Status of Neutron Cross Section Standards Measurements Including NIST Activity

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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
$^{10}B(n,\alpha)$	thermal to 1 MeV
$^{10}B(n,\alpha_1\gamma)$	thermal to 1 MeV
C(n,n)	thermal to 1.8 MeV
$^{197}Au(n,\gamma)$	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

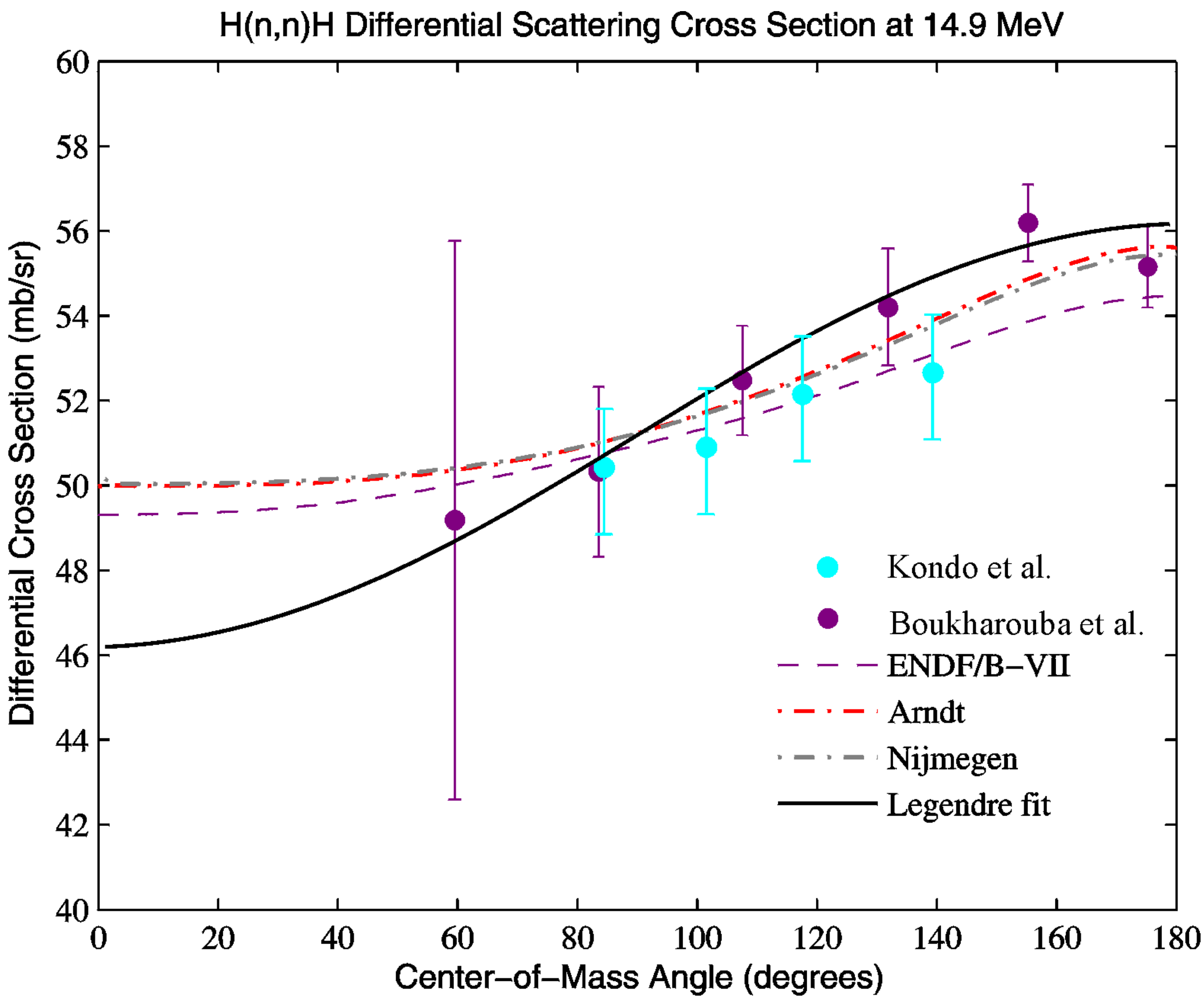
H(n,n)H Angular Distribution Measurements (cont.)

•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 given at the ND2007 conference. The data were obtained at 14.9 MeV neutron energy. The data analysis is complete and a journal publication is now being written.

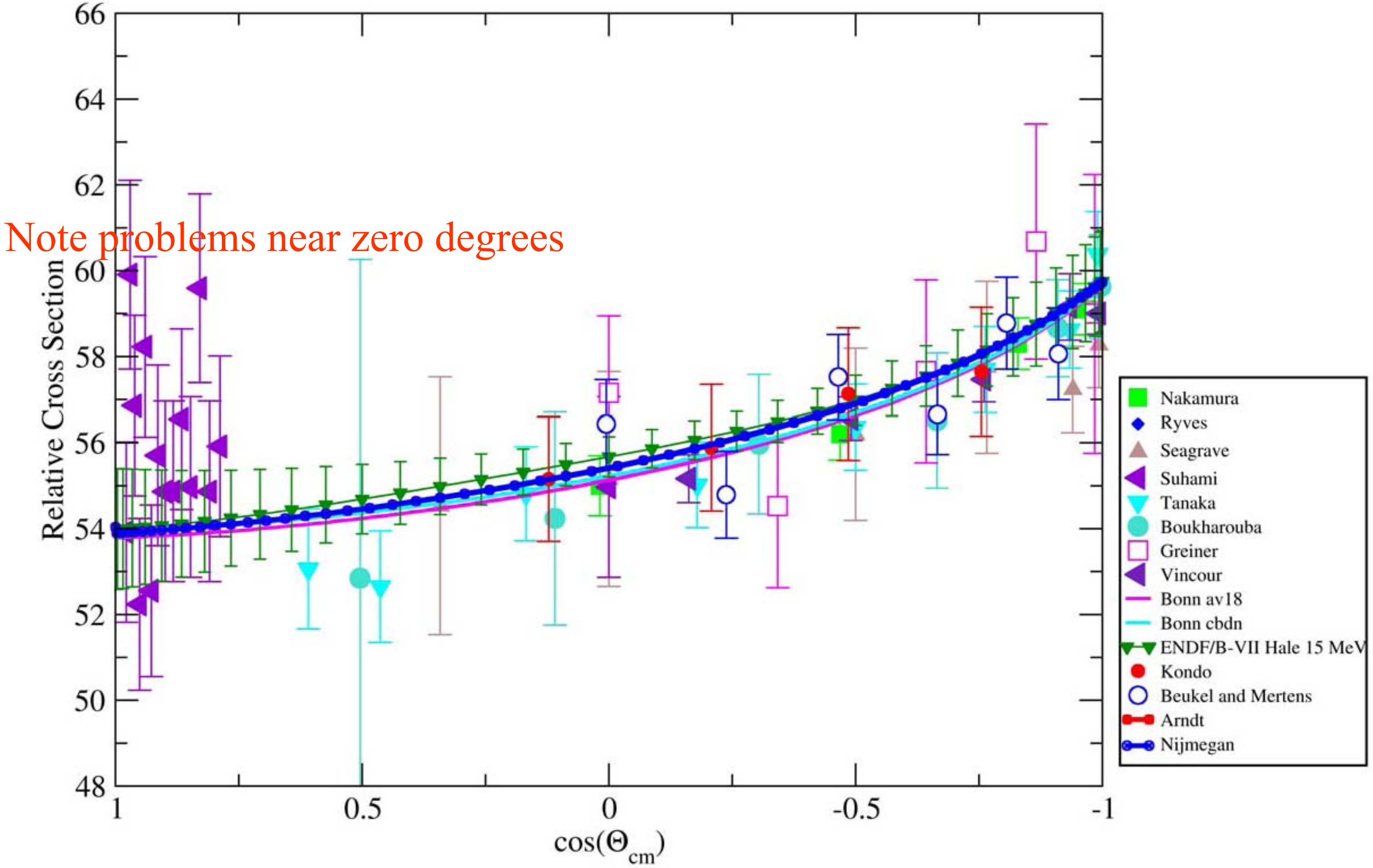
(collaboration of NIST, Ohio University, LANL and the University of Guelma)

