Recent Measurements of Cross Sections Relevant for An Evaluation of the Neutron Cross Section Standards

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Presented at the
IAEA Consultants' Meeting
on
Extending and Updating the
International Neutron Cross Section Standards
Vienna, Austria
13 October, 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

•There has been experimental work indicating an anomalous drop of about 40% in the n-p differential scattering cross section, compared with accepted values for 10 – 200 eV neutrons.

•It was suggested that quantum entanglement of protons could cause the effect. If so the effect would show up more clearly at higher energies.

•This led to experiments reported by Moreh, Block and Danon measuring the neutrons scattered from CH_2 and C. The ratio of these experiments clearly shows the effect is not present for incident neutron energies of 100 eV to 140 keV.

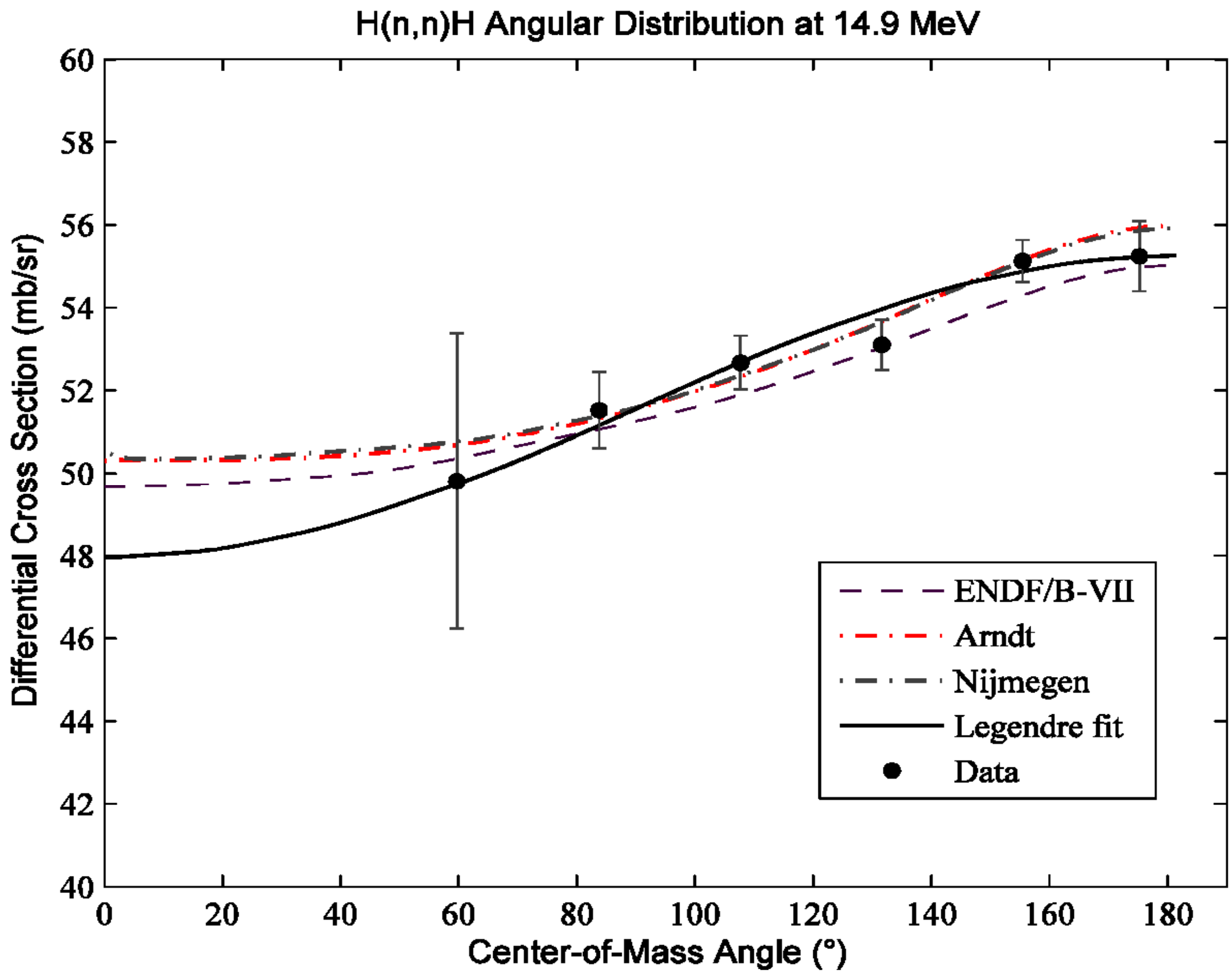
It has been suggested that the "anomaly" may be due to an error in the efficiency of the monitor detectors used in the experimental work that found the 40% anomaly.

H(n,n)H Angular Distribution Measurements

•Problems with the ENDF/B-VI evaluation resulted from questionable measurements at about 14 MeV. To improve that database, measurements were made by Boukharouba *et al.*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. A paper on this work was recently published in Phys. Rev. The data were obtained at 14.9 MeV neutron energy.

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

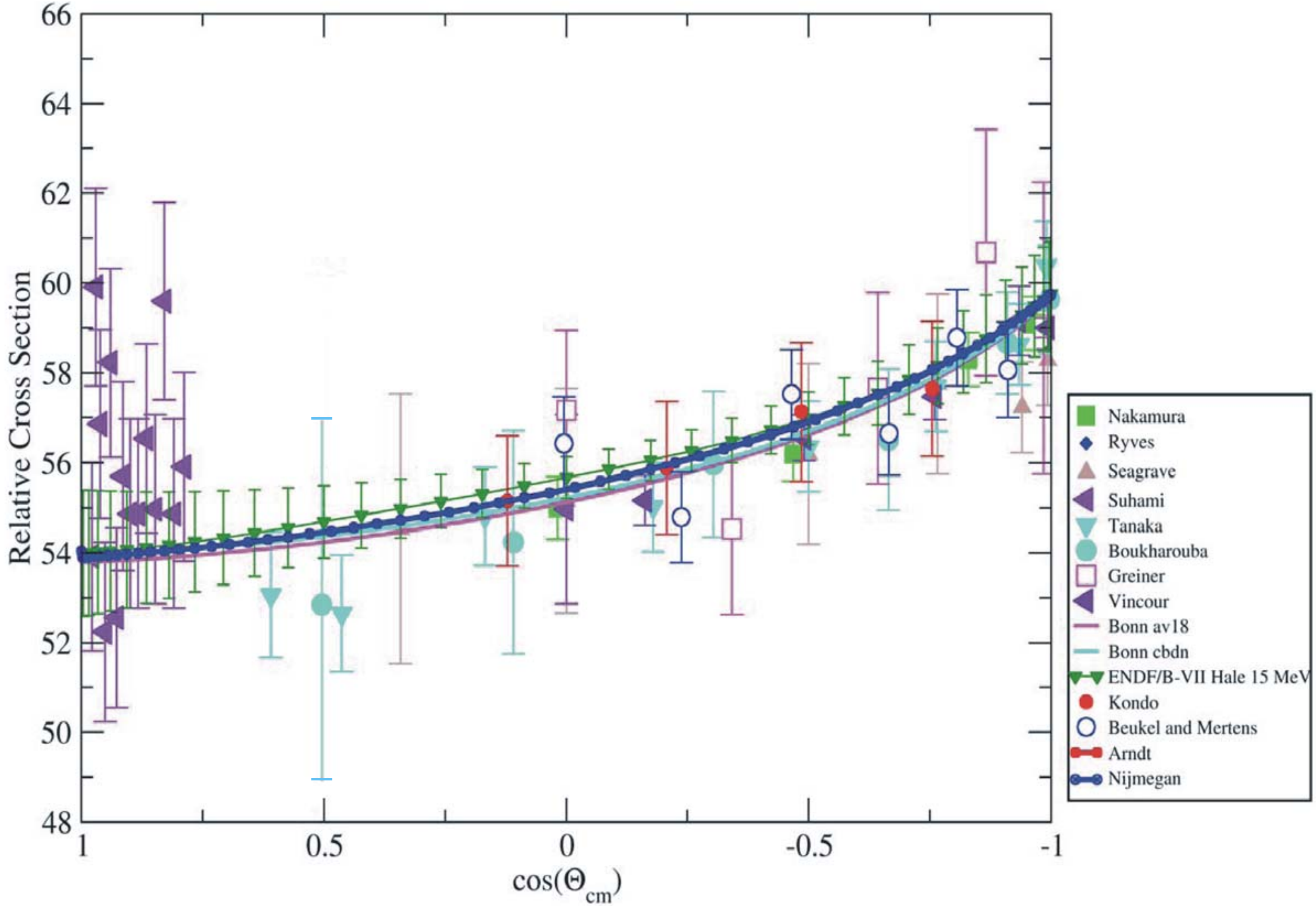
Measurements by Boukharouba *et al.*(shown as Data) compared with Evaluations and Calculations



H(n,n)H Angular Distribution Measurements

•By detecting the recoil proton, measurements were made by Kondo *et al.* at laboratory proton recoil angles of 20 degrees, 30 degrees, 40 degrees, and 50 degrees at the Osaka University FNS facility. The data were obtained at 14.2 MeV neutron energy A paper was Published in Nuclear Instruments and Methods A 568 (2006) p.723. The data are now available in XFOR 20070219

