NIST Measurements and Standards Related Work at Other Facilities

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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.

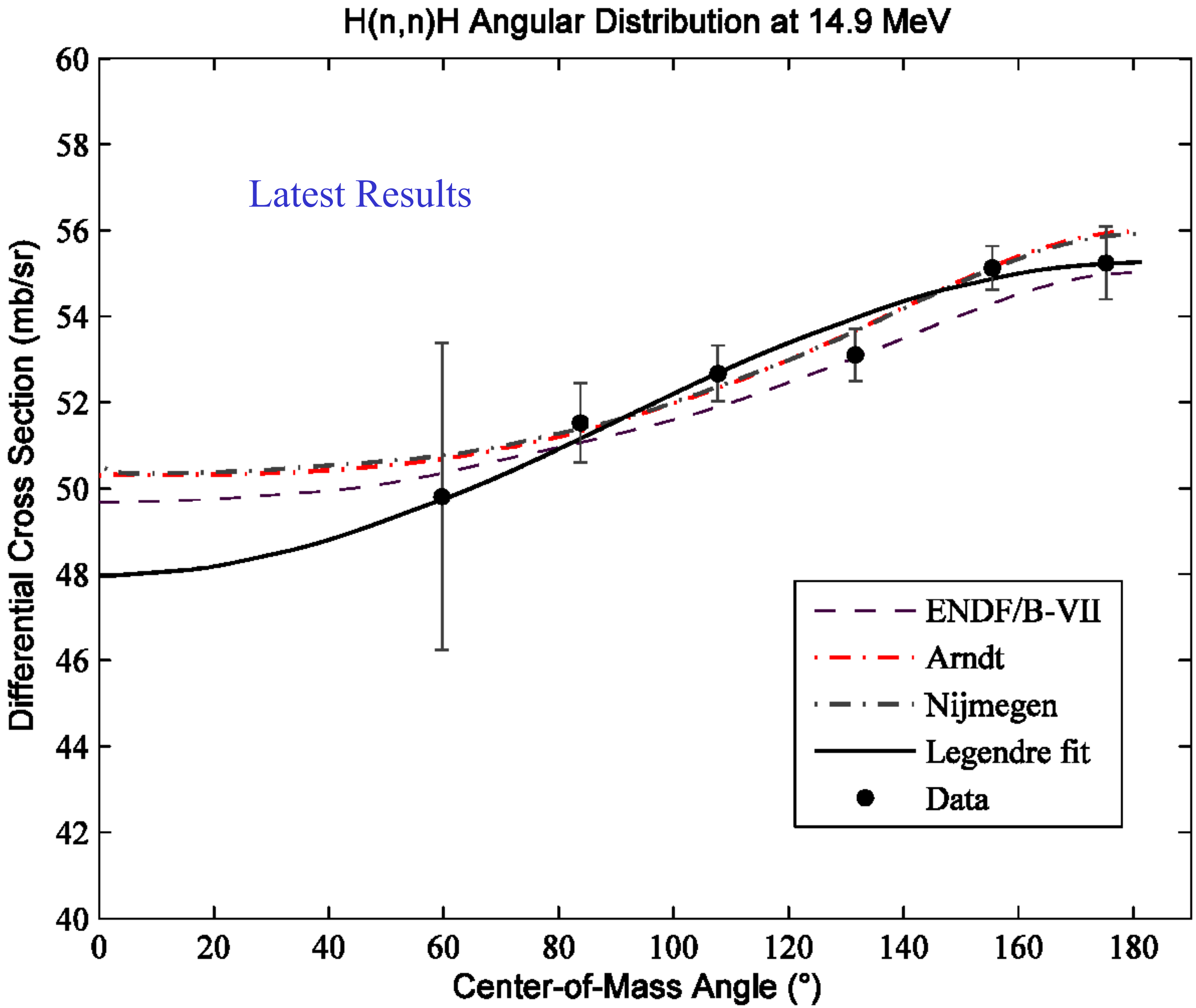
•This led to experiments reported last year, by Moreh, Block and Danon measuring the neutrons scattered from CH_2 and C. The ratio of these experiments clearly shows the effect is not present for incident neutron energies of 100 eV to 140 keV.

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

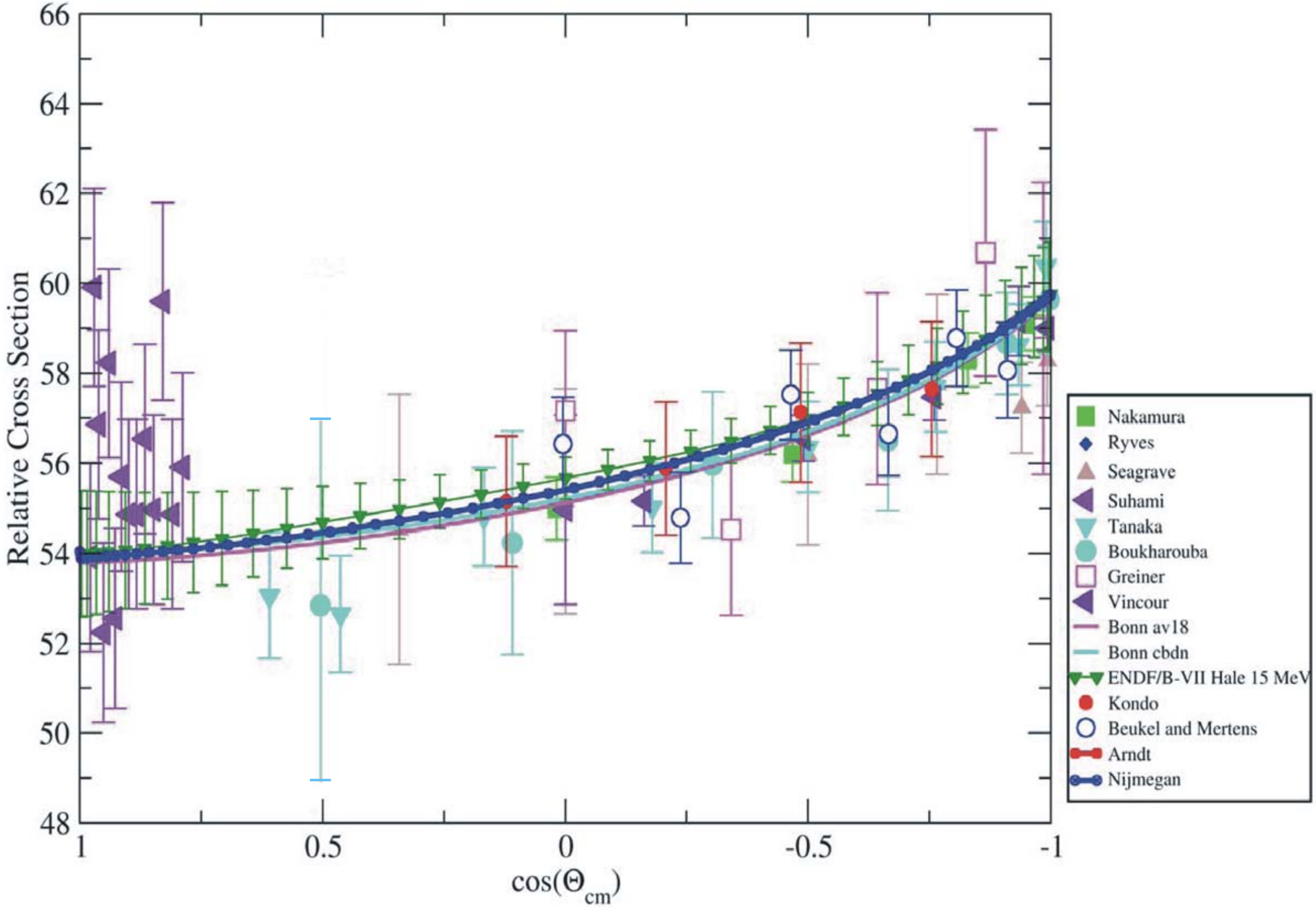
•A journal publication on the measurements of Boukharouba *et al.* at 14.9 MeV is nearly completed. This work was initiated to resolve problems with the hydrogen database used for the ENDF/B-VI hydrogen evaluation. To improve that database, measurements were made at laboratory proton recoil angles of 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.