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

•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 recently published in Nuclear Instruments and Methods on this work.


H(n,n)H Differential Scattering Cross Section at 14.9 MeV
Differential Cross Section (mb/sr)
Center–of–Mass Angle (degrees)
60
58
56
54
52
50
48
46
44
42
40
0
20
40
60
80
100
120
140
160
180
Kondo et al.
Boukharouba et al.
ENDF/B–VII
Arndt
Nijmegen
Legendre fit

14 MeV Angular Distribution Data



All data have been converted to 14 MeV

H(n,n)H Angular Distribution Measurements

•Using the method of detecting the scattered neutron, measurements will be made by Boukharouba *et al.* at laboratory neutron scattering angles from about 60 to 15 degrees at the Ohio University accelerator facility. Data can be obtained at smaller scattering angles by detecting the scattered neutron compared with proton recoil detection. Data will be obtained at 14.9 MeV neutron energy. Diagnostic work will be done at lower energies where the angular distribution is nearly isotropic.

•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)

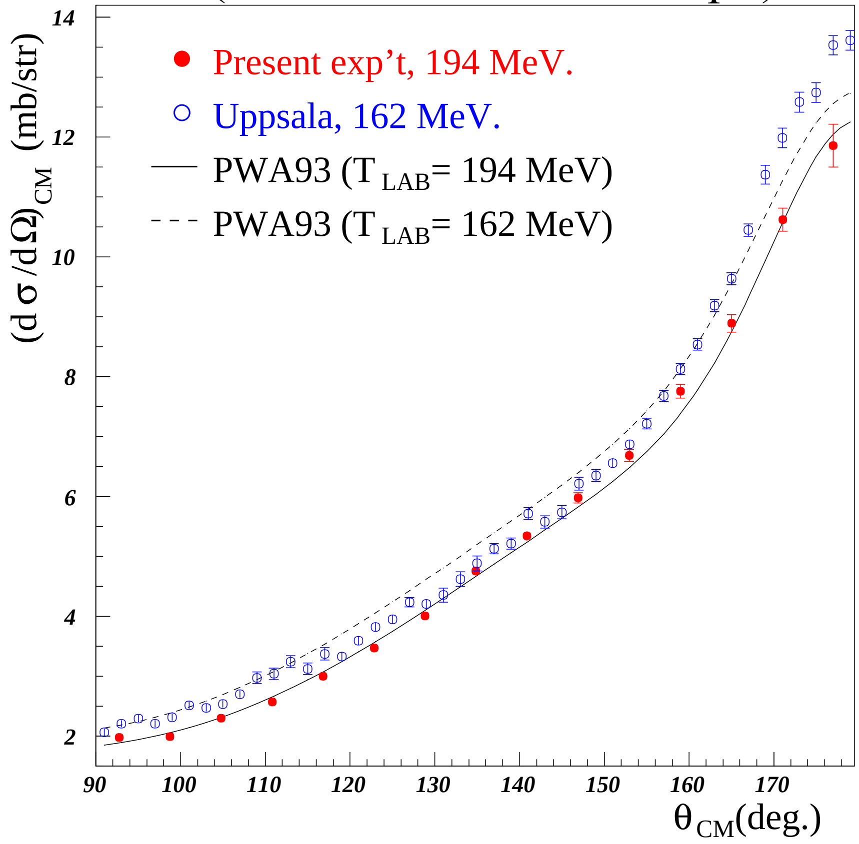
Hydrogen Angular Distribution at High Neutron Energies (cont.)

•Measurements have been made at Uppsala (96 and 162 MeV) and PSI (many energies from about 280 MeV to 580 MeV) indicating larger cross sections at back angles compared with other measurements and calculations. The data were obtained using the $^{7}Li(p,n)$ reaction producing a pseudo-monoenergetic source. The data are relative measurements

•Recent measurements have been made at Indiana University by Vigdor *et al*. at 194 MeV using neutrons tagged by detection of the associated protons from the D(p,n)2p reaction. These data are absolute and were obtained with small systematic uncertainties. These data tend to agree with calculations.