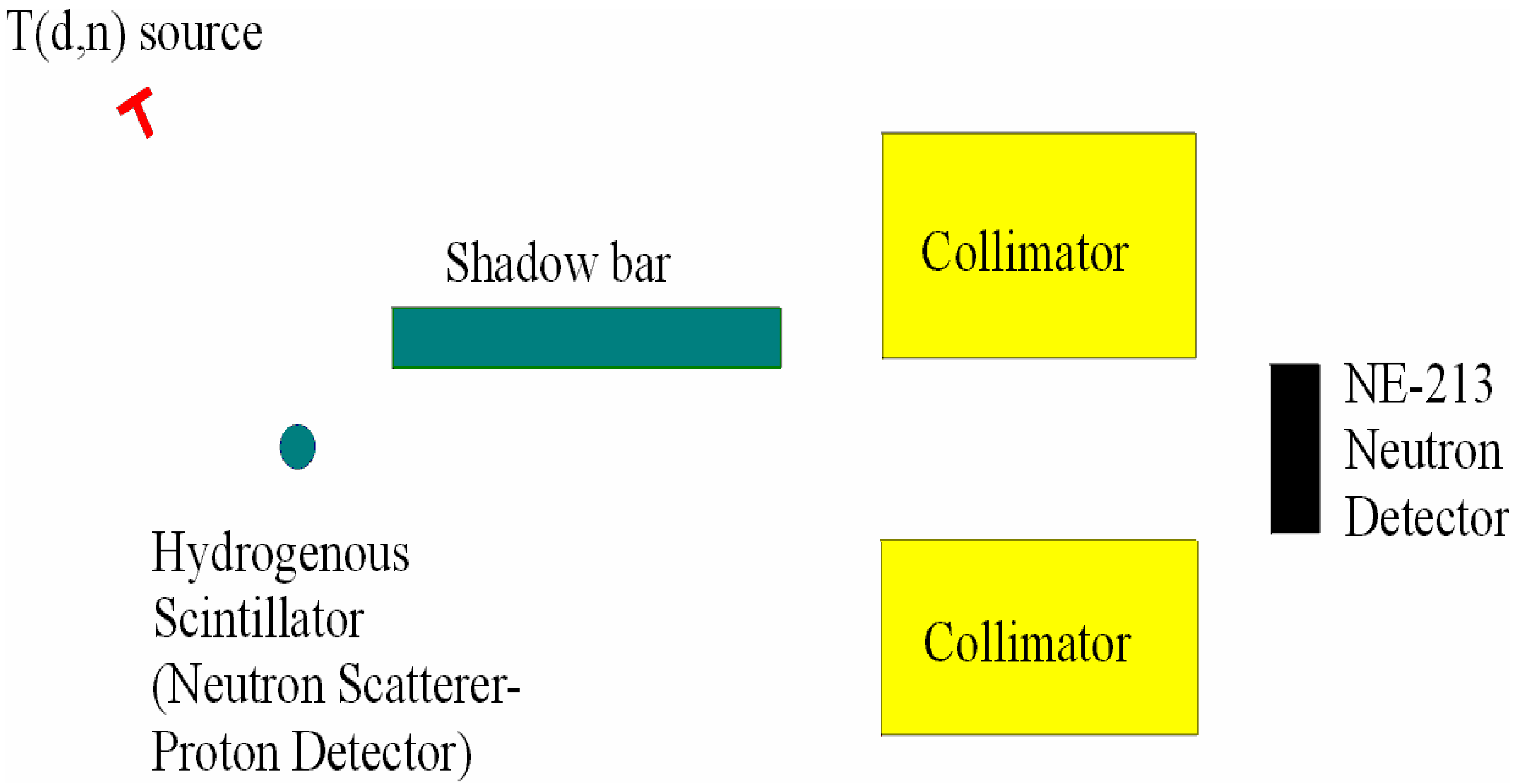
14 MeV Angular Distribution Data



Note problem near zero degrees

All data have been converted to 14 MeV

Experimental Setup for Measurements Detecting the Scattered Neutrons at Ohio University



H(n,n)H Angular Distribution Measurements

•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.

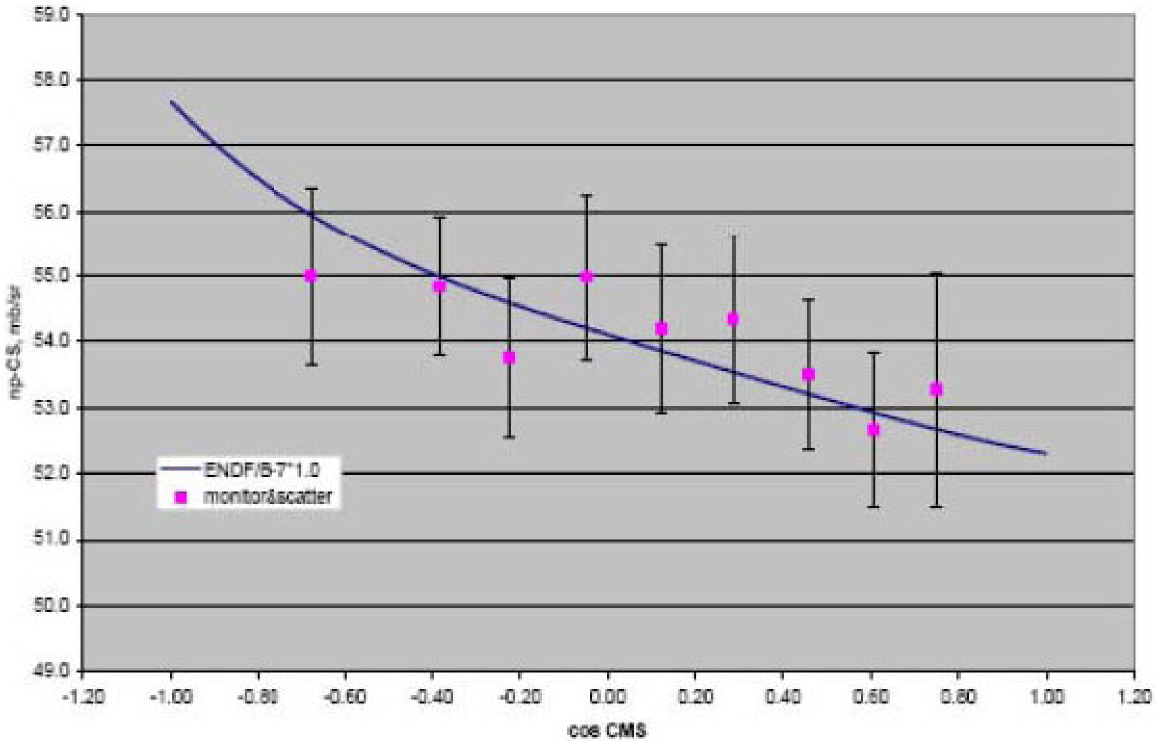
•The work is being done at the Ohio University accelerator facility. Preliminary measurements have been made at laboratory neutron scattering angles from 20 degrees to 65 degrees in 5 degree steps for 14.9 MeV incident neutrons. The plan is to increase the accuracy of the measurements and extend the 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 Results for the Ohio U. Experiment at 14.9 MeV



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

•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

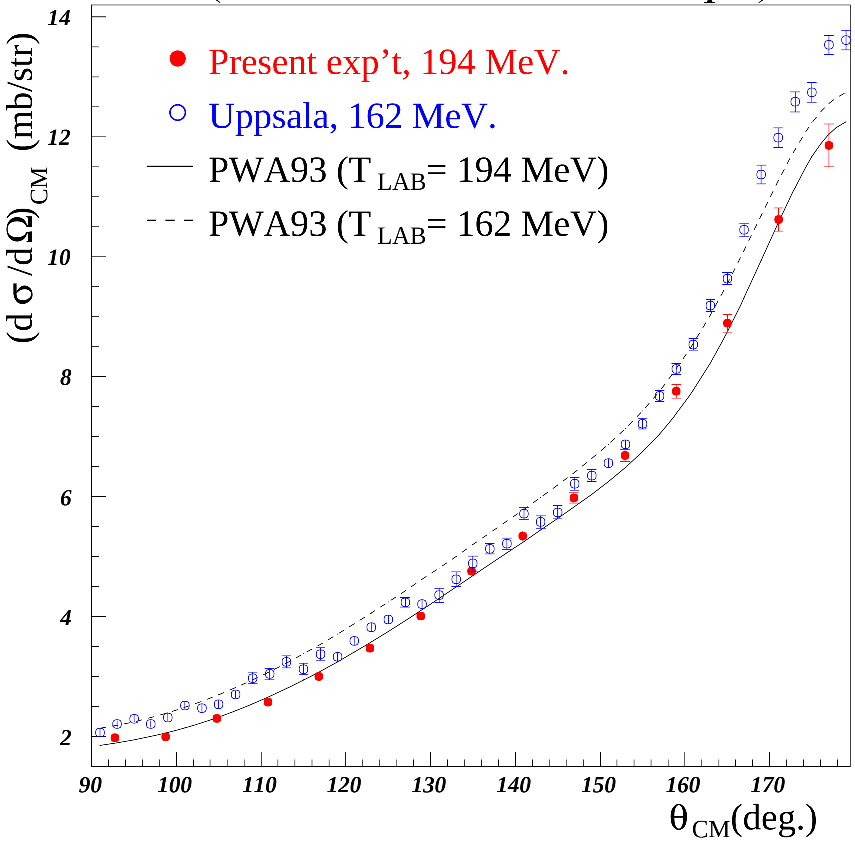
•The most recent measurements of the hydrogen angular distribution in the 100 MeV energy region are not consistent at back angles. Larger cross sections were measured at Uppsala (96 and 162 MeV) and PSI (many energies from about 280 MeV to 580 MeV), both using pseudo-monoenergetic sources. The work at 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

•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)

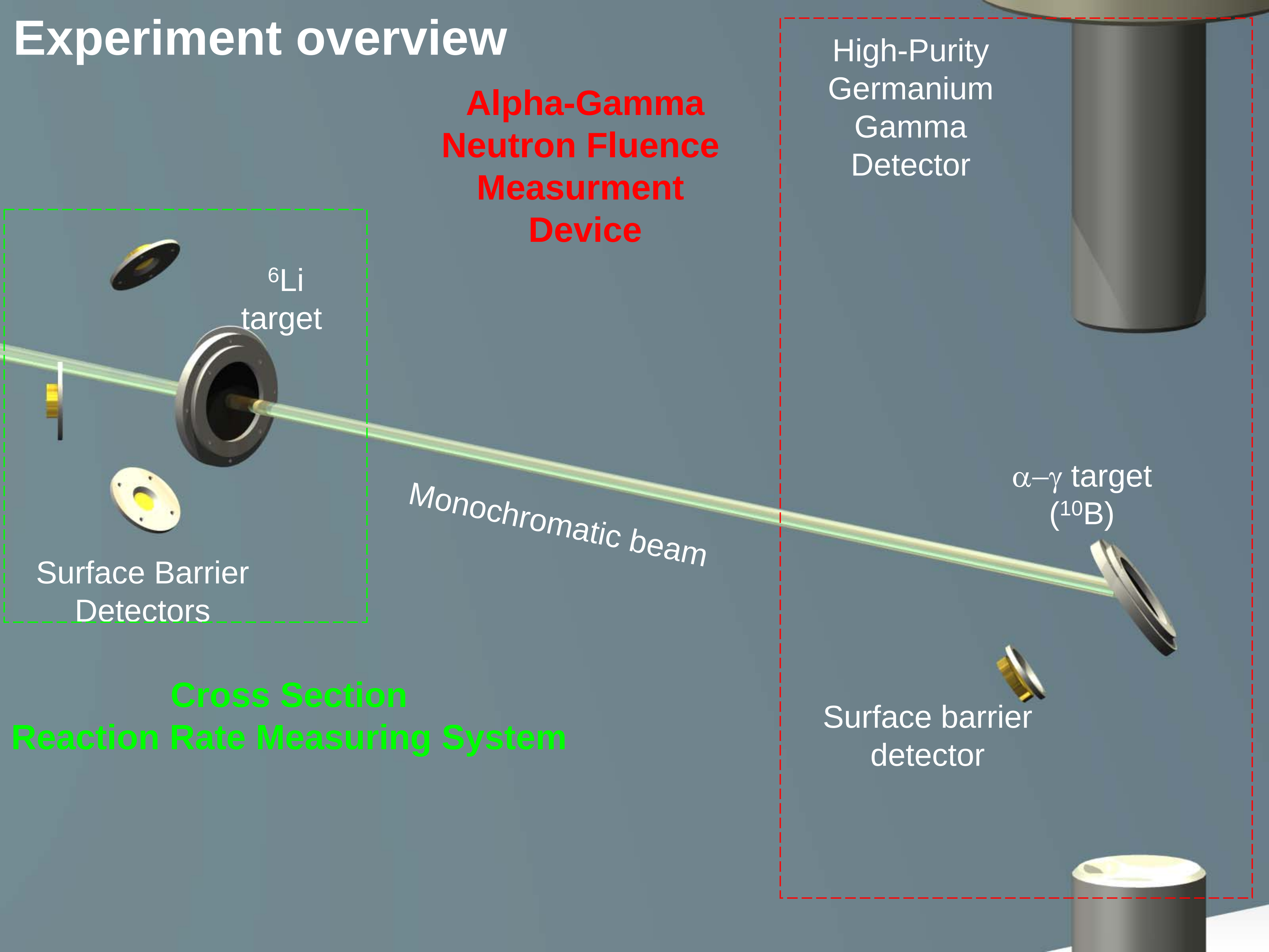
$^{6}Li(n,t)$ Measurements

•Measurements are now underway 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. The primary effort has been focused on measuring the fluence accurately. These fluence measurements are based on counting prompt gamma-rays that originate from neutron capture in a totally absorbing boron target. The gamma-ray efficiency is known accurately from alpha-gamma coincidence measurements using a thin ^{10}B target and also indirectly from measurements using a standard alpha source. The fluence (efficiency) has now been determined with an uncertainty of less than 0.1%. The solid angle uncertainty is about 0.1%.