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



H(n,n)H Angular Distribution at 14.9 MeV
Latest Results
Differential Cross Section (mb/sr)
Center-of-Mass Angle (°)
60
58
56
54
52
50
48
46
44
42
40
0
20
40
60
80
100
120
140
160
180
ENDF/B-VII
Arndt
Nijmegen
Legendre fit
Data

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

•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. Measurements have been made at laboratory neutron scattering angles of 20 and 25 degrees for 14.9 MeV incident neutrons. Measurements will continue in 5 degree steps up to 70 degrees.

•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) cross section standard

•Following the completion of this work, measurements will be made at 10 MeV incident neutron energy to help fill in the small angle gap in the work done by this collaboration at 10 and 14.9 MeV.

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

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. It is expected that work using this chamber can begin early in 2010.

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

Hydrogen Angular Distribution at High Neutron Energies

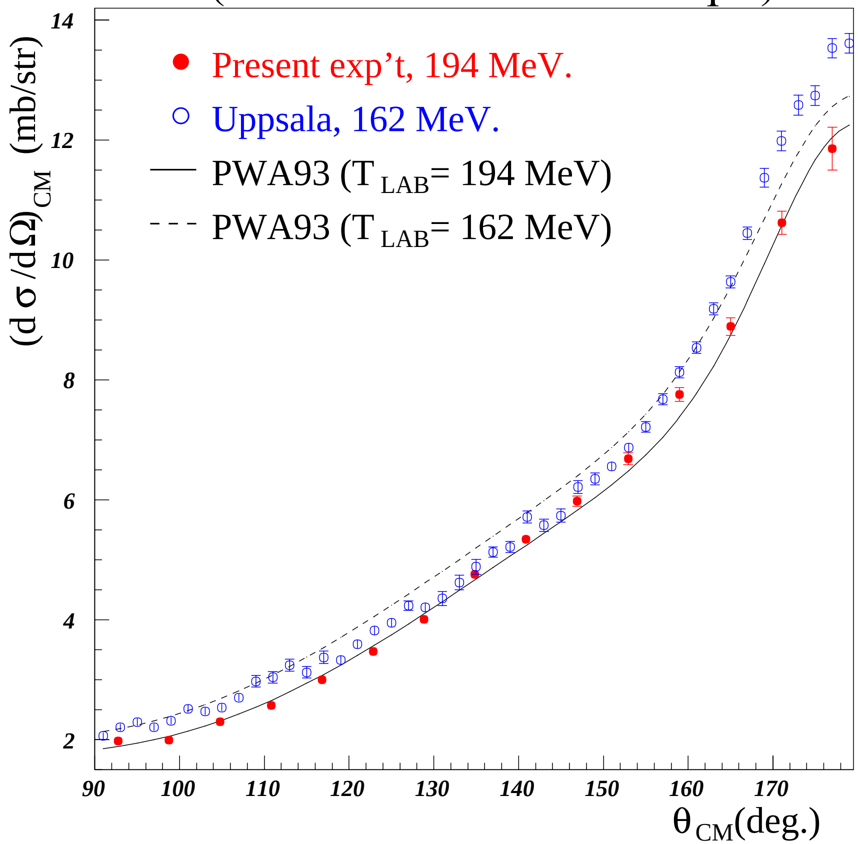
- The most recent measurements of the hydrogen angular distribution in the 100 MeV energy region are not consistent at back angles. Larger cross sections were measured at Uppsala (96 and 162 MeV) and PSI (many energies from about 280 MeV to 580 MeV), both using pseudo-monoenergetic sources. The work 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 measurements previously made of the n- ^{3}He coherent scattering length which were recently published. These data can be used in R-matrix evaluations to improve the ^{3}He(n,p) standard cross section.

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

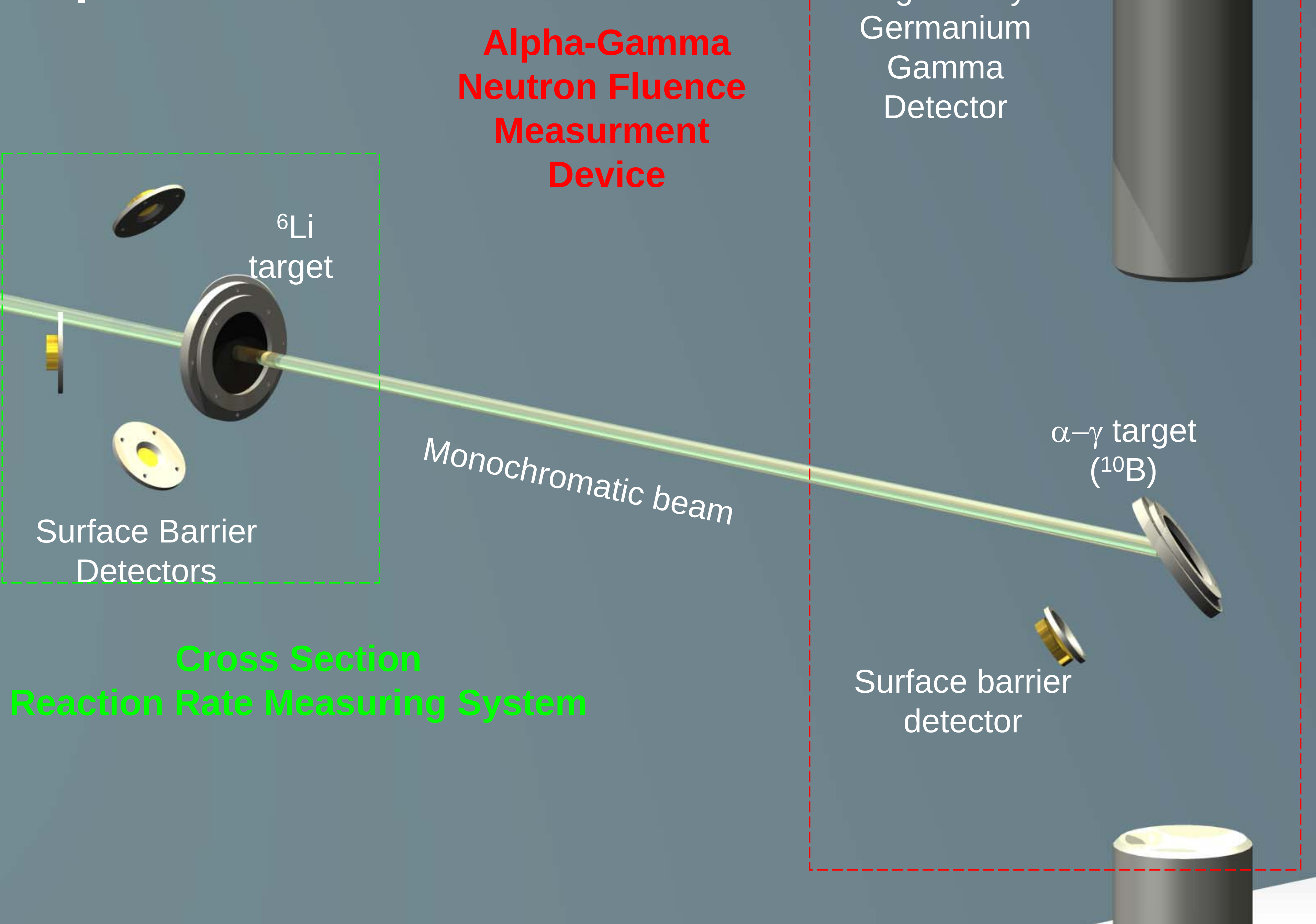
^{6}Li(n,t) Measurements

•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. A 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%.