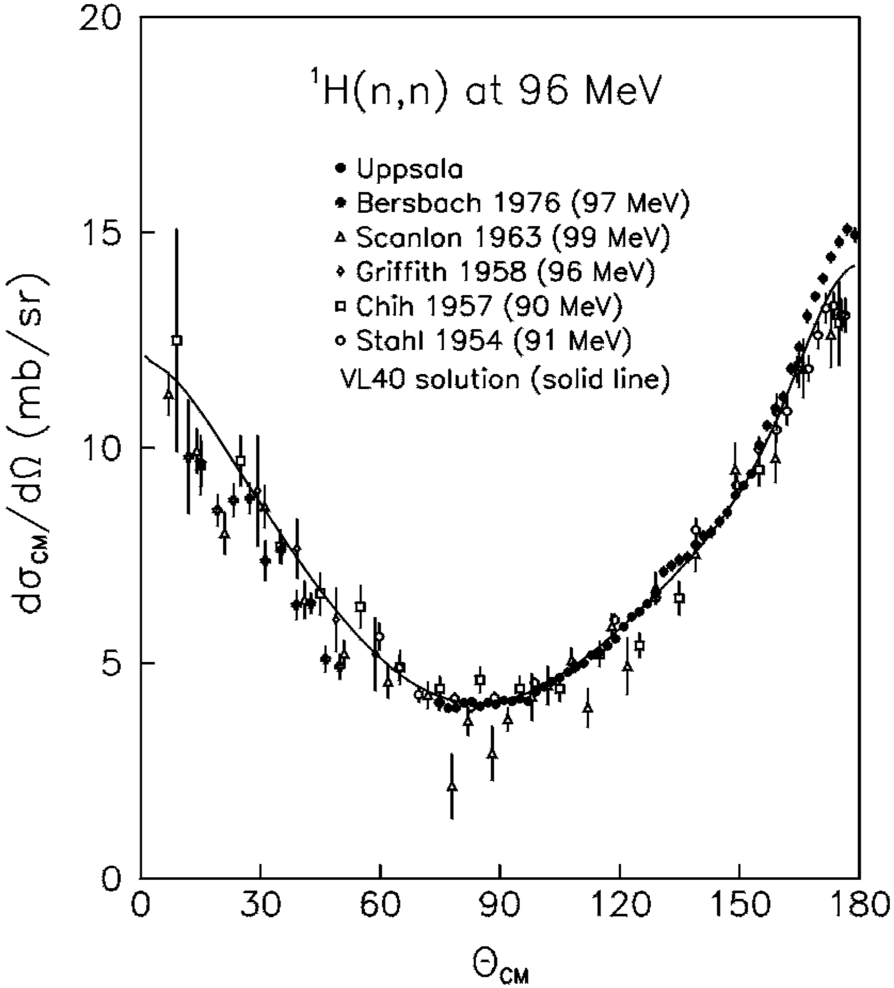
H(n,n)H Angular Distribution Work at ~200 MeV

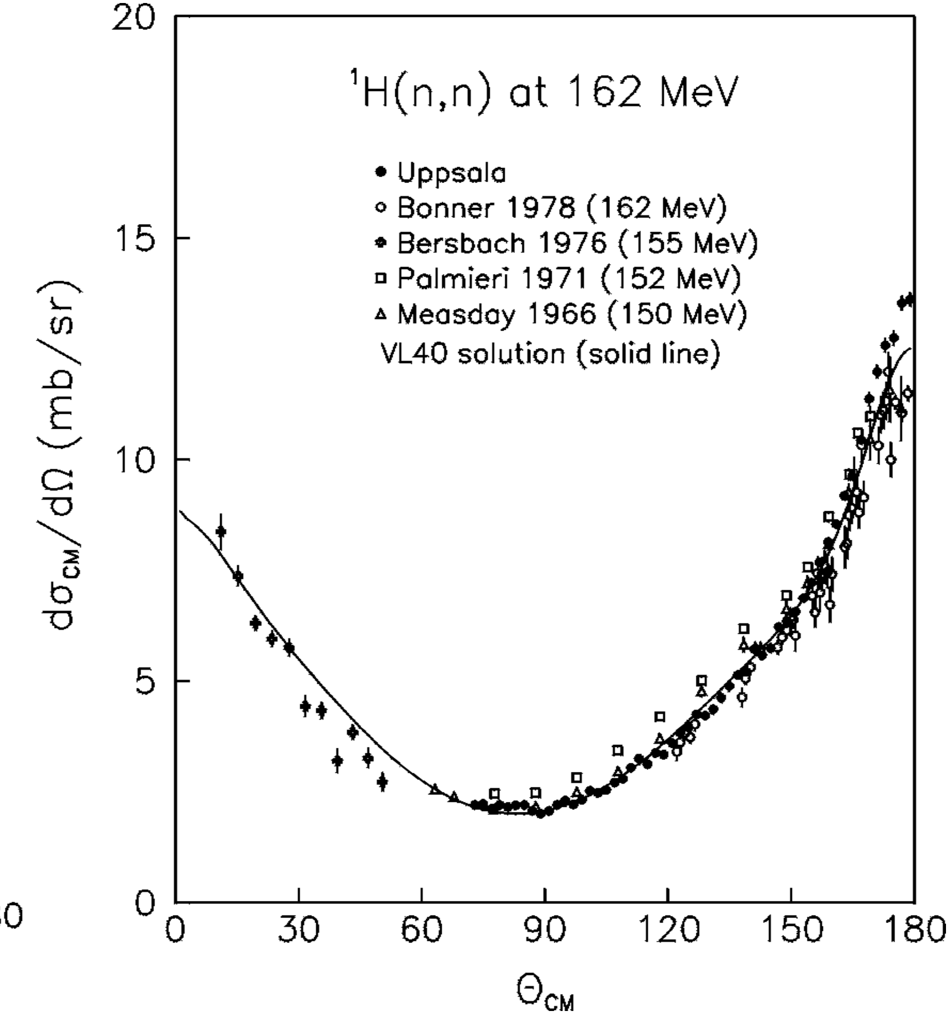
•There is a discrepancy between the results of the Uppsala University and Indiana University measurements (shown here as Present exp't).



Hydrogen Angular Distribution at High Neutron Energies

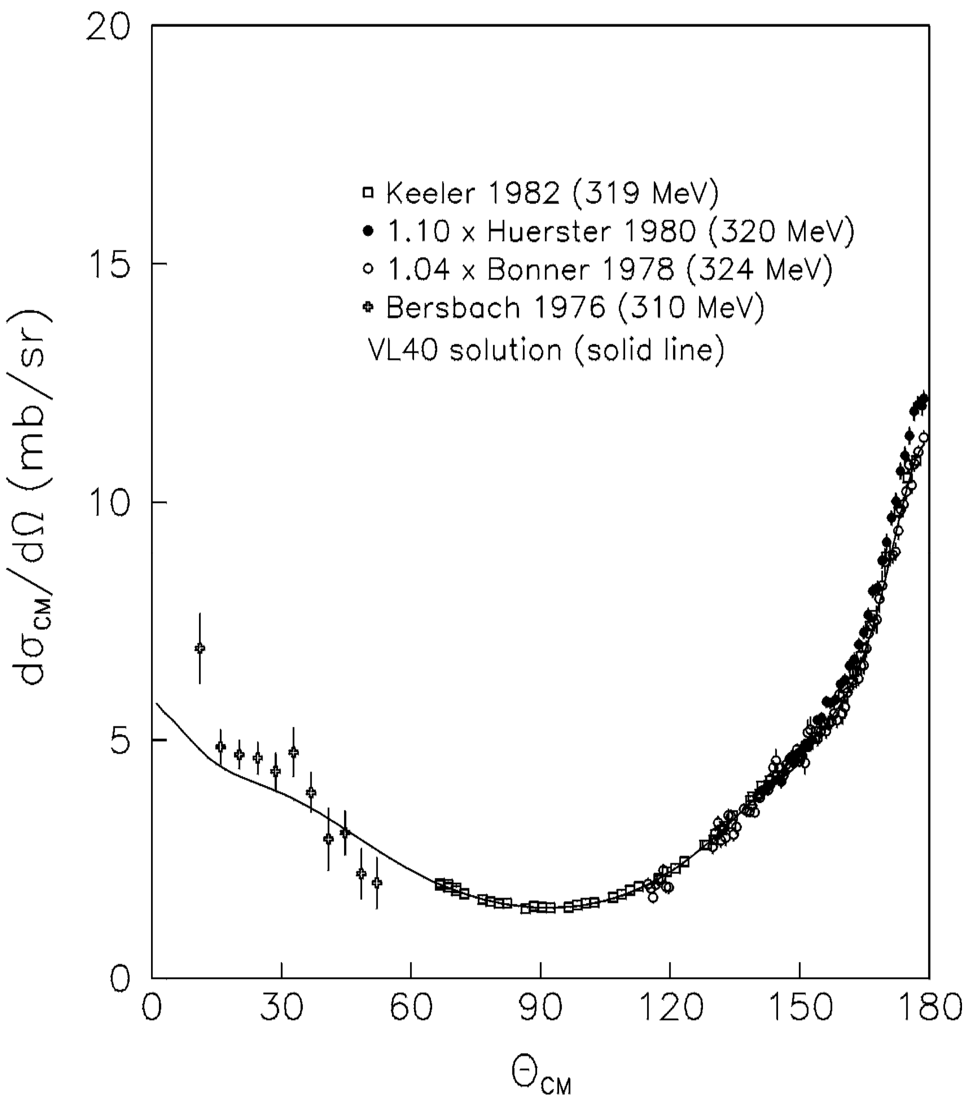
- Uppsala data showing larger cross sections at 180 degrees in the CMS