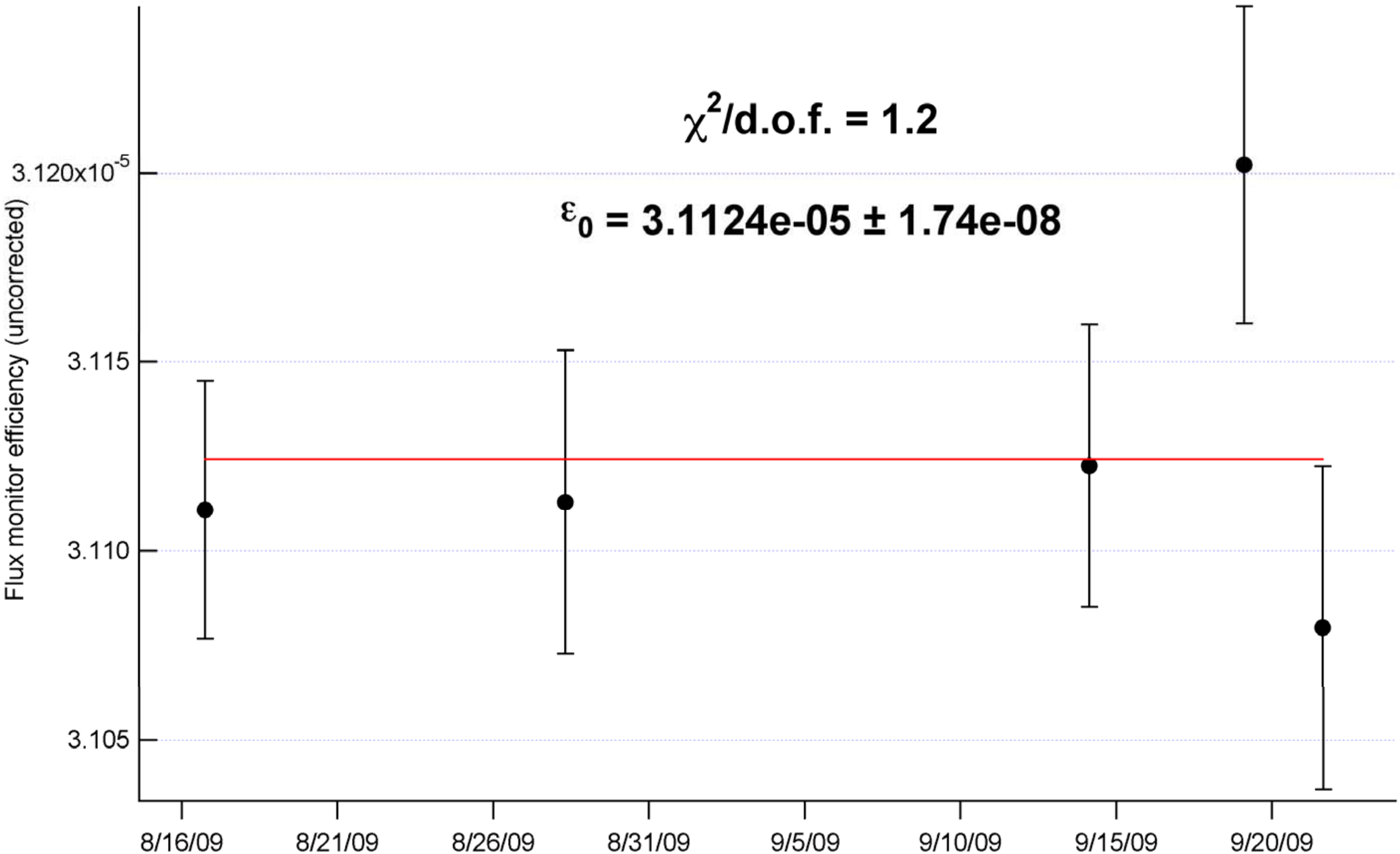
•The $^{6}Li(n,t)$ cross section measurement is made using solid state detectors and a thin ^{6}Li target. The limitation on the accuracy of the $^{6}Li(n,t)$ cross section measurement is the mass uncertainty of the ^{6}Li target. The present uncertainty is about 0.25%. Further studies will be made to compare the mass with the value obtained when it was characterized a number of years ago. It is expected that an 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)