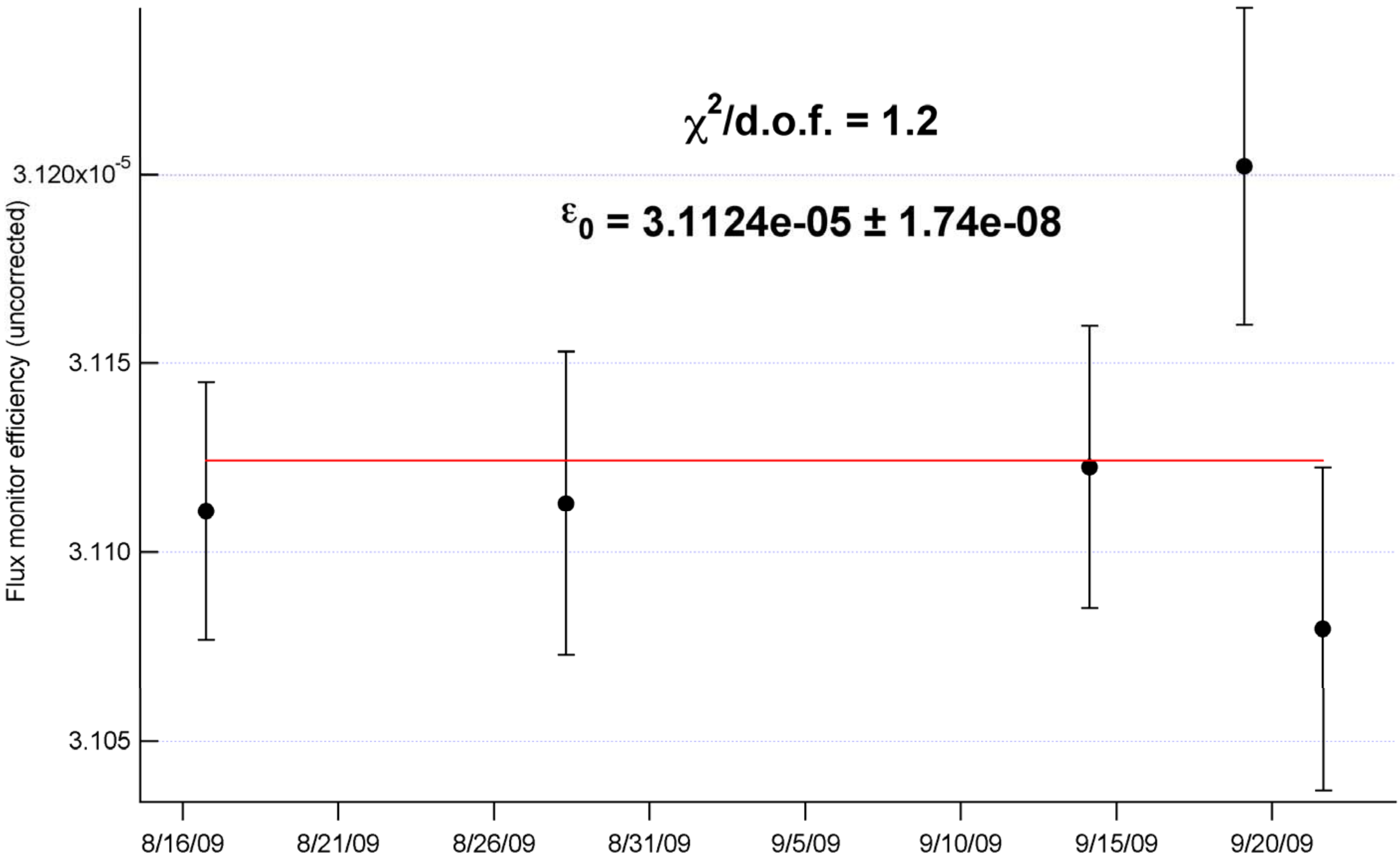
•The ^{6}Li(n,t) cross section measurement is made using solid state detectors and a thin ^{6}Li target. The limitation on the accuracy of the ^{6}Li(n,t) cross section measurement is the mass uncertainty of the ^{6}Li target. The present uncertainty is about 0.25%. Further studies will be made to compare 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