Hydrogen Angular Distribution at High Neutron Energies

- PSI data (Huerster) showing larger cross sections at 180 degrees in the CMS



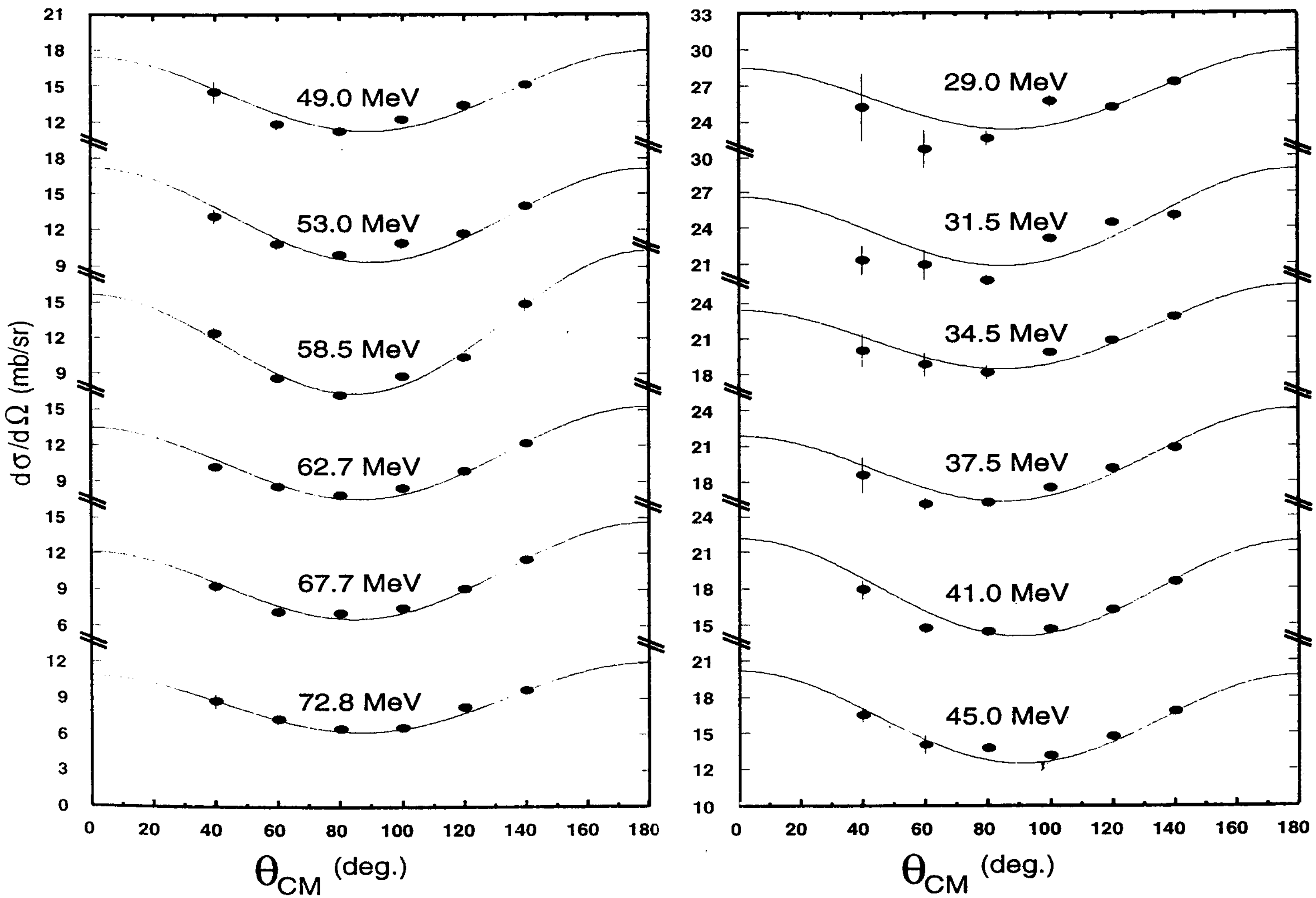
Hydrogen Angular Distribution at High Neutron Energies (cont.)

•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. So we still have a discrepancy.

•There are very few angular distribution measurements available in the energy range from about 30 MeV to 150 MeV and often the angular interval is very limited. The data by Benck *et al*. show the problem with limited angular range.

•Measurements need to be made in this intermediate energy region. There is a possibility that the back angle problem may exist there.

Measurements of the H(n,n) Angular Distribution by Benck *et al*.



^{3}He(n,p) Measurements

•Work has been completed at NIST of a 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. The work has been submitted for journal publication. 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 with Indiana University and the University of North Carolina)

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

•NIST collaborative measurements are being made of the $^{6}Li(n,t)$ cross section standard at ~ 4 meV. These are the first direct and absolute measurements of this cross sections in this neutron energy range using monoenergetic neutrons. The major effort to date has been focused on making fluence measurements with very high accuracy.

•The neutron 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 $^{6}Li(n,t)$ cross section measurement is made using solid state detectors and a thin ^{6}Li target whose geometry and target mass are both well known. This procedure is capable of achieving an accuracy of ± 0.25%.