Experiment overview



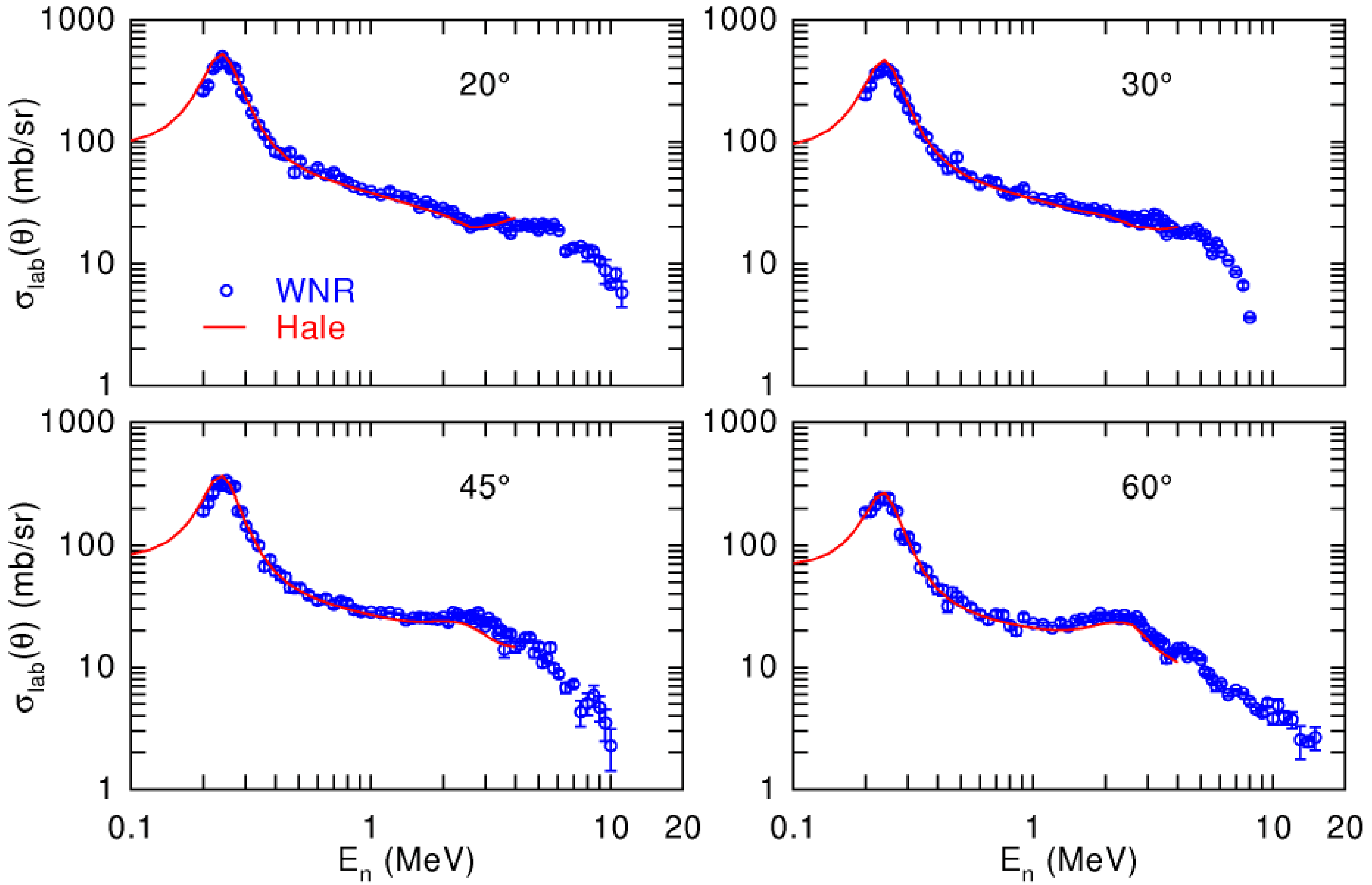
Fluence (Flux) Monitor Efficiency



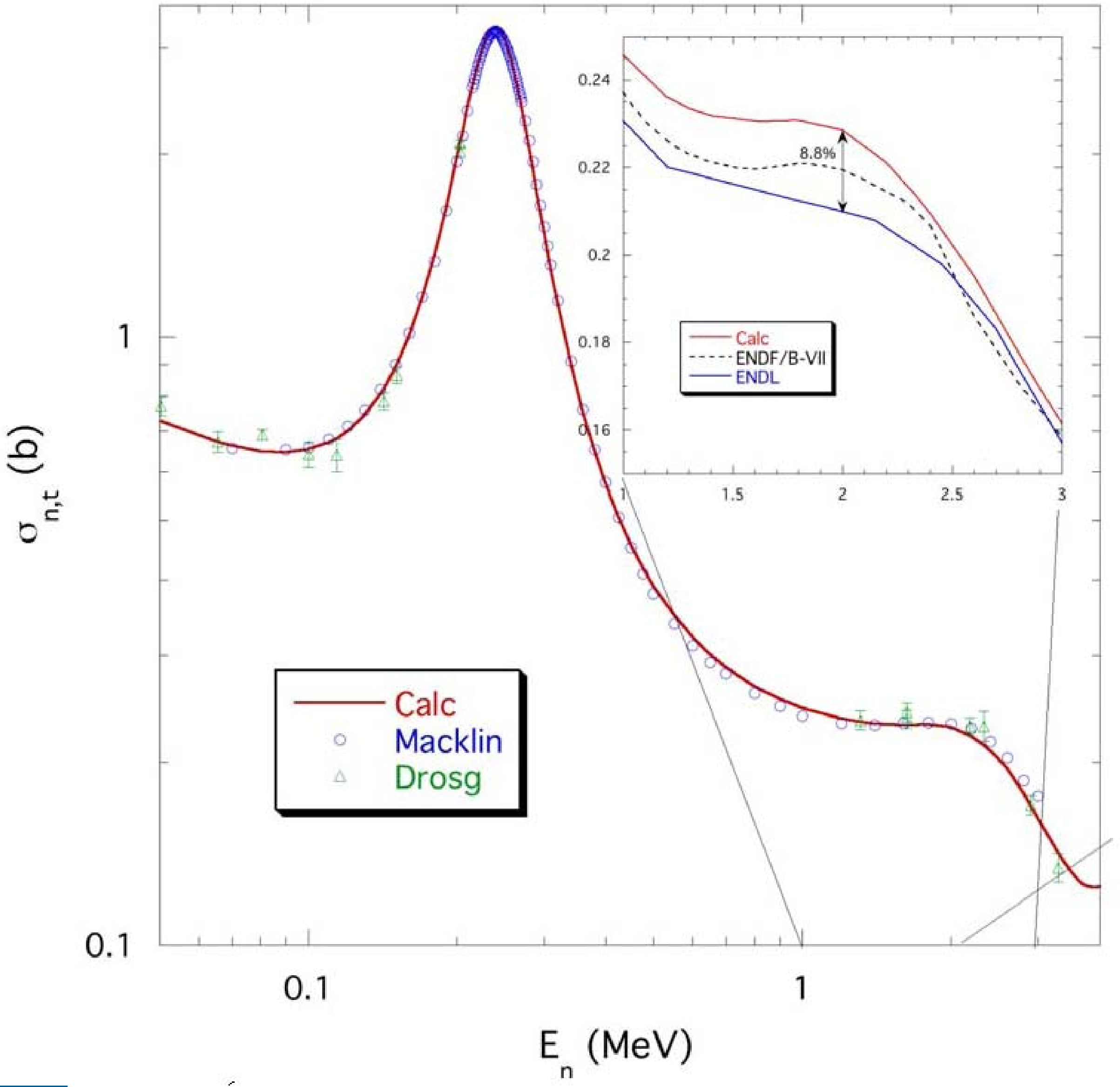
$^{6}Li(n,t)$ Measurements

•The analyses of the $^{6}Li(n,t)$ measurements by Devlin et al. at LANL have been completed. This work was initiated to improve the cross section in the 2 MeV energy region where the uncertainties in this cross section are large. 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. The uncertainties are about 5%. These data have been added to the existing R-matrix database used by Hale for a new evaluation of the $^{6}Li(n,t)$ cross section. Additional measurements by Devlin et al. using a detector system composed of two closely spaced silicon solid state detectors were not used in the evaluation due to the large uncertainties in those data. The new Hale evaluation is consistent with the Devlin et al. data.

Excitation Functions Measured by Devlin for Tritons From the ^{6}Li(n,t) Reaction for 4 Angles



Calculation of the ^{6}Li(n,t) Cross Section Using the Devlin Data Compared With Other Measurements



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

•It should be noted that the ENDF/B-VII.0 evaluation for the $^{6}Li(n,t)$ cross section up to 2.6 MeV is obtained from the international standards evaluation. That evaluation was produced from a comprehensive evaluation process but most of the weight came from the combination of an R-matrix evaluation by Hale (without the Devlin et al. results) and another R-matrix evaluation by Chen Zhenpeng. At 2 MeV, the Hale R-matrix result used in that evaluation was about 2% higher than the final output result from the evaluation (ENDF/B-VII.0). The result from the new evaluation by Hale including the results from the Devlin et al. data is about 4.5% higher than ENDF/B-VII.0 at 2 MeV. Thus the Devlin et al. data had an important impact on the new Hale evaluation.

•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

•The Frisch gridded ionization chamber work of Zhang et al. has been published. (Guohui Zhang, et al., Nucl. Instr. And Meth. A 566, 615 (2006))
Angular distribution measurements were made at 1.05, 1.54, 1.85, 2.25, 2.67, 3.67 and 4.42 MeV. Integrated cross sections were obtained at 1.05 MeV and 1.54 MeV relative to the $^{10}B(n,\alpha)$ standard; and at 1.85, 2.25, 2.67, 3.67 and 4.42 MeV relative to the $^{238}U(n,f)$ standard. Corrections are not made for the “particle leaking effect”; but the range of angles where the effect is present was calculated.

•The data at 1.85 MeV are the only ones not in our database. There is still some question about the uncertainty due to the exclusion of data showing the “particle leaking effect”. The higher energy data at the present time can not be used in our database.

•A request has been made for the final results and a clarification concerning the extent of “particle leaking effects.”

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

•As was pointed out previously, the thermal data on this cross section should be handled differently than was done for the evaluation. There are only 3 measurements available:

Meadows (ANL report CONF-701002, p. 129 (1971) pulsed neutron technique

Becker (ANL report CONF-701002, p. 125 (1971) total minus scattering

Silk (AERE –M-2366, (1970)) pulsed neutron technique

An evaluation was done using the Becker and Silk data and entered as Poenitz/Holden. The Meadows value was entered separately.

By using the separate values the weighting is done more properly since only one significant digit is used. Also each experiment is given proper acknowledgement.

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

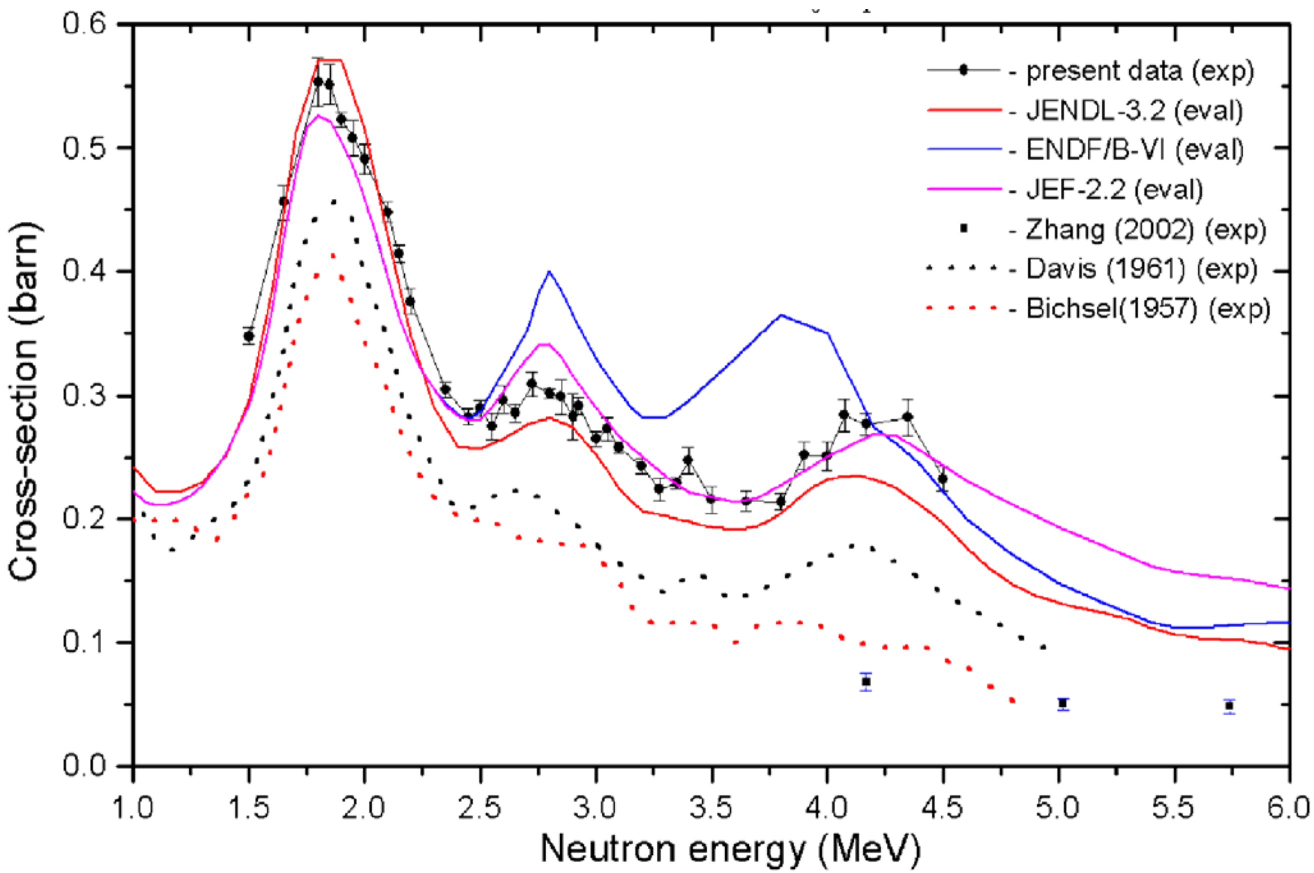
•The angular distribution measurements of Hambsch have been published in Nuclear Science and Engineering. He has taken additional data on the branching ratio, the angular distribution and the $^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1\gamma)$ cross sections relative to the $^{235}U(n,f)$ standard up to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

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

To complement their Frisch gridded ionization chamber work on the $^{10}B(n,\alpha)$ cross section relative to the $^{238}U(n,f)$ standard at 4 and 5 MeV, Guohui Zhang plans to make angular distribution measurements from 1 to 6 MeV. Their earlier measurements were effected by the “particle leaking” effect but they now have a method to minimize that effect. A request has been made for the status of the experiment.

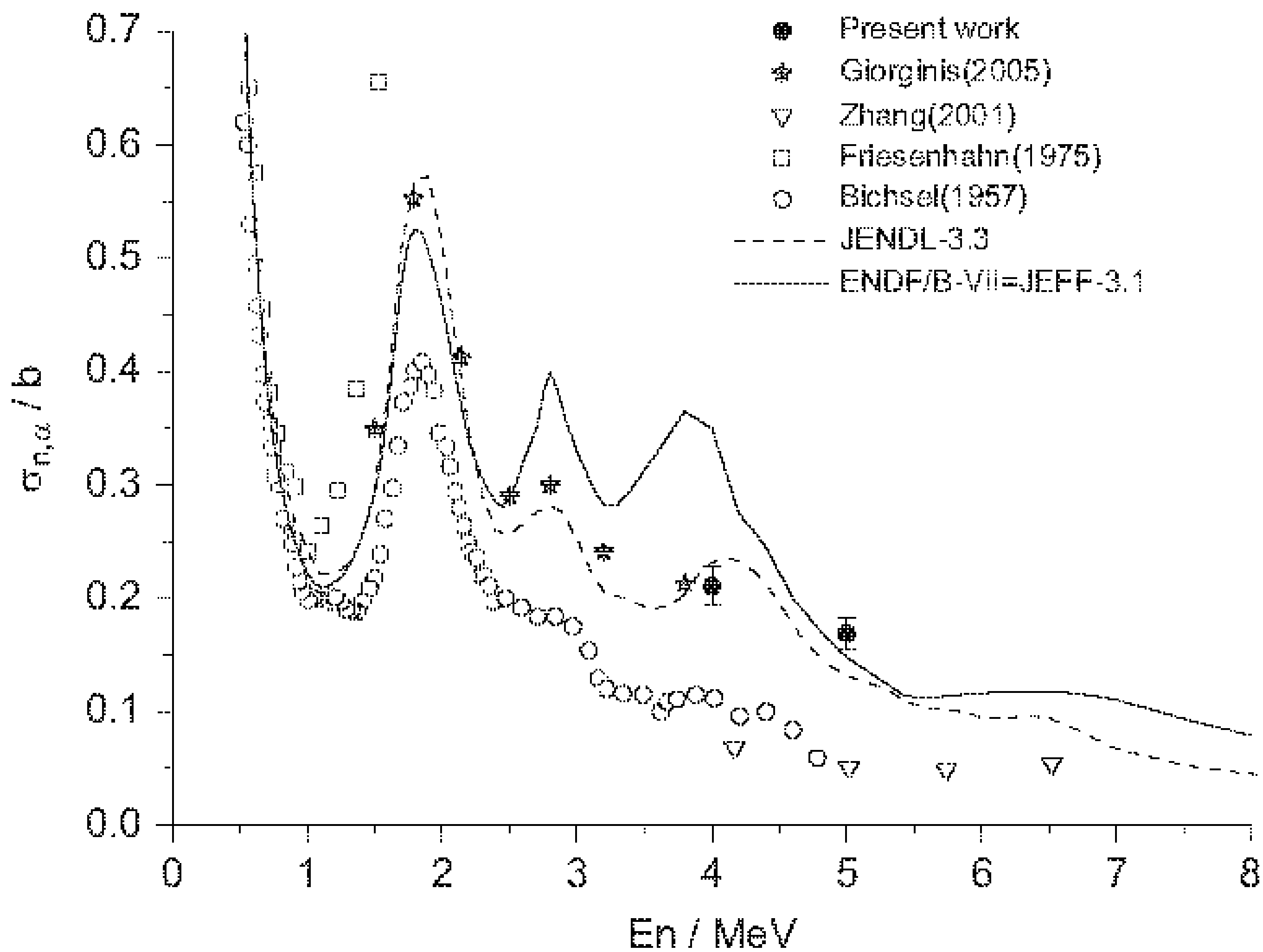
$^{10}B(n,\alpha)$ Measurements Above 1 MeV

- Note the very low values of the early Zhang (2002) data.
- The "present data" in the plot are those of Giorginis and Khriachkov



$^{10}B(n,\alpha)$ Measurements Above 1 MeV

- Note the better agreement for the new Zhang data shown as “present work”.