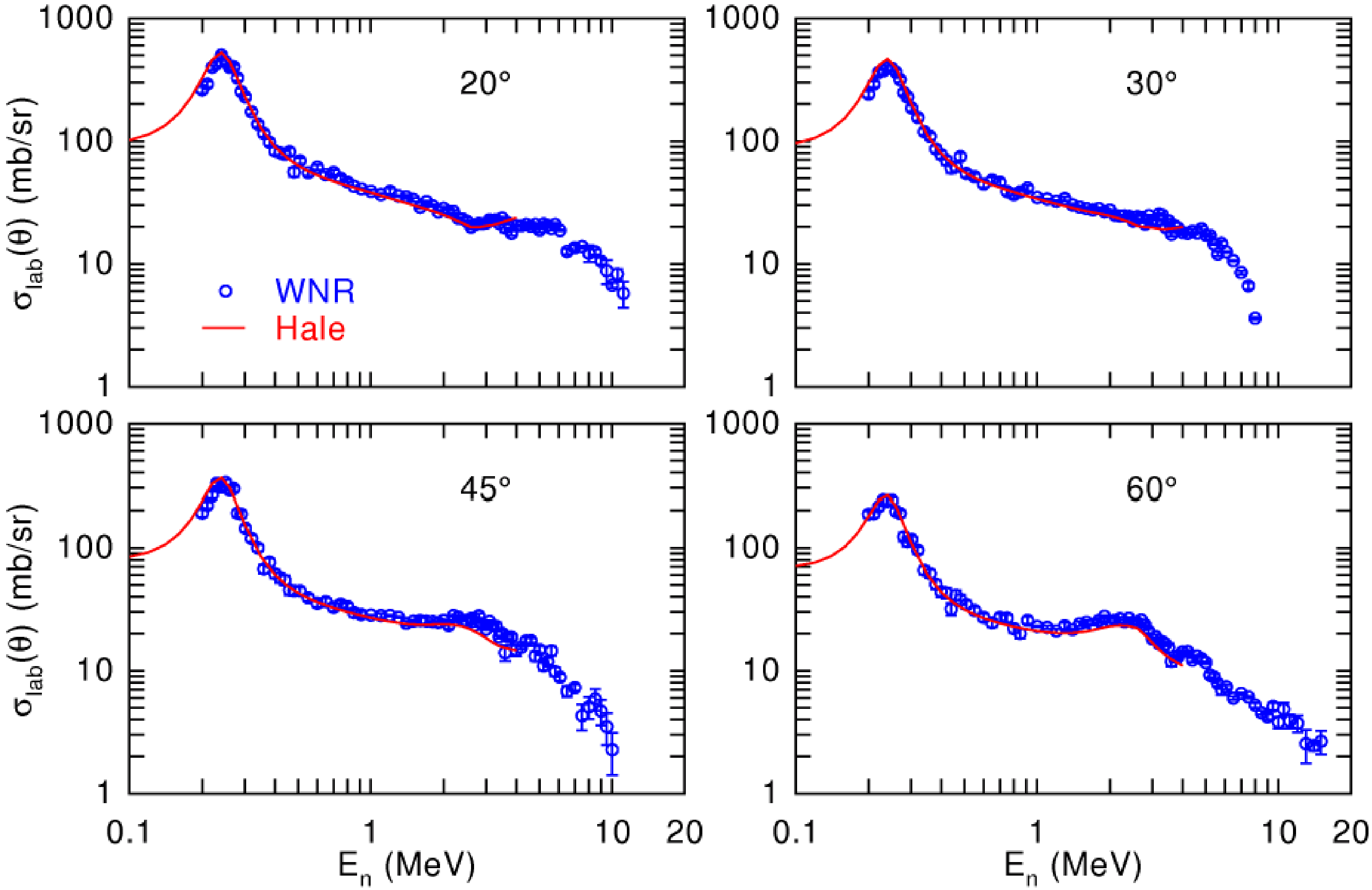
Fluence (Flux) Monitor Efficiency



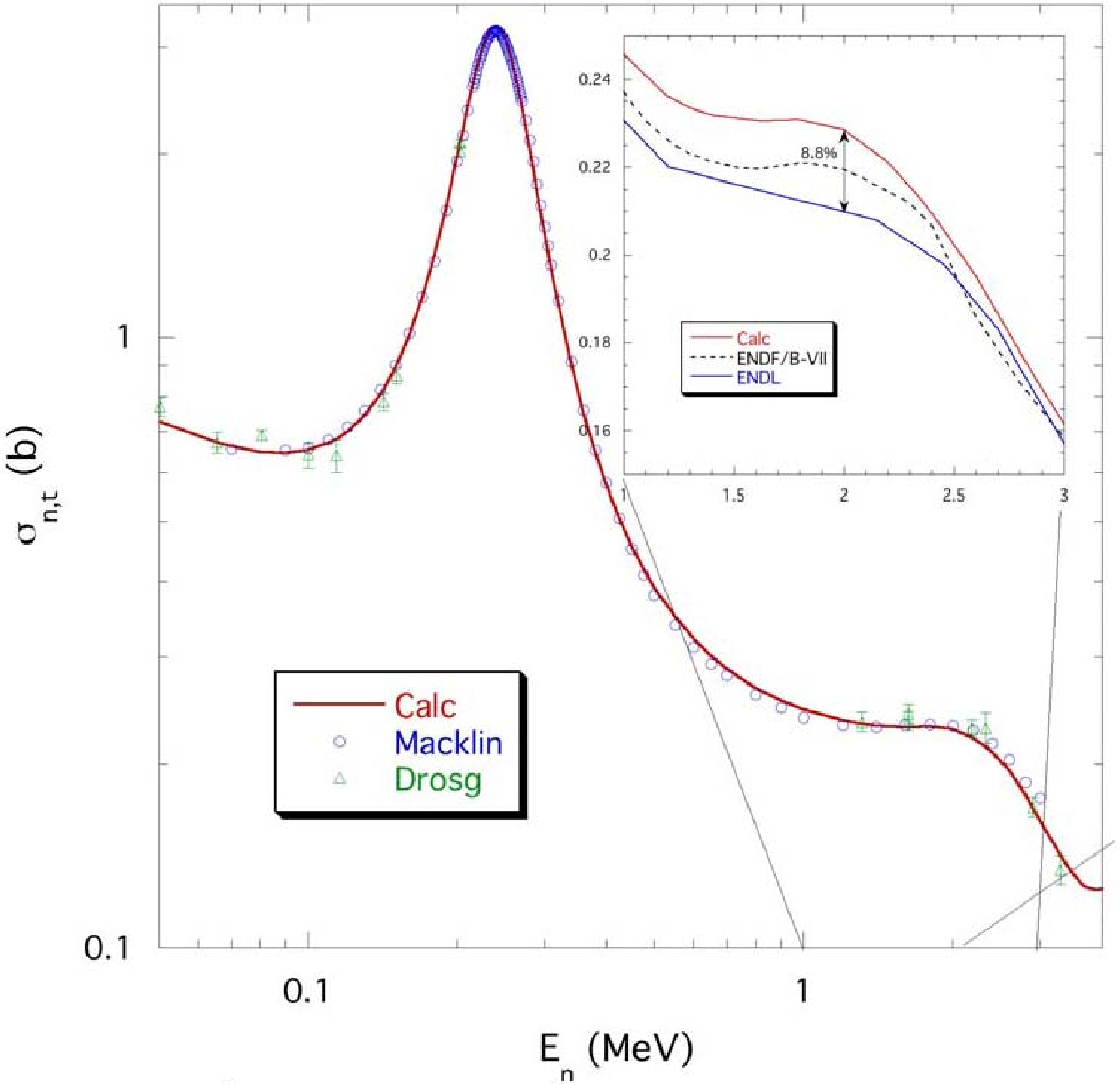
^{6}Li(n,t) Measurements

•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 (cont.)

•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. The work will extend to about 3 MeV so they can cover the strong resonance at about 0.25 MeV and the weak resonances at about 2 MeV. They plan to have the ^{6}Li deposits made at IRMM.

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

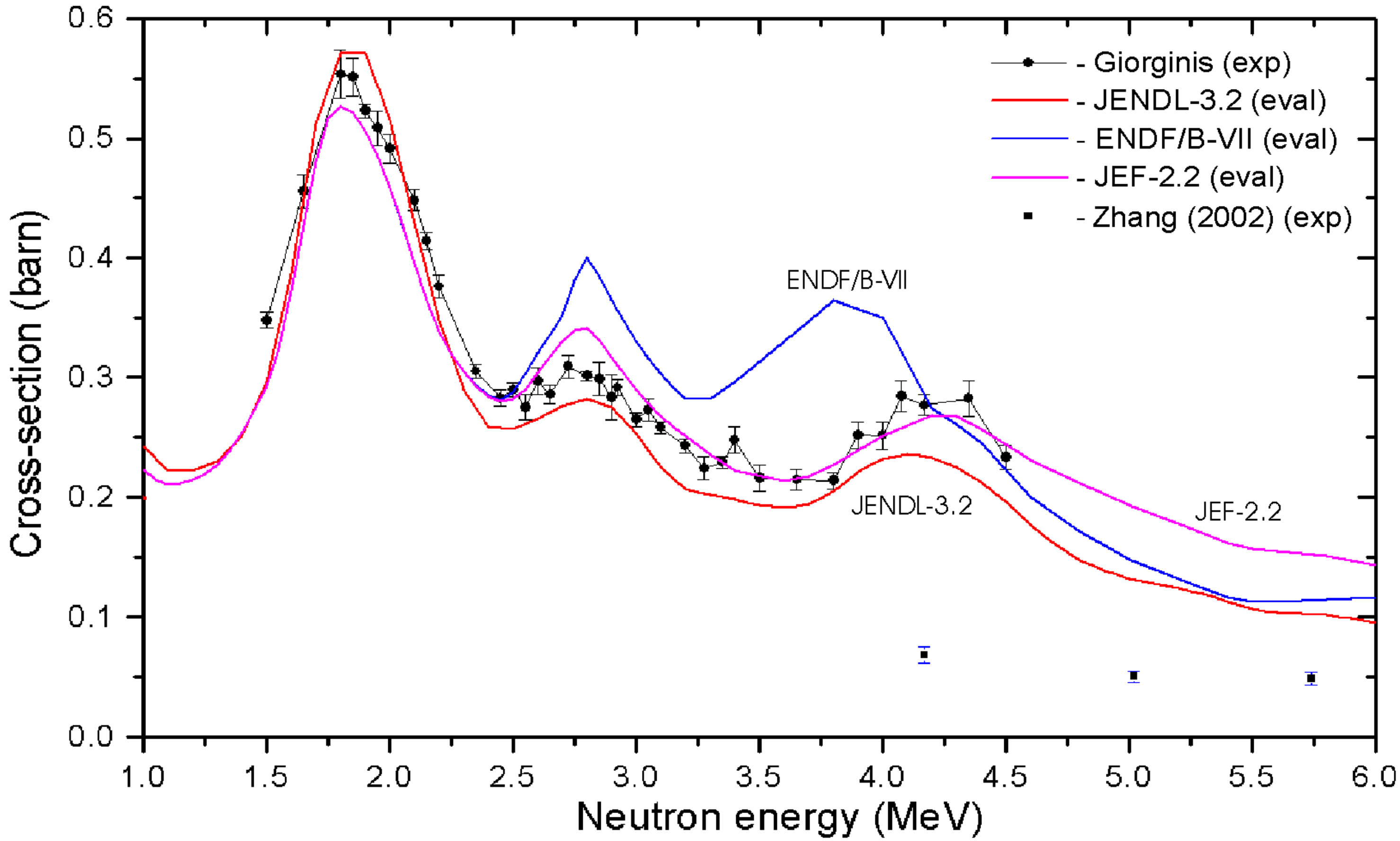
•The angular distribution measurements of Hambsch have been Published in Nuclear Science and Engineering. He continues to accumulate data on the branching ratio, the angular distribution and the $^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1\gamma)$ cross sections relative to the $^{235}U(n,f)$ standard up to about 3 MeV. He plans to have 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.