(collaboration with the University of Tennessee and Tulane University)

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

•The Frisch gridded ionization chamber work of Zhang et al. has been recently published. 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,α) 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 1.05, 1.54, 2.25, 3.67 and 4.42 MeV are the only ones not in the standards database. The higher energy data at the present time can not be used in our database.

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

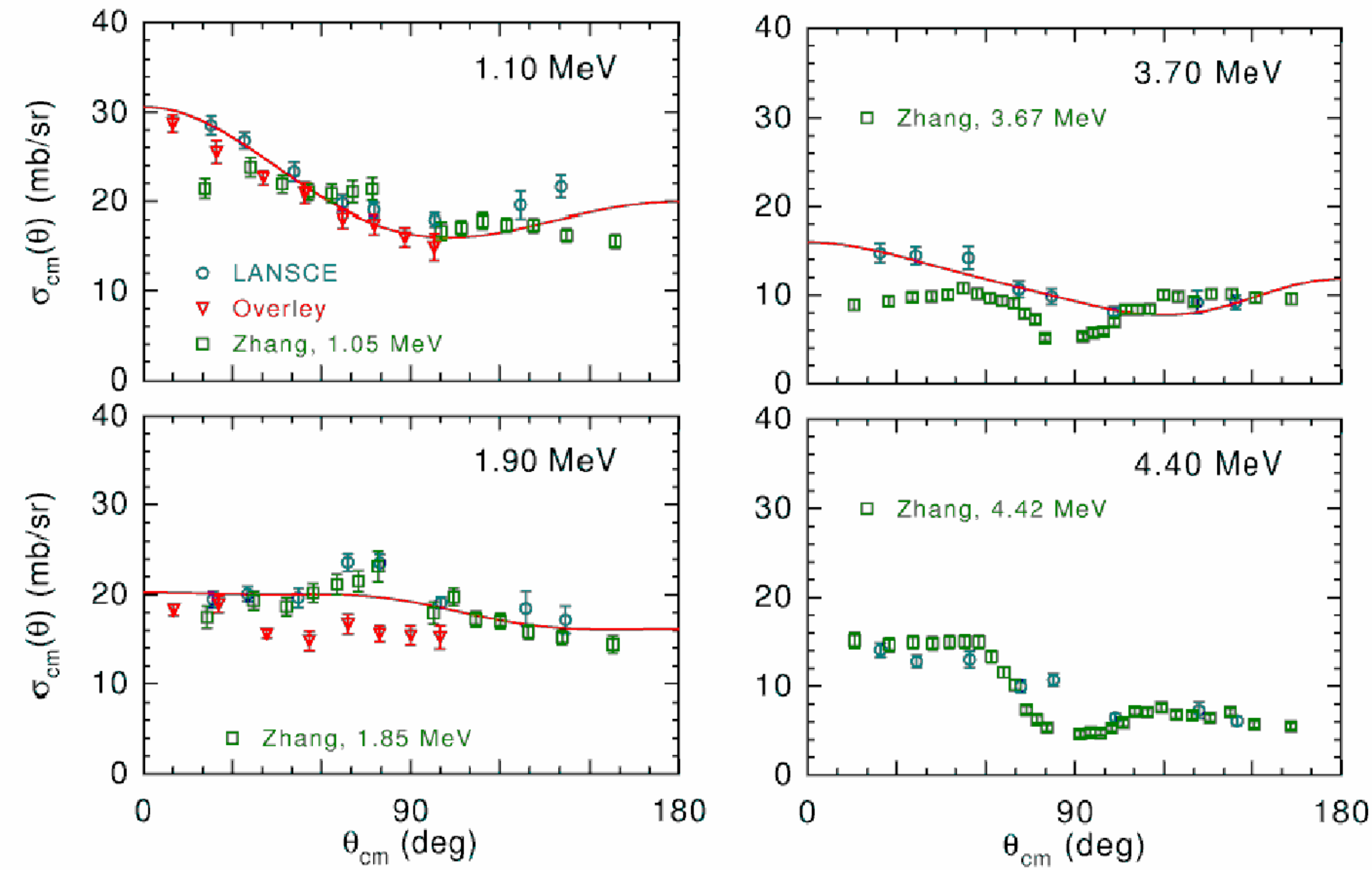
•New measurements have been made by Devlin et al. at LANL.
(M. Devlin, *et al*., LANL report LA-UR-08-06048 (2008))

Angular distribution data were 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%. The results of this work are about 4.5% higher than ENDF/B-VII at 2 MeV.

Also cross sections are being obtained with a detector system composed of two closely spaced silicon solid state detectors for the energy range from 0.1 to 8 MeV. These are absolute ratios to the $^{235}U(n,f)$ cross section. Target thickness difficulties lead to uncertainties at this time of about 10%.

^{6}Li(n,t) Angular Distributions

•The LANSCE data are those of Devlin *et al*.



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

•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.