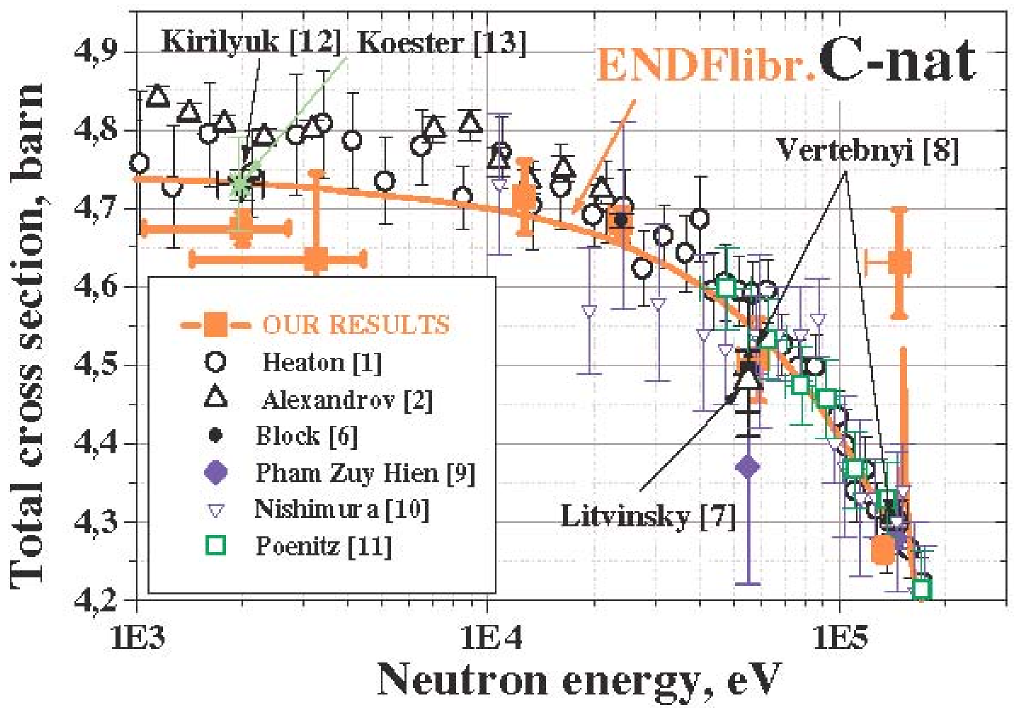


C(n,n) data

•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.

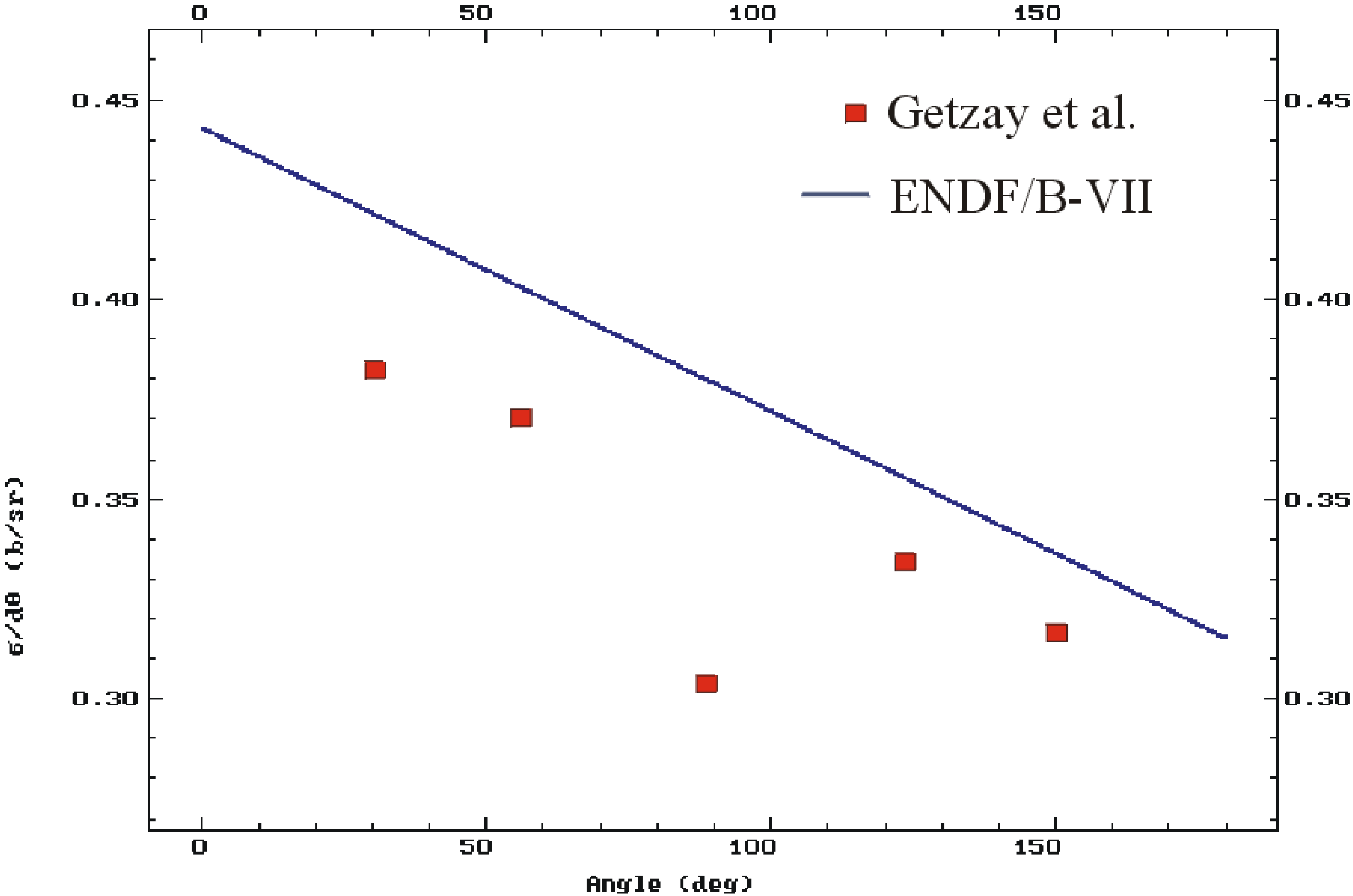
Gritzay et al. reported at the ND2007 conference carbon total cross section data taken at the Kyiv reactor using filtered beams with energies of 2, 3.5, 12, 24, 55, 59, 133 and 148 keV. They are generally in good agreement with the ENDF/B-VII evaluation. However at the lower energies their results are 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, 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! 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



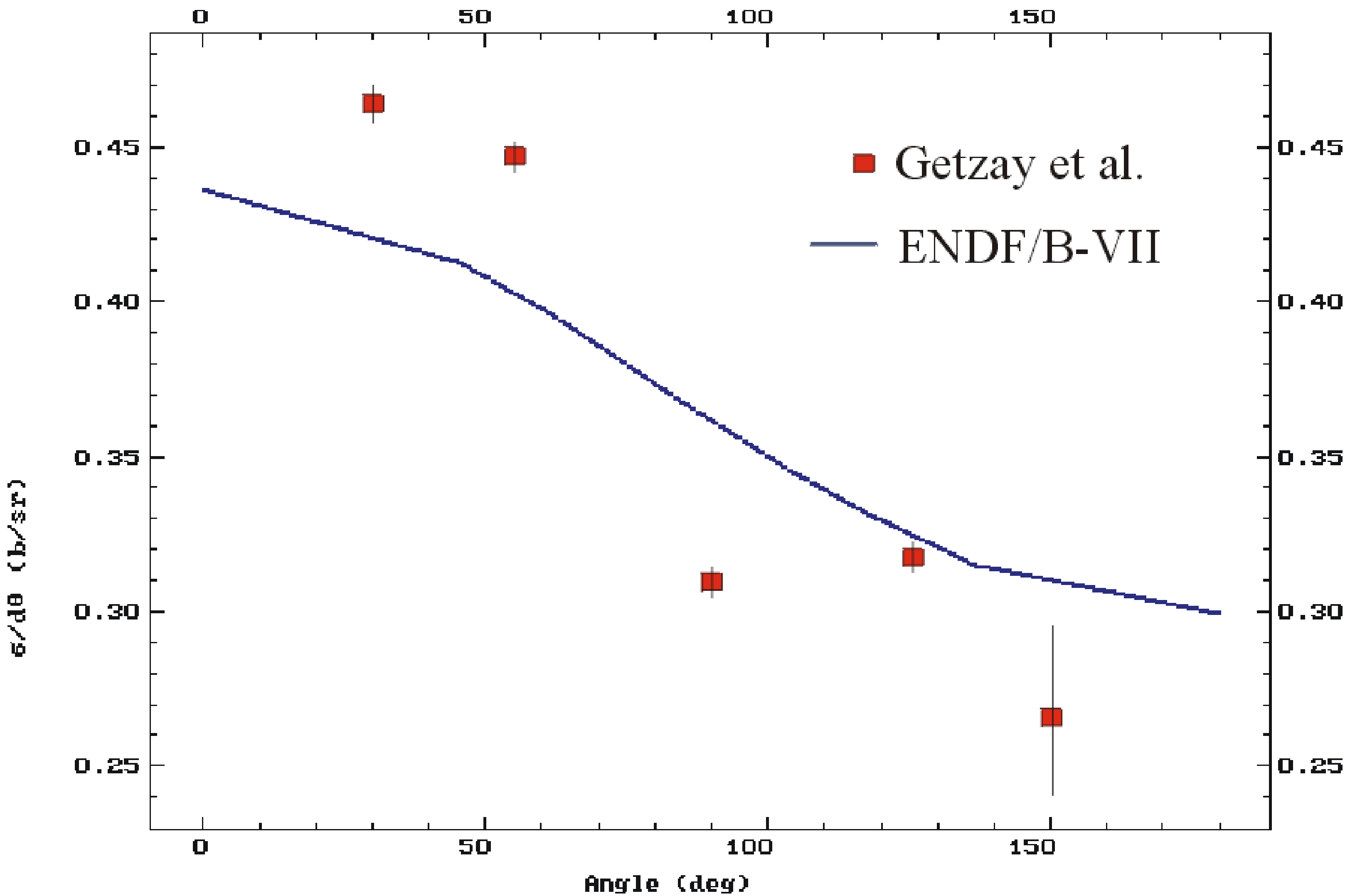
Our results for C-nat. total neutron cross sections, experimental data from database EXFOR/CSISRS and ENDF libraries.