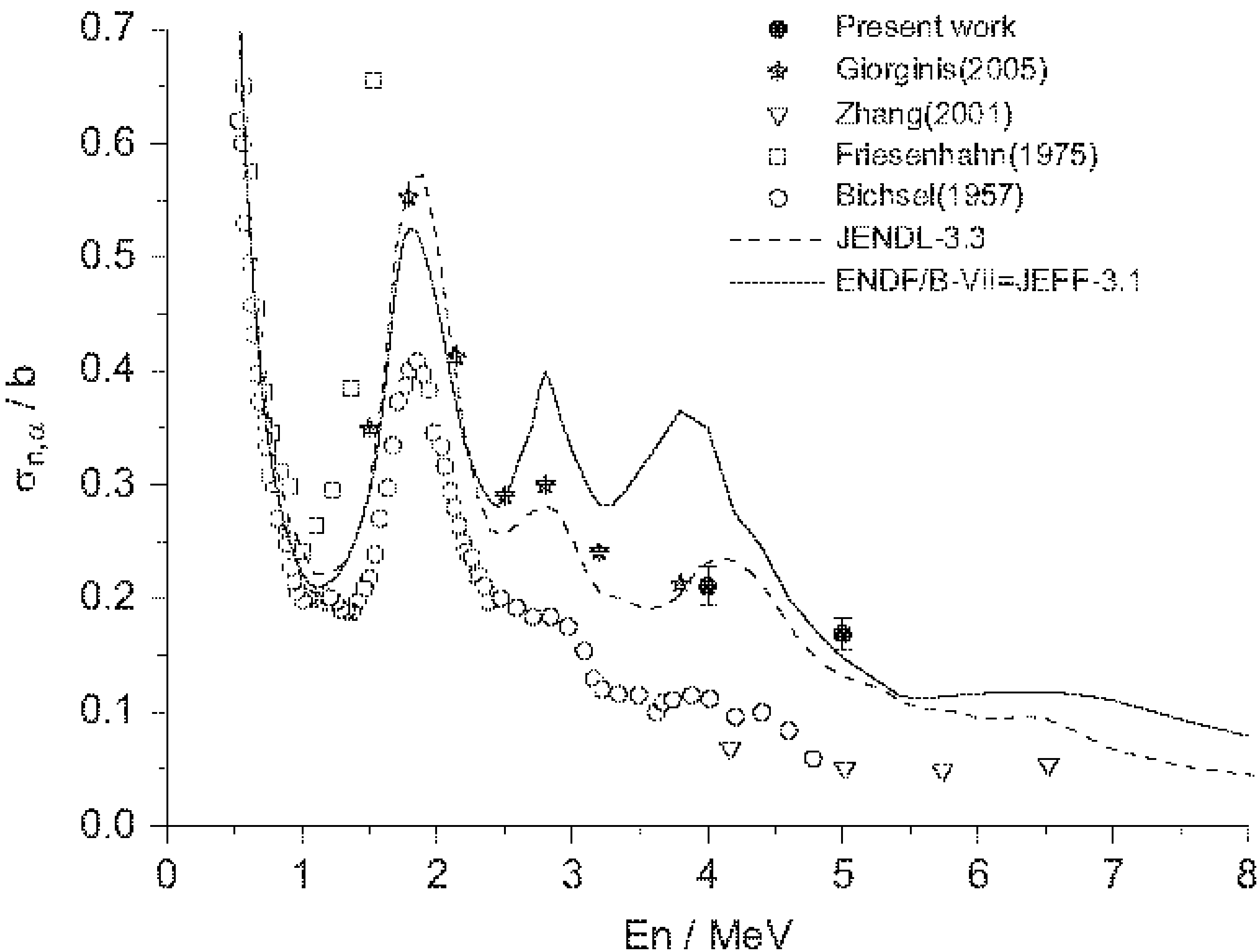
$^{10}B(n,\alpha)$ Data Above 1 MeV (cont.)

•Note the very low values of the early Zhang (2002) data.



$^{10}B(n,\alpha)$ Data Above 1 MeV (cont.)