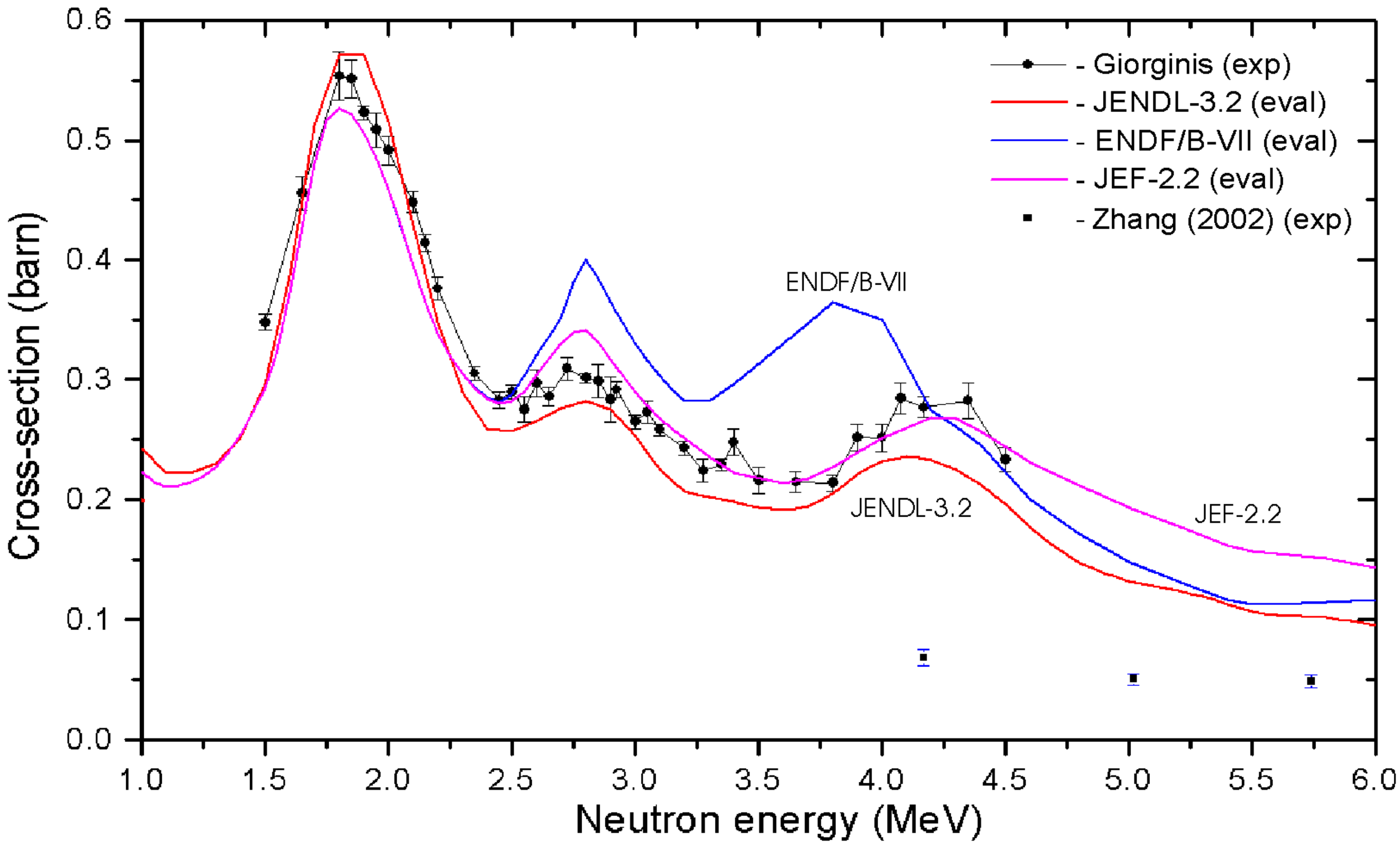
•Branching ratio measurements of Hambsch have been published,
Earlier results of this work are in our database. Some differences are present.
The angular distribution measurements of Hambsch have been submitted for
Publication in Nuclear Science and Engineering.
Data accumulation continues for measurements 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 about 3 MeV.

^{10}B(n,α) Measurements (cont.)

•New measurements using a Frisch gridded ionization chamber have been completed at 4 and 5 MeV by Zhang of the ^{10}B(n,α) cross section relative to the ^{238}U(n,f) standard. Plans have been made to make angular distribution measurements from 1 to 6 MeV.
(Guohui Zhang *et al.*, Appl. Radiat. Isot. 66, 1427 (2008))
Their earlier measurements were effected by the "particle leaking" effect.

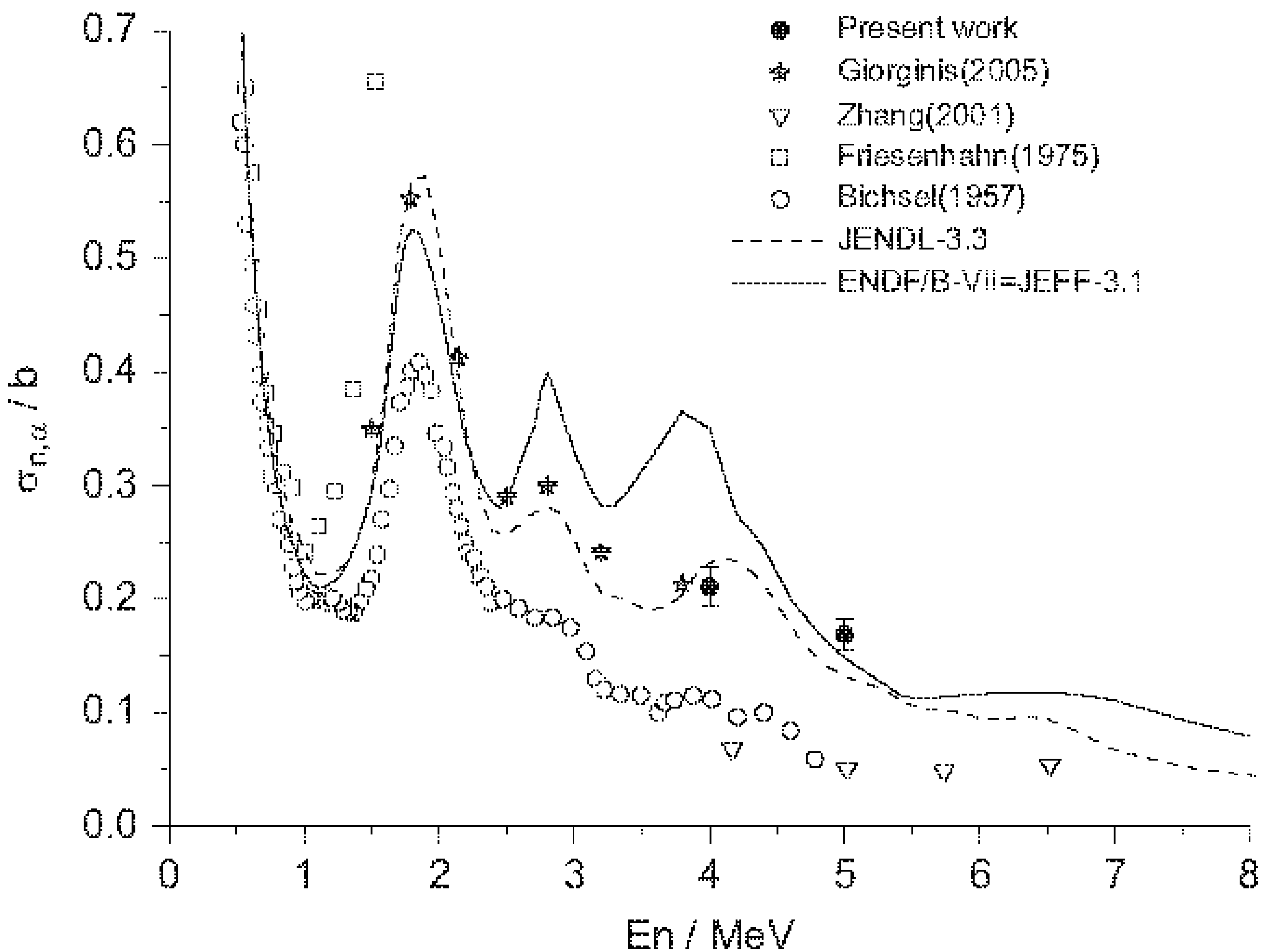
$^{10}B(n,\alpha)$ Data Above 1 MeV

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



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

- 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.