C(n,n) E = 2 keV



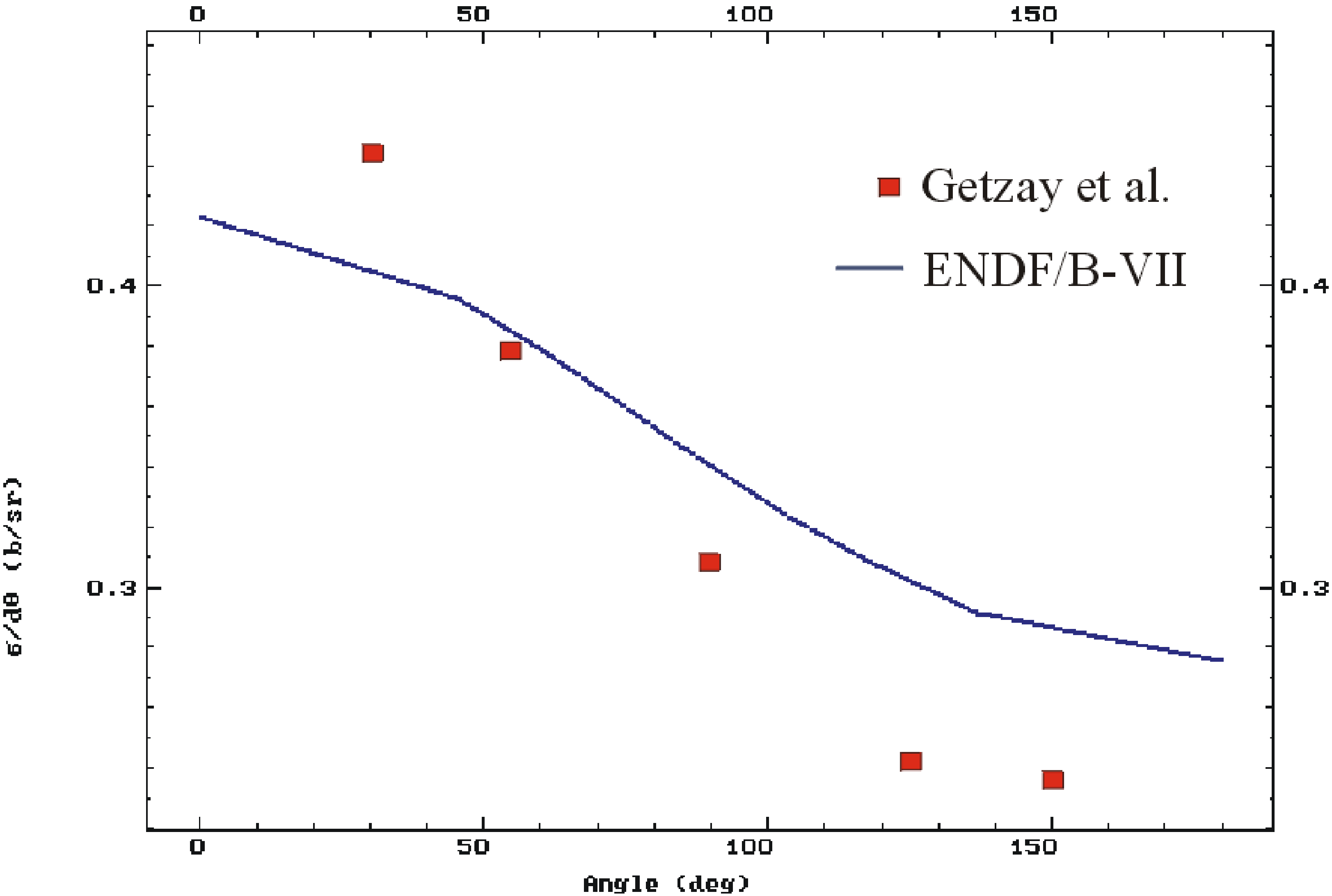
Getzay et al.
ENDF/B-VII
0
50
100
150
0.45
0.40
0.35
0.30
σ/dΩ (b/sr)
Angle (deg)

C(n,n) E = 59 keV



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

C(n,n) E = 133 keV



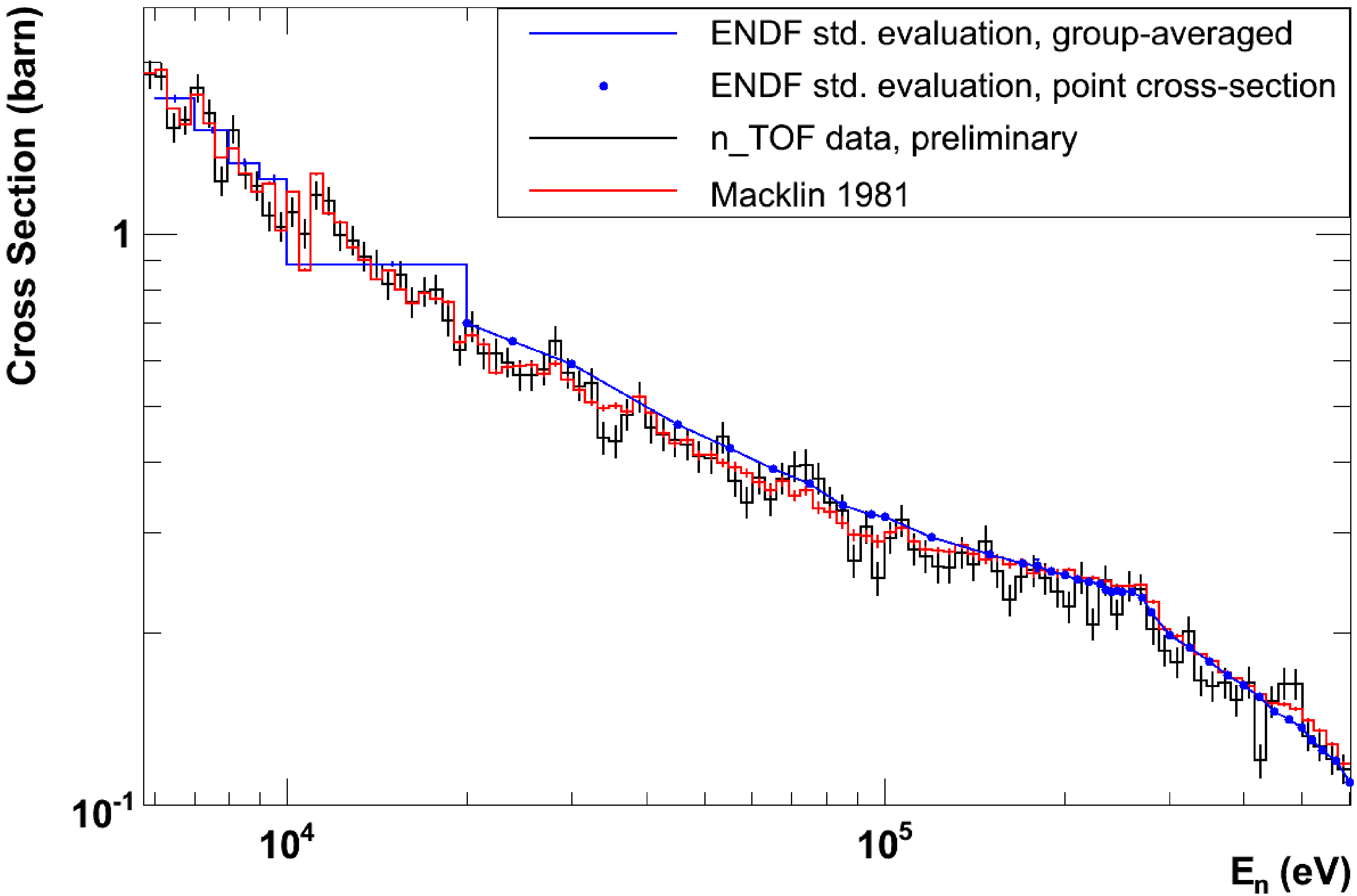
Au(n,γ) Cross Section Measurements

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

    - The work of Massimi et al. has remained focused on the analysis of the lower energy region (below 5 keV) for their measurements of the capture cross section for Au. The data are relative to the shape of the $^{6}Li(n,t)$ standard using the saturated resonance technique for normalization. Though the C_6D_6 TOF data were obtained to high energies (about 1 MeV), Massimi is concerned about the quality of their data at the highest energies. Lederer has extended the analysis to about 600 keV. The TOF data are systematically slightly lower than the standards results from 10 keV to 200 keV. In the standards energy region, above 200 keV, they agree.

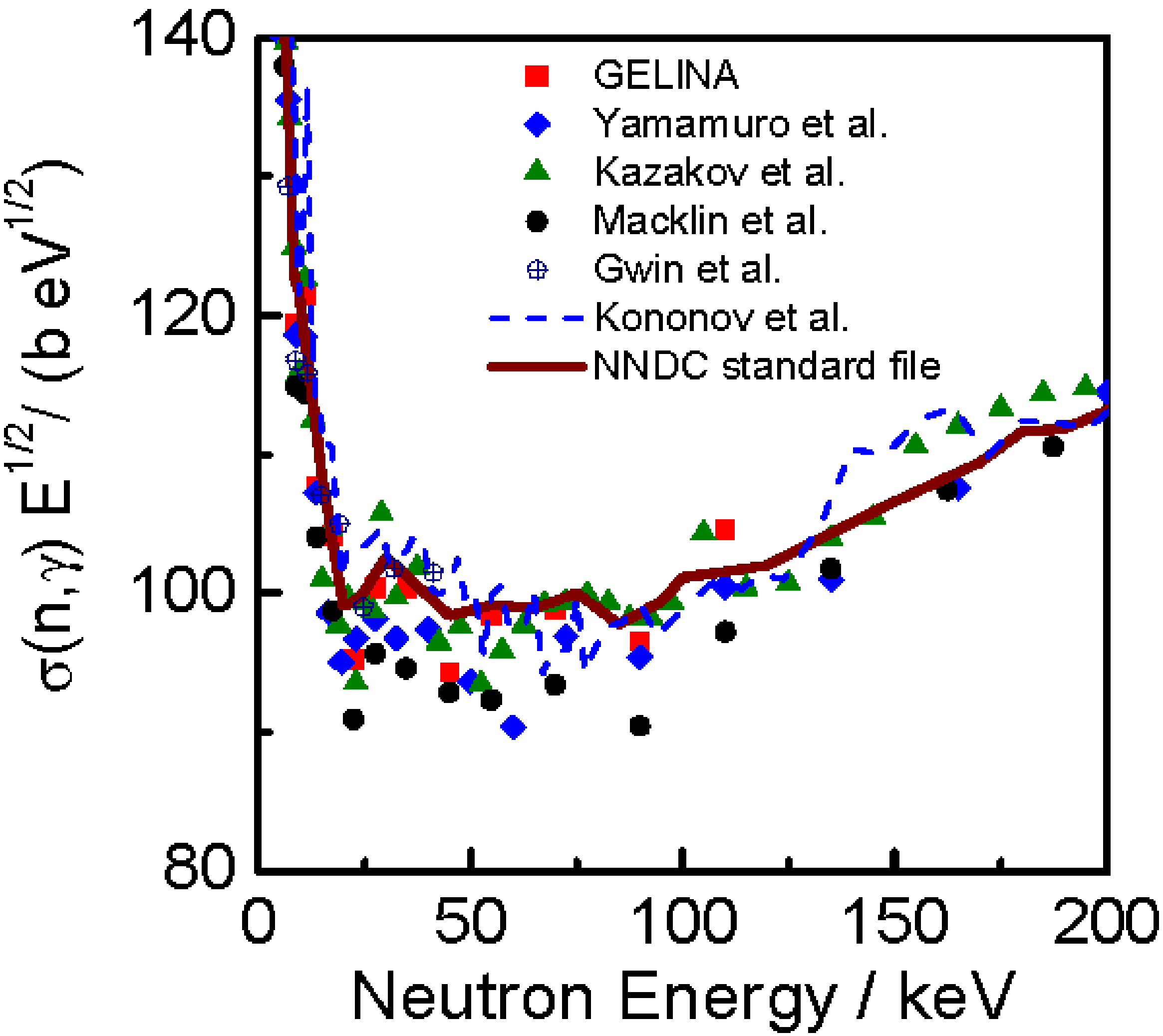
    - Borella et al. made measurements at IRMM at the GELINA facility relative to the $^{235}U(n,f)$ and $^{10}B(n,\alpha)$ standards. These data extend to about 200 keV and generally support the ENDF/B-VII.0 standards evaluation results.