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



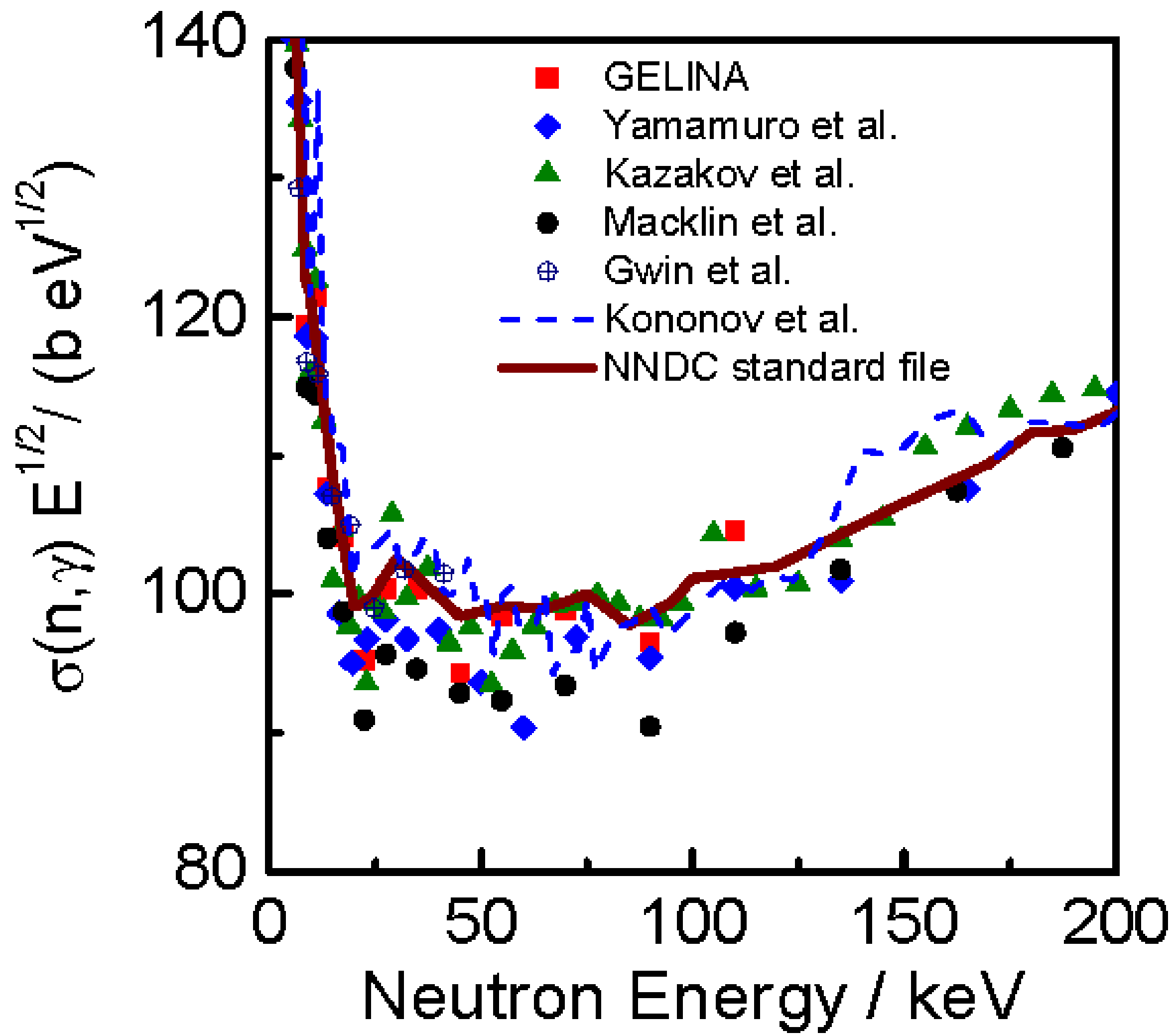
Au(n,γ) and ^{238}U(n,γ) Measurements

- 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.

  - 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), they are concerned about the quality of their data at those higher energies. Massimi has made measurements in collaboration with IRMM (Schillebeeckx et al.) at the GELINA facility 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 standards evaluation results.

Au(n,γ) Cross Section Data

- The GELINA data are Schillebeeckx et al.



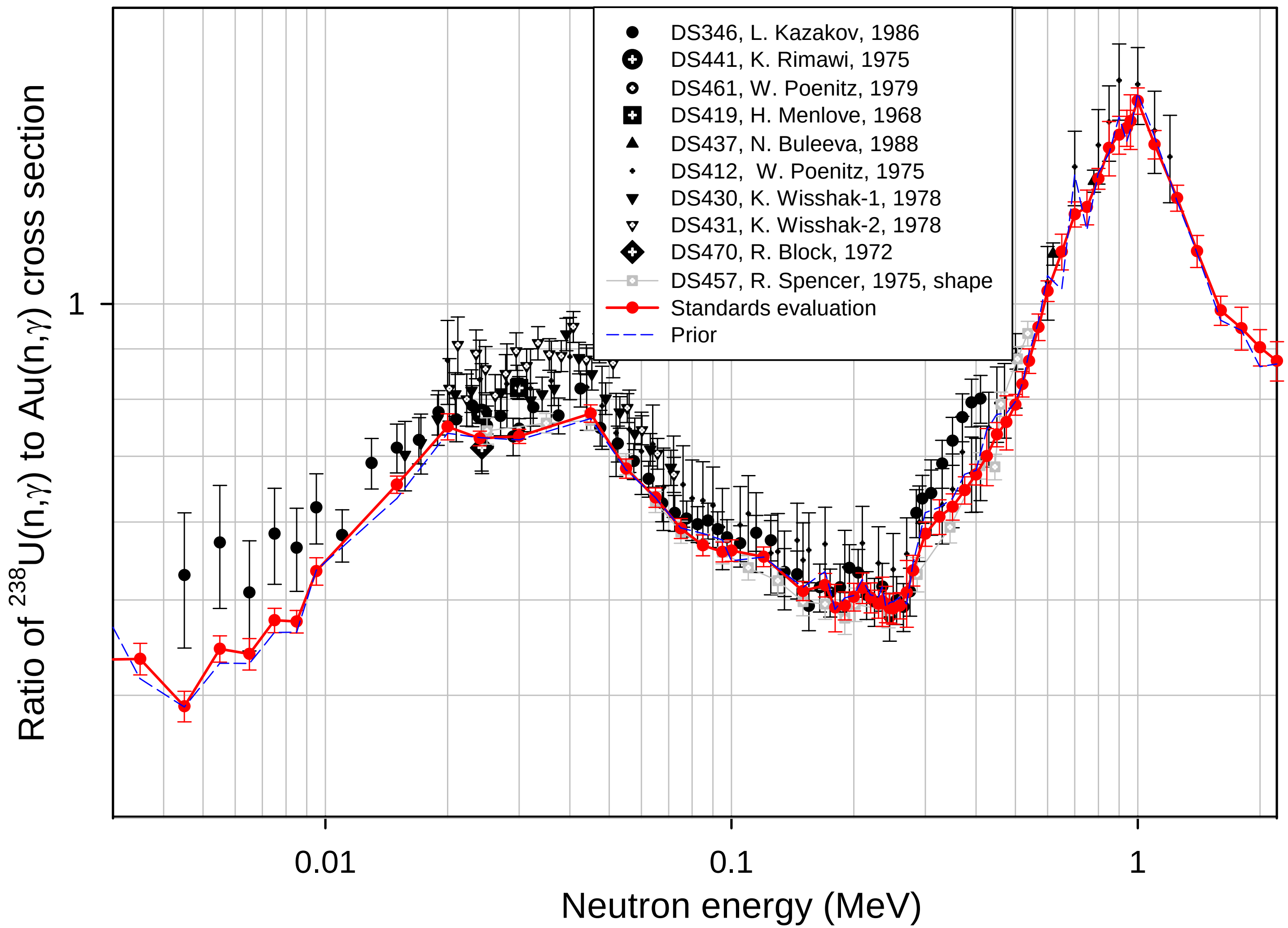
Au(n,γ) and ^{238}U(n,γ) Measurements

•Measurements are being 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.