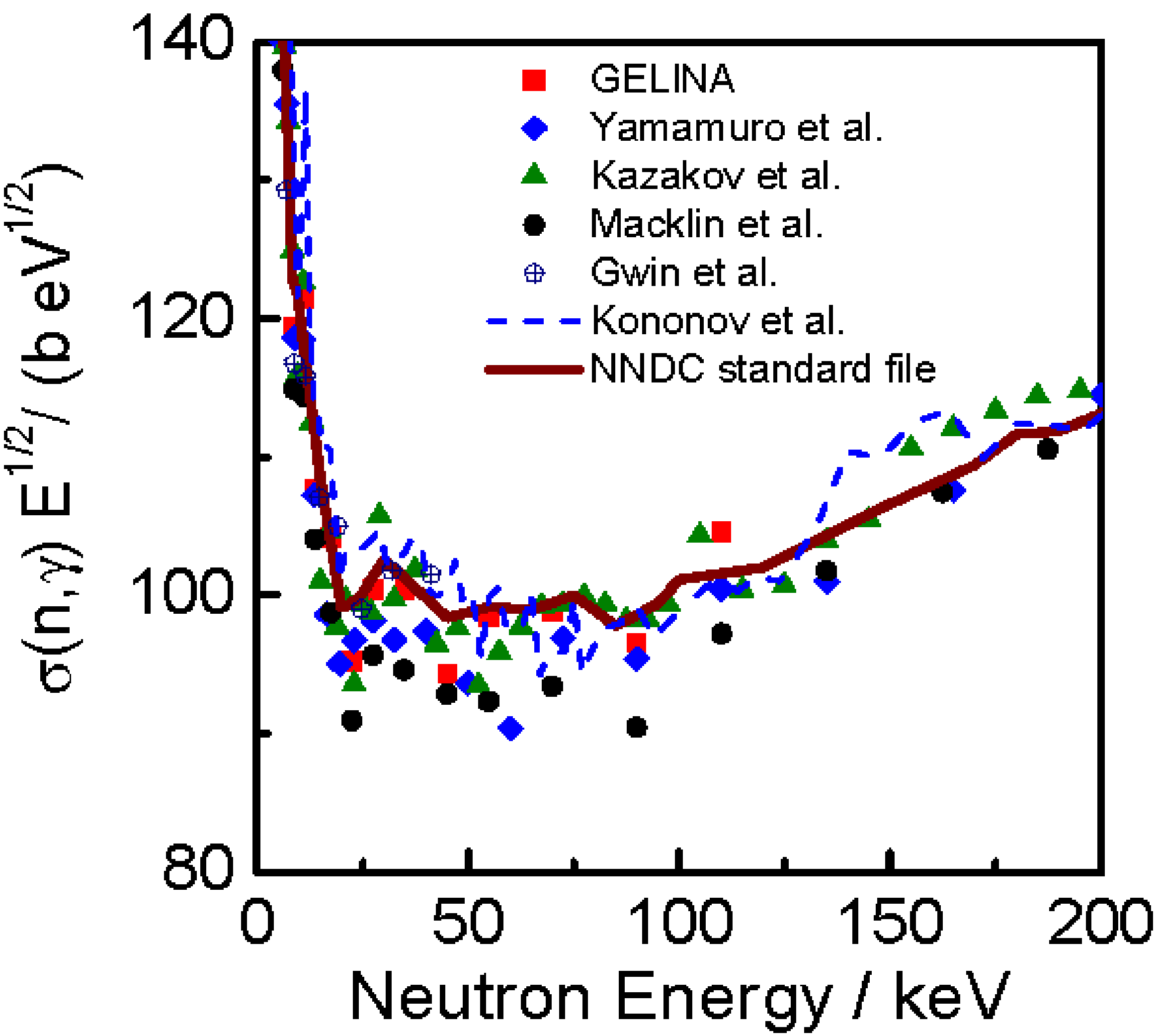
Au(n,γ) and ^{238}U(n,γ) Measurements

•Measurements of the capture cross section for Au have been made at the n_TOF facility by Massimi et al. with the objective of of adding the energy range from 1 eV to 10 keV to the standards energy region. Data obtained from 1 eV to 1 keV using two different detector systems were shown at the ND2007 conference. Analysis of the data from one of the Detectors (the C_6D_6) could provide results to 1 MeV. The data are relative to the shape of the ^{6}Li(n,t) standard using the saturated resonance technique for normalization. There are concerns about the quality of the high energy data. Measurements are also being made by this group in collaboration with IRMM (Schillebeeckx et al.) at the GELINA facility relative to the ^{235}U(n,f) and ^{10}B(n,α) standards.

•Measurements are being made by Wallner (U. of Vienna) of the ^{238}U(n,γ) cross section at 500 keV , at thermal energy and with cold neutrons using mass spectrometry to measure the resulting ^{239}Pu. Also data were obtained with a simulated 25 keV maxwellian spectrum. The data are relative to the Au(n,γ) cross section.

Au(n,g) Cross Section Data

- The GELINA data are Schillebeeckx et al.