Au(n,γ) Cross Section Data



Au(n,γ) Cross Section Data

- The GELINA data are Borella et al.



Au(n,γ) and ^{238}U(n,γ) Measurements

•Measurements have been made by Wallner (U. of Vienna) of the ^{238}U(n,γ)/^{197}Au(n,γ) cross section ratio at 500 keV, at thermal energy and with cold neutrons. The neutron irradiations have been made and accelerator mass spectrometry is now being used to measure the resulting ^{239}Pu. Activation was used for the gold measurements. The 500 keV measurement had a large (150 keV FWHM) energy spread. Also data were obtained with a simulated 25 keV Maxwellian spectrum. That spectrum is the same one that was used by Ratynski and Kaeppler for their Au(n,γ) cross section measurement. Estimated uncertainties of 2-5% are expected.

Au(n,γ) and ^{238}U(n,γ) Measurements

• 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. 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.

$^{238}U(n,\gamma)$ 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 ^6Li F detector and a ^3He 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

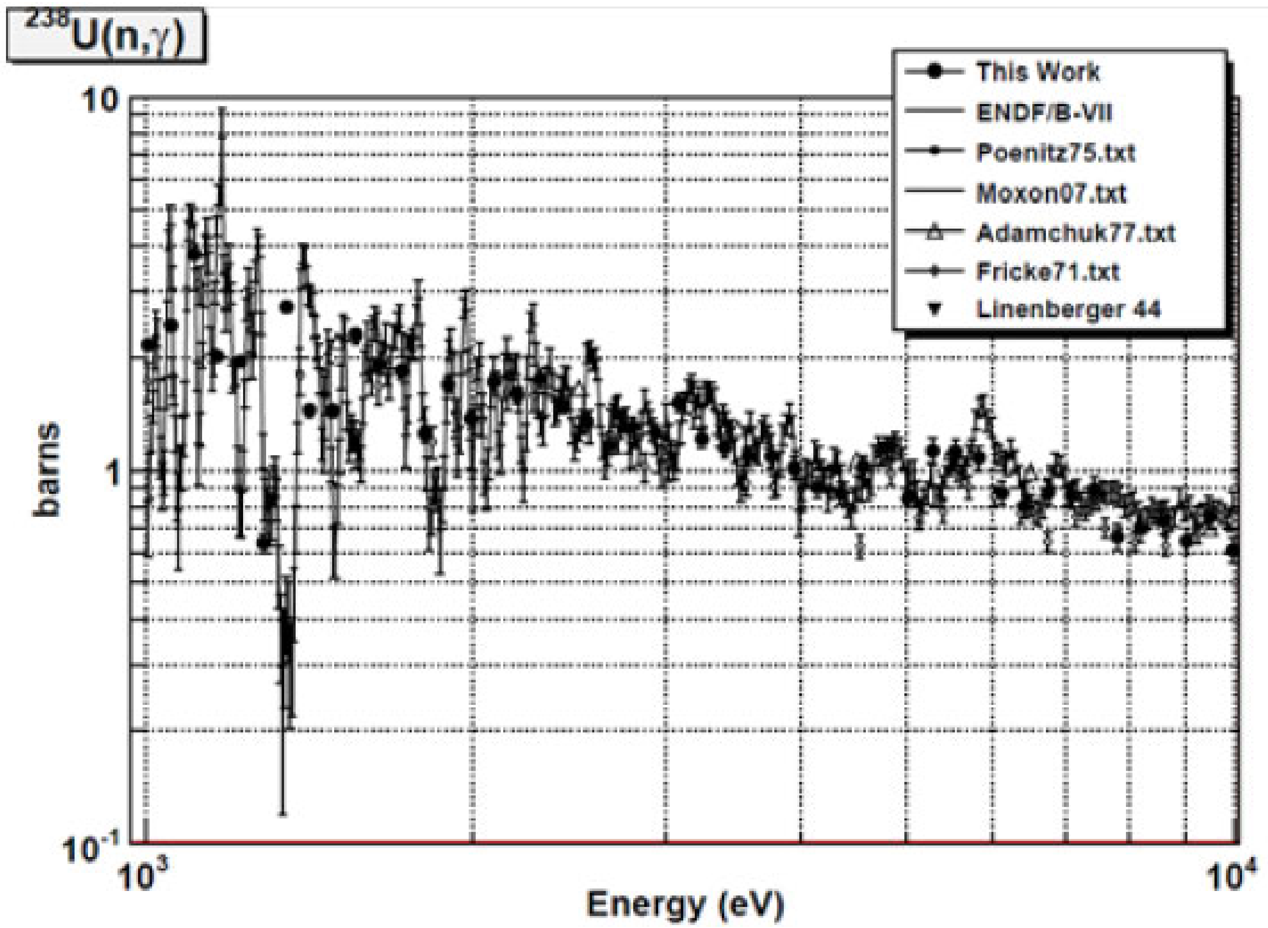


Fig. 2. Measured cross section in the 1 to 10 keV range compared with previous measurements[4].

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

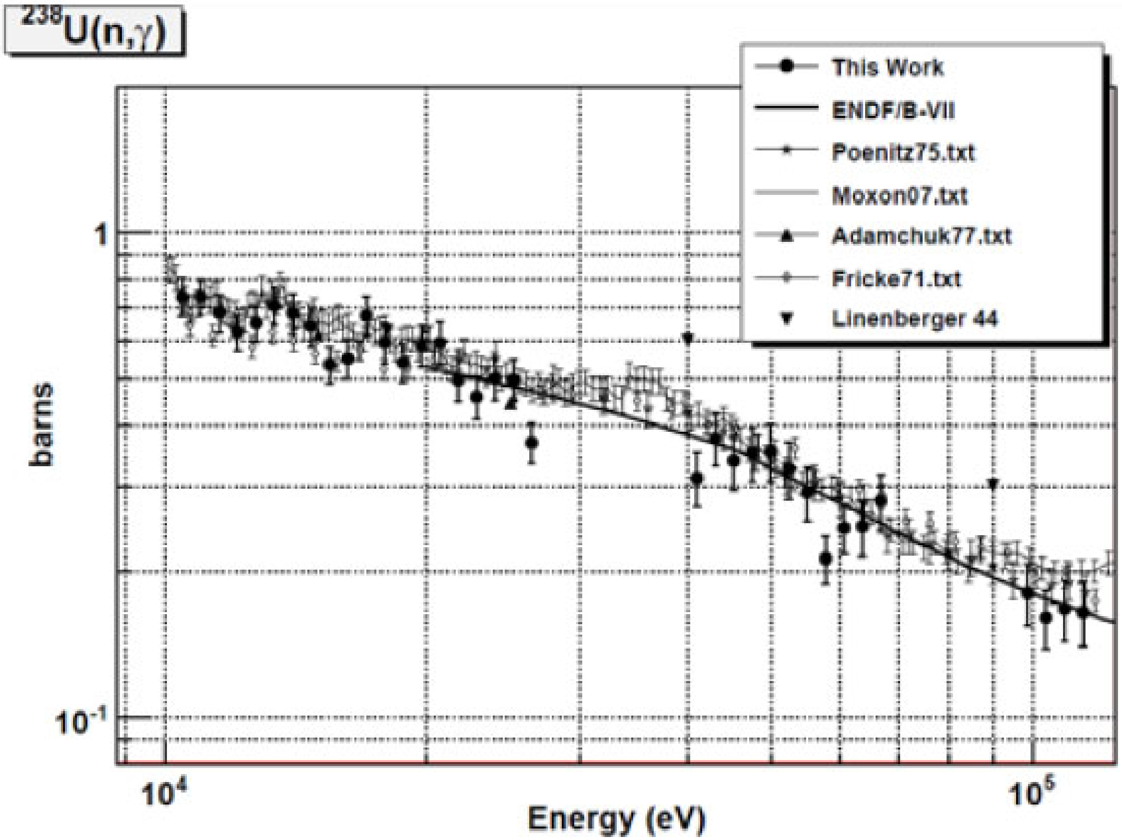


Fig. 3. Measured cross section in the 10 to 100 keV range compared with previous measurements[4] and the ENDF/B-VII evaluation.