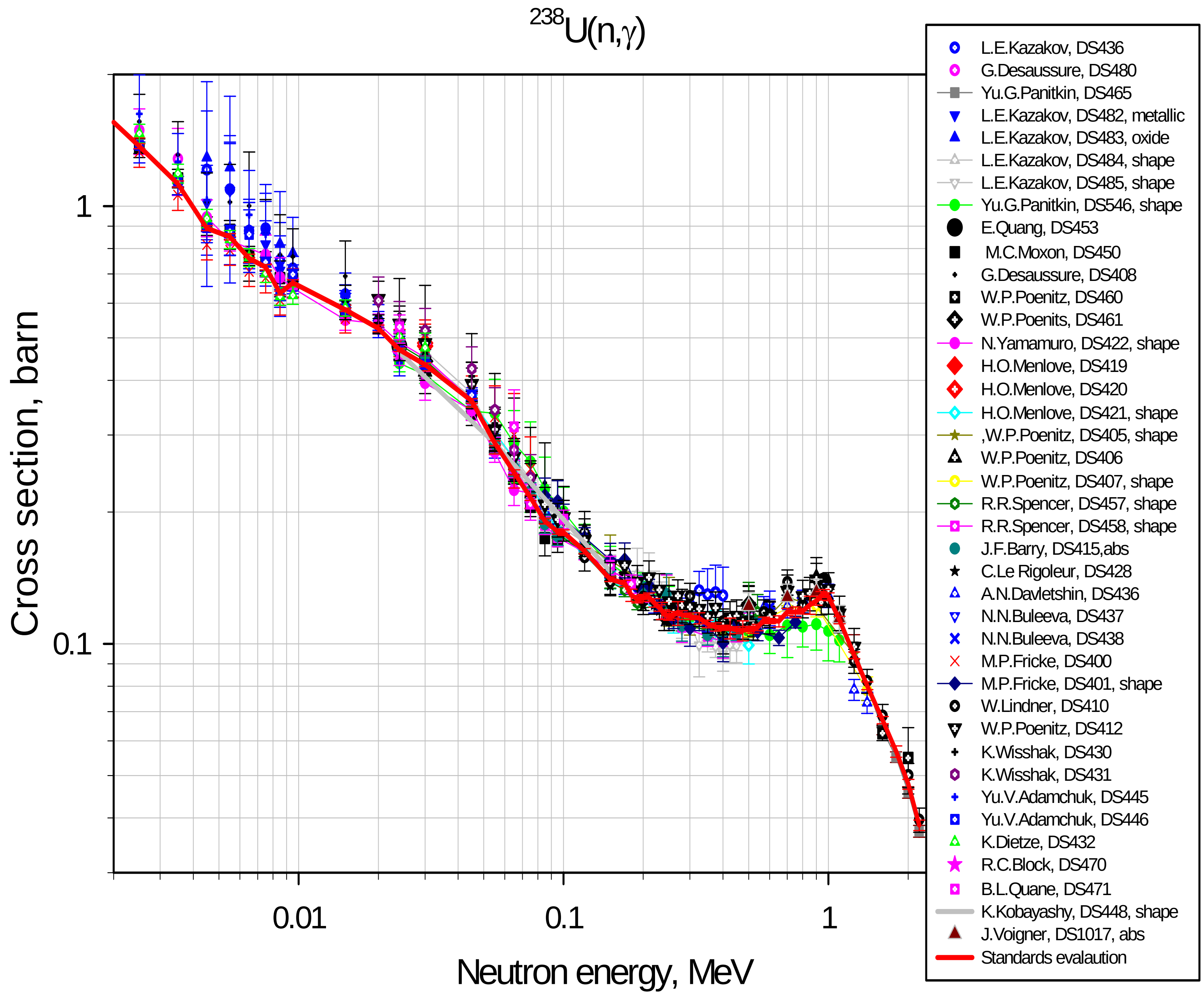
Au(n,γ) and ^{238}U(n,γ) Measurements

• 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. 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.

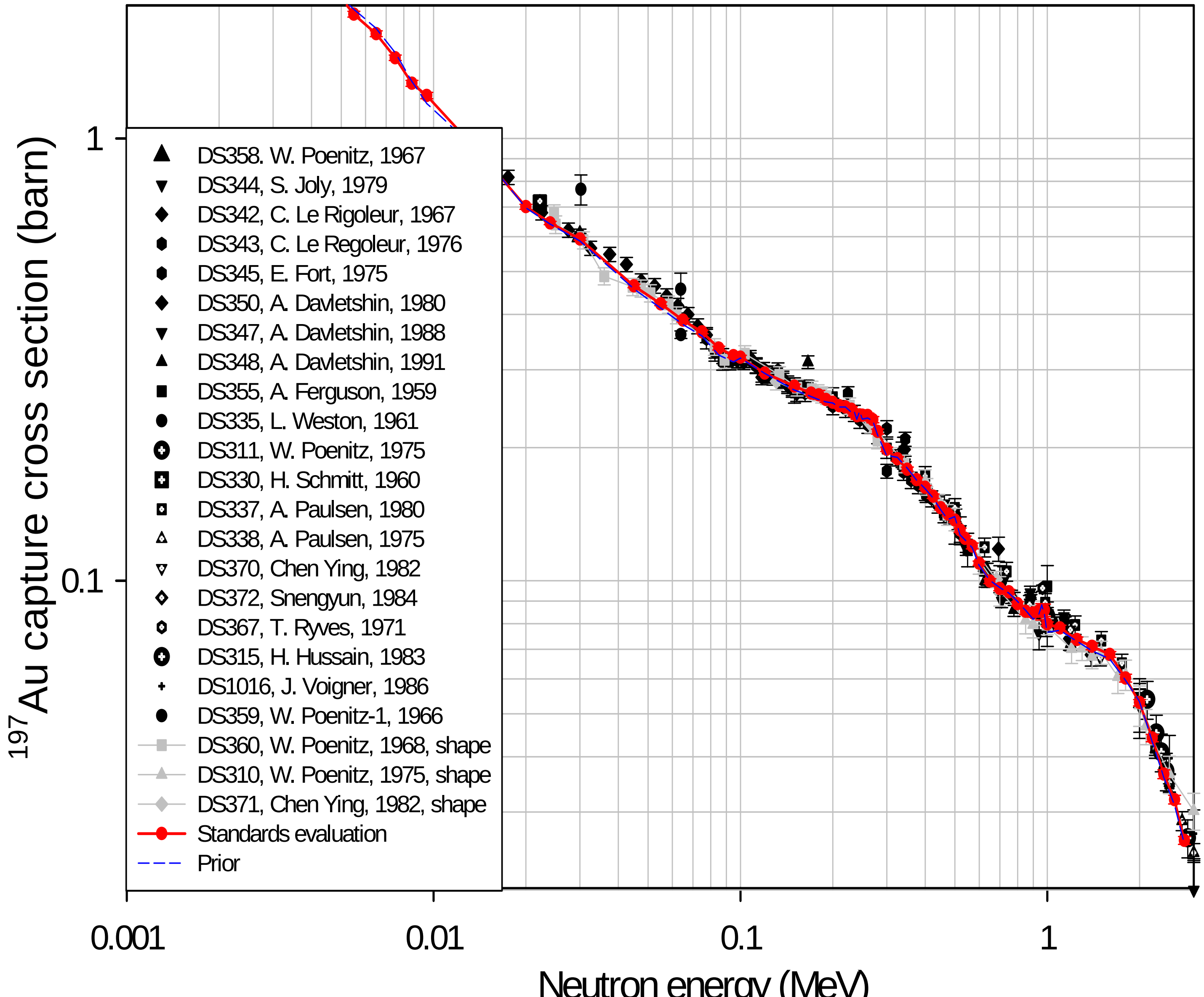
$^{238}U(n,\gamma)/Au(n,\gamma)$ Measurements