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

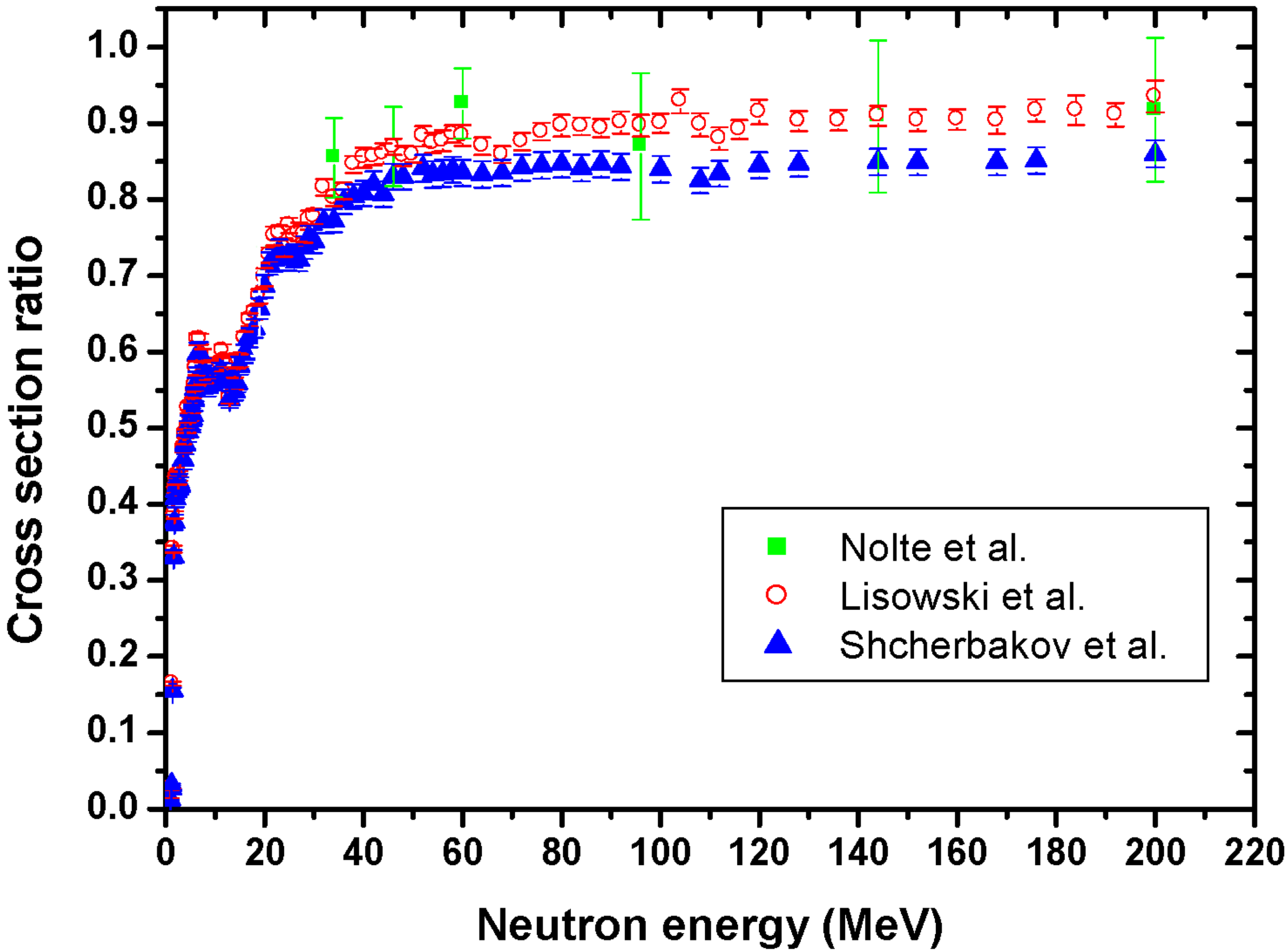
•The Nolte et al. $^{235}U(n,f)$ and $^{238}U(n,f)/^{235}U(n,f)$ cross section measurements which extend from about 32 to 200 MeV were published.
(Nucl. Sci. Eng. 156, 197 (2007))
The data agree with the Lisowski *et al*. data.
There are differences compared with the preliminary data in the standards database.

•Measurements of the $^{238}U(n,f)/^{235}U(n,f)$ cross section ratio have been made by two experimental groups at the n_TOF facility. Both groups gave papers on their work at the ND-2007 conference. Both sets of measurements tend to support the Lisowski *et al*. data rather than the Shcherbakov *et al*. data. Additional measurements are planned.

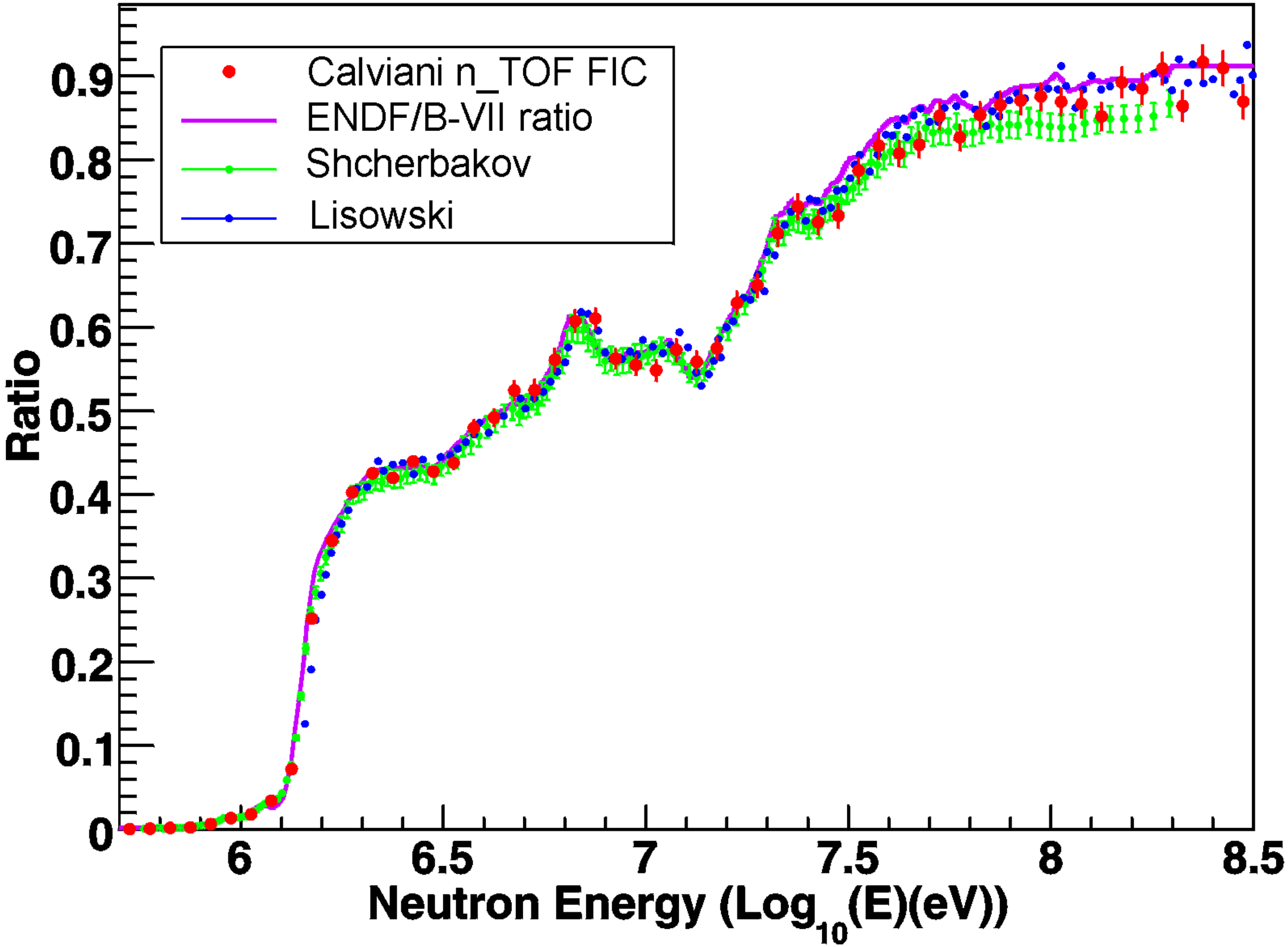
•Data from the Calviani et al. experiment were obtained with fission ionization chambers. Preliminary results of the data analysis are available to about 300 MeV.

•Audouin et al. made measurements by detecting fission fragments in coincidence using Parallel Plate Avalanche Counters. The data extend to about 1 GeV. The data are preliminary.

