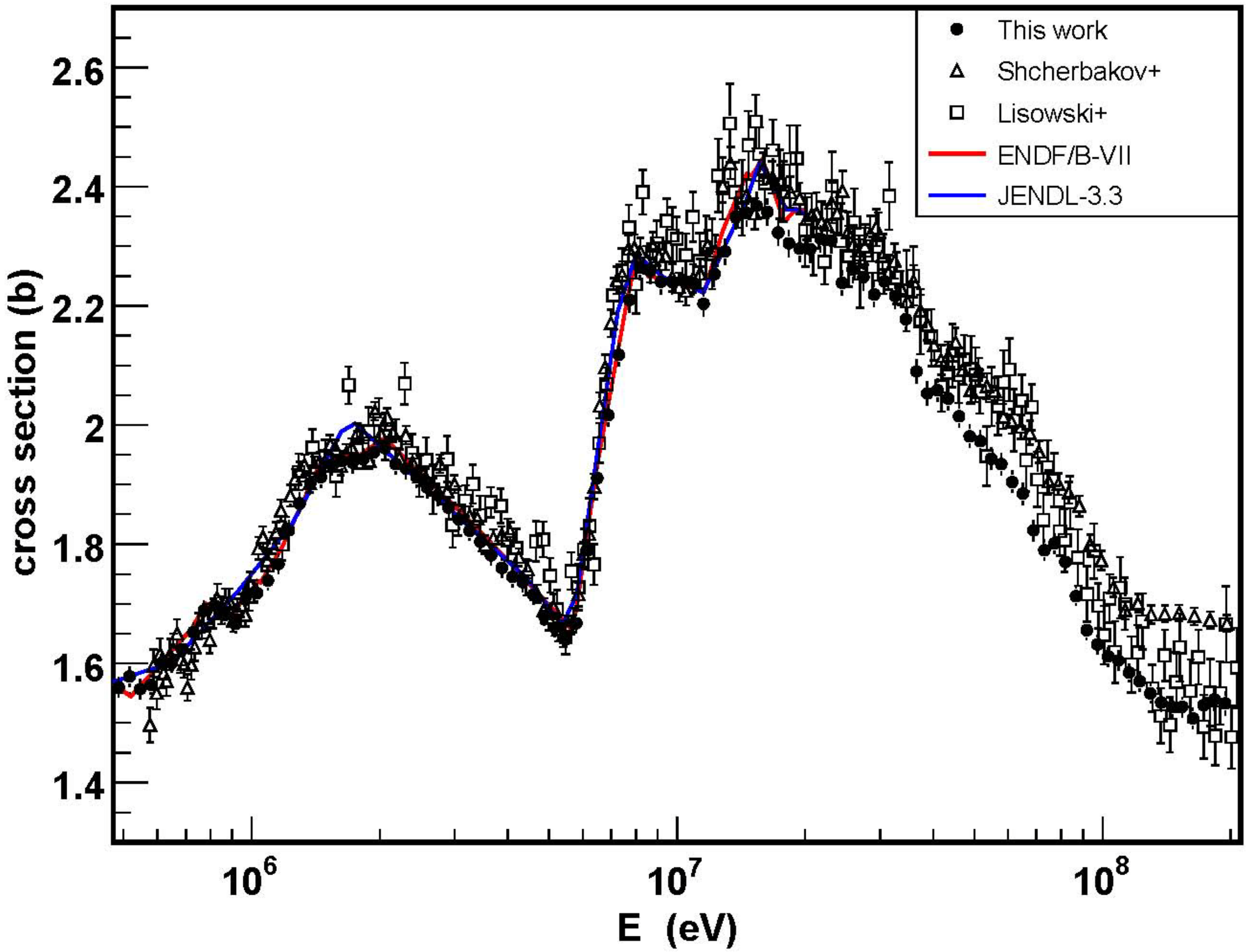


^{239}Pu(n,f) Measurements

•New measurements have been made of the ^{239}Pu(n,f) cross section by Tovesson and Hill at the WNR facility at LANL. The data are relative to the ^{235}U(n,f) cross section. In the MeV enery region, they agree 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 the 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. The data were published this year and final tabular data have been obtained

•Additional work on the ^{239}Pu(n,f) cross section in the MeV energy is expected from a collaboration initiated by staff at LANL and LLNL with several universities. This work will use Time Projection Chambers for fission detection. Very accurate measurements should be possible with these detectors. Plans have also been made to make measurements of the ^{235}U(n,f) and ^{238}U(n,f) cross sections with this detector.

Measurements of the ^{239}Pu(n,f) Cross Section by Tovesson & Hill (labelled "This work"), Shcherbakov et al. and Lisowski et al. Compared With the ENDF/B-VII Evaluation



Conclusions

•Recent experimental activity has improved the quality of the standards database. In most cases the data are in reasonable agreement with the evaluation. Areas of concern are:

•H(n,n) at small angles in the CMS near 15 MeV

•H(n,n) at intermediate and high energies where data are sparse and typically not available for a large angular range. Also there is the lingering concern for back angles in the hundred + MeV region.

•Both ^{6}Li(n,t) and the ^{10}B standards need additional work as the emphasis is on extending the energy range to higher energies

Measurements at low energies for C(n,n) dosagree with the evaluation

Additional work should be done in the high energy region on the ^{235}U(n,f), ^{238}U(n,f) and ^{239}Pu(n,f) cross sections to support of the needs for better standards in that energy region .