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



Au(n,γ) Measurements



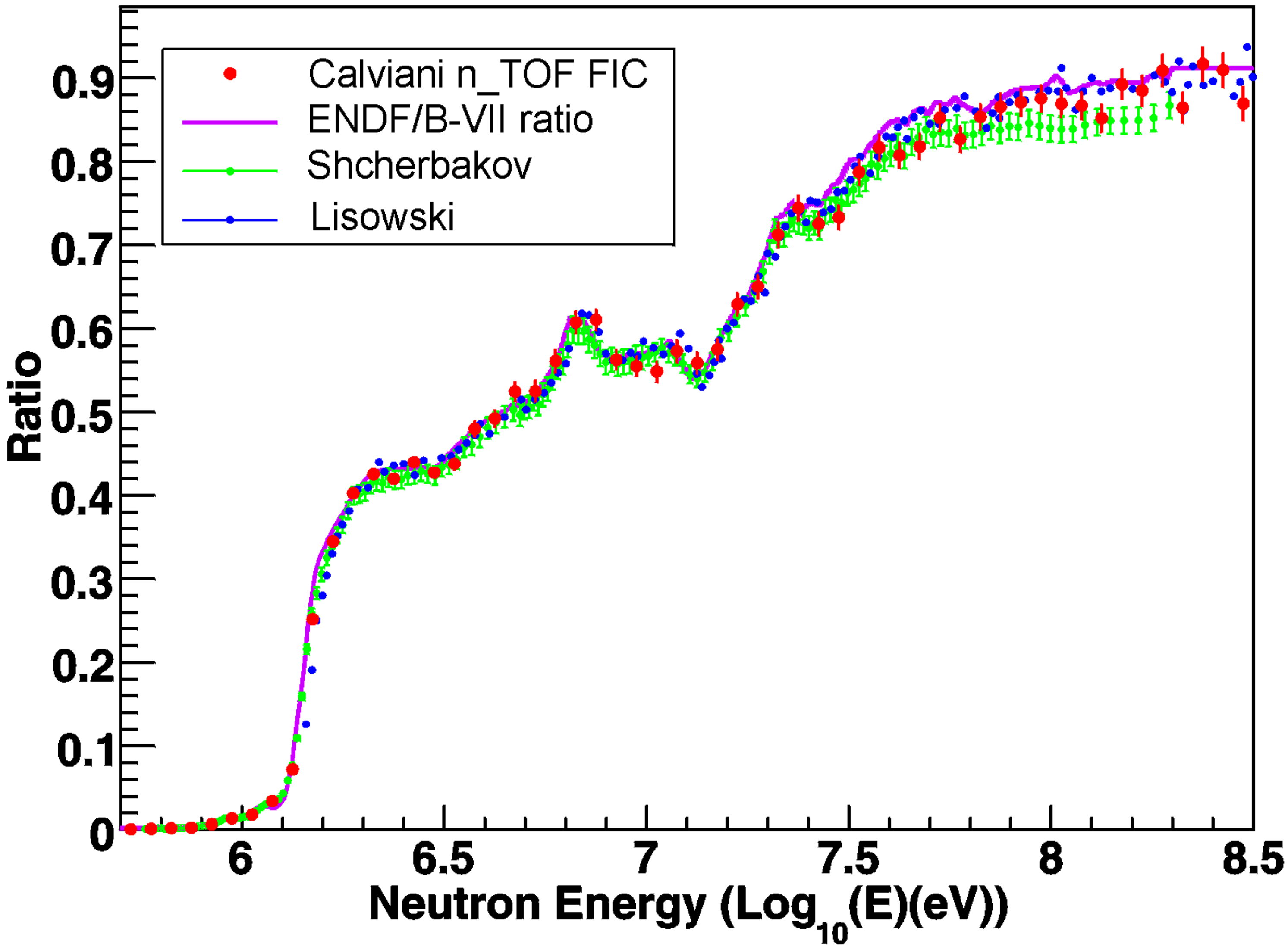
$^{235,\,238}U(n,f)$ Measurements

•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

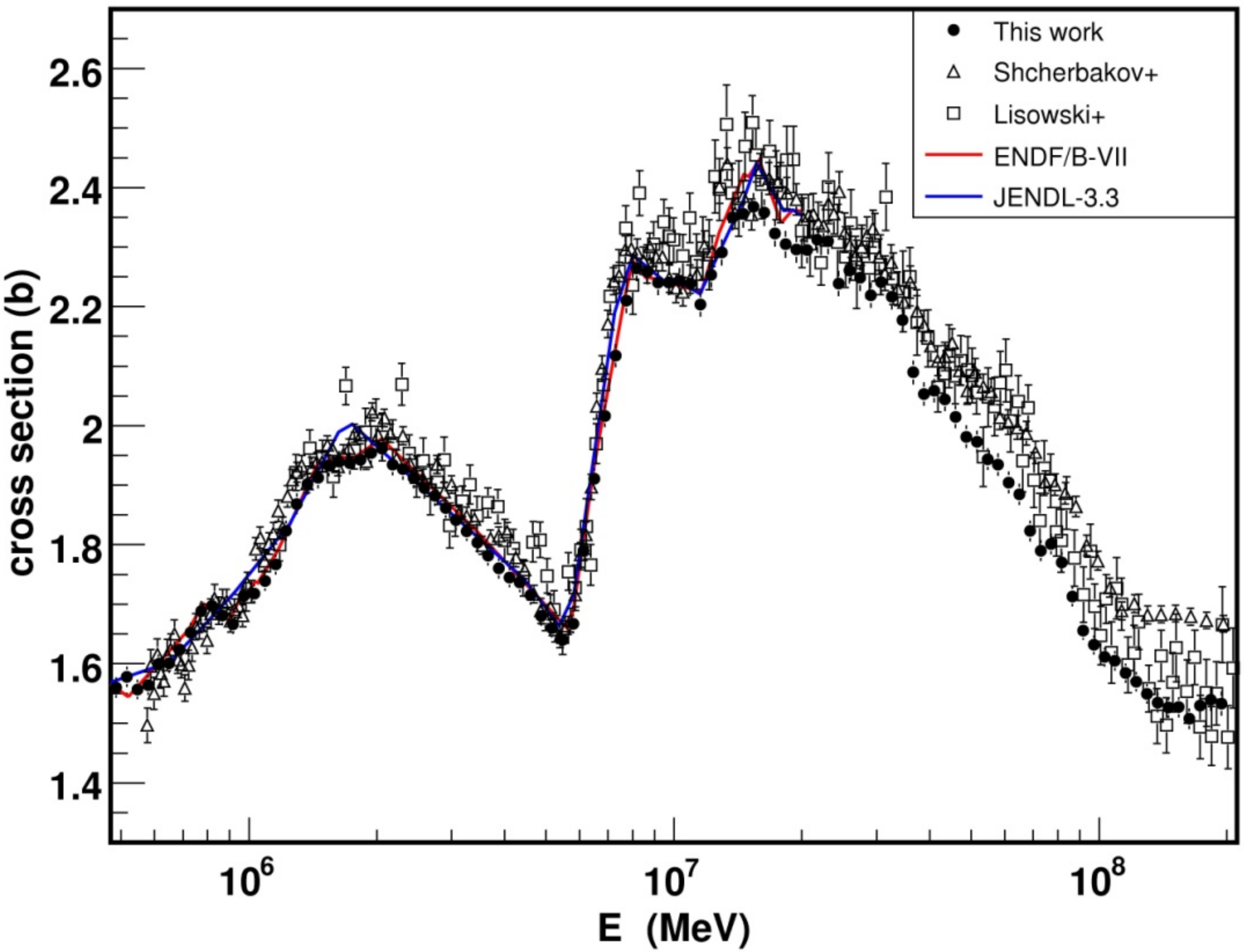


^{239}Pu(n,f) Measurements

•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.

•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. It may be possible to also make measurements of the ^{235}U(n,f) and ^{238}U(n,f) cross sections.

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
- •More work should be done on the Au(n,γ) cross section and the ^{238}U(n,f)/Au(n,γ) cross section ratio in support of "reference" cross section needs.
- •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 .