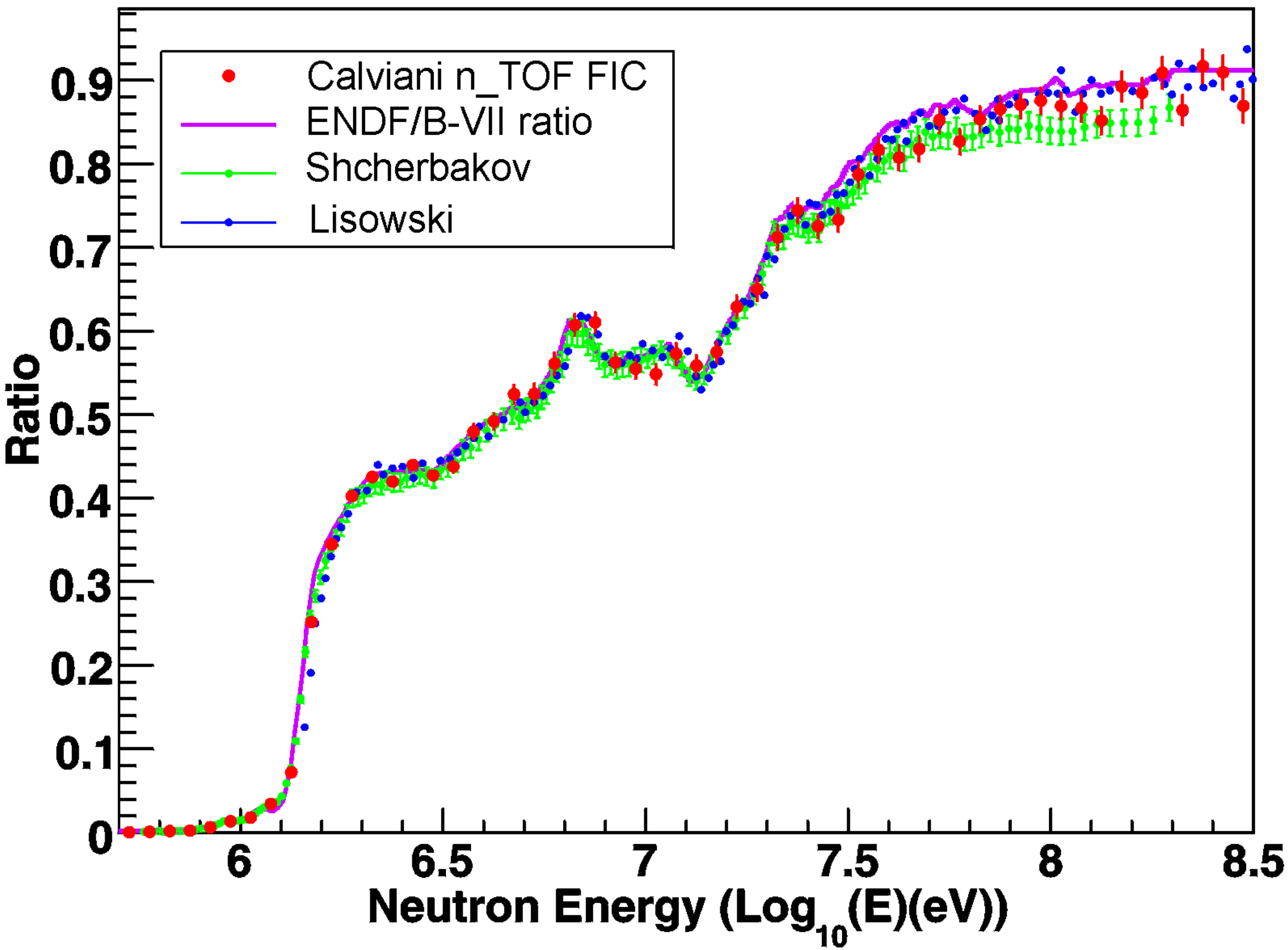
$^{235, 238}$U(n,f) Measurements

•There has been no new measurement activity since the last Consultants'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. Also there is an n_TOF proposal to measure the ^{235}U(n,f) cross section relative to n-p scattering.

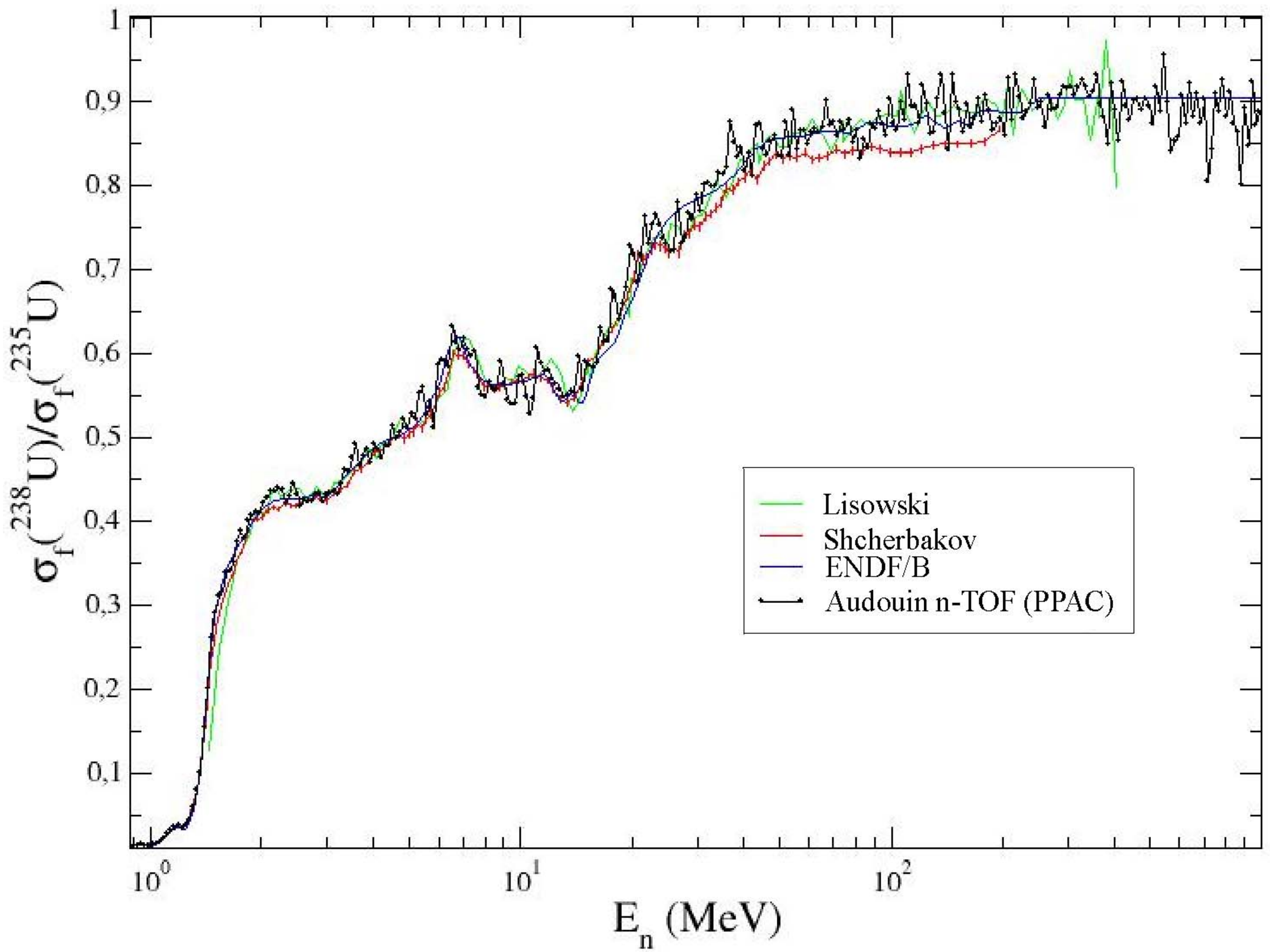
•Data from the Calviani et al. n_TOF experiment were obtained with fission ionization chambers. Preliminary results of the data analysis are available to about 300 MeV. This was his thesis work. The thesis is available but the tabular data are not. They have been requested.

•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. Tabular data have been obtained but they are not to be distributed until the work is finalized.

Comparison of Recent Measurements of the $^{238}U/^{235}U$ Fission Cross Section Ratio of Calviani (n-TOF) With Other Work



Comparison of Recent Measurements of the $^{238}U/^{235}U$ Fission Cross Section Ratio of Audouin (n-TOF) With Other Work

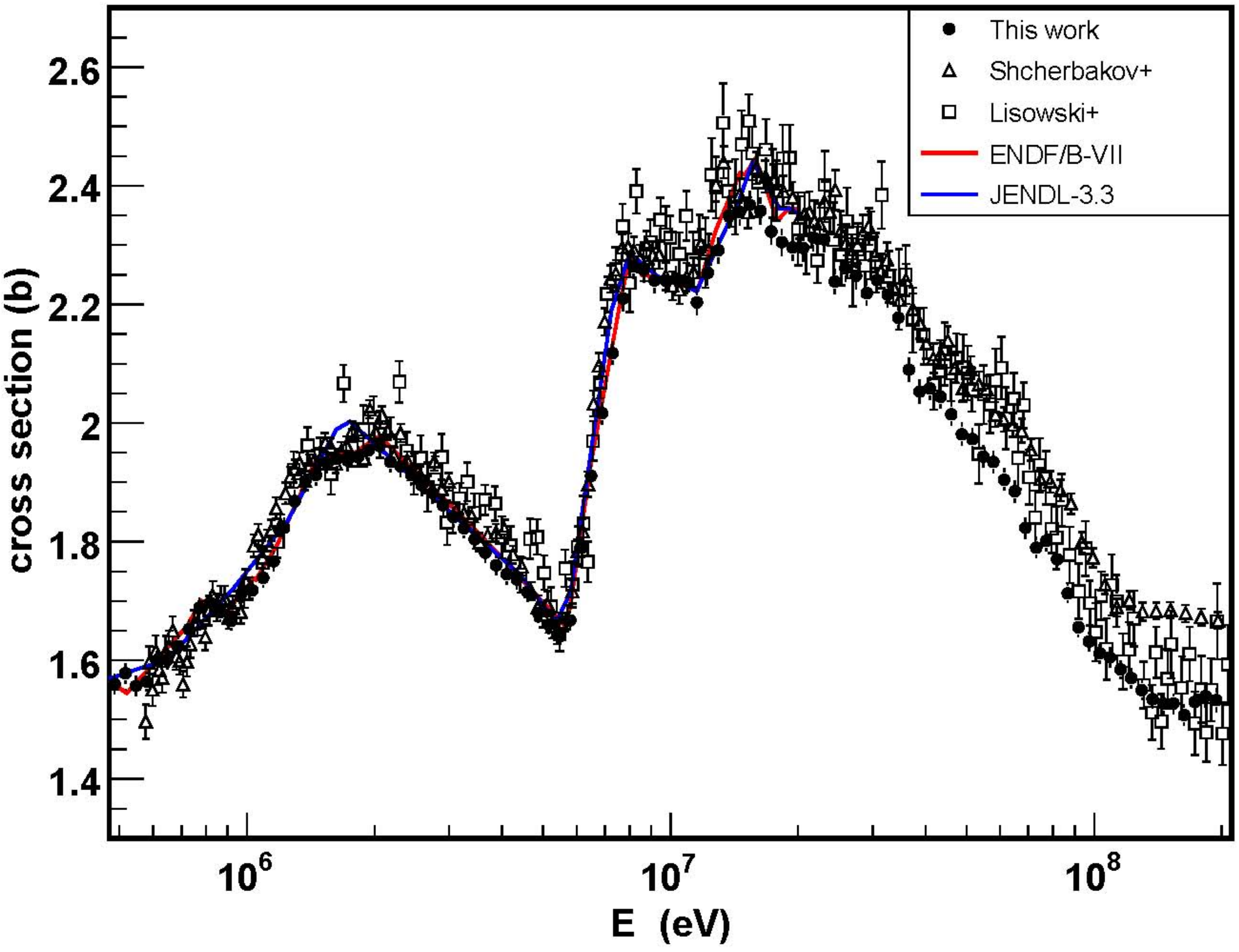


$^{239}Pu(n,f)$ Measurements

•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 have been published 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

•Considerable experimental activity has occurred since the last Consultants' Meeting related to a new standards evaluation. 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

•Little work has been done on the Au(n,γ) cross section in the standards energy region

More work should be done to understand the ^{238}U(n,γ)/Au(n,γ) cross section ratio problem.

•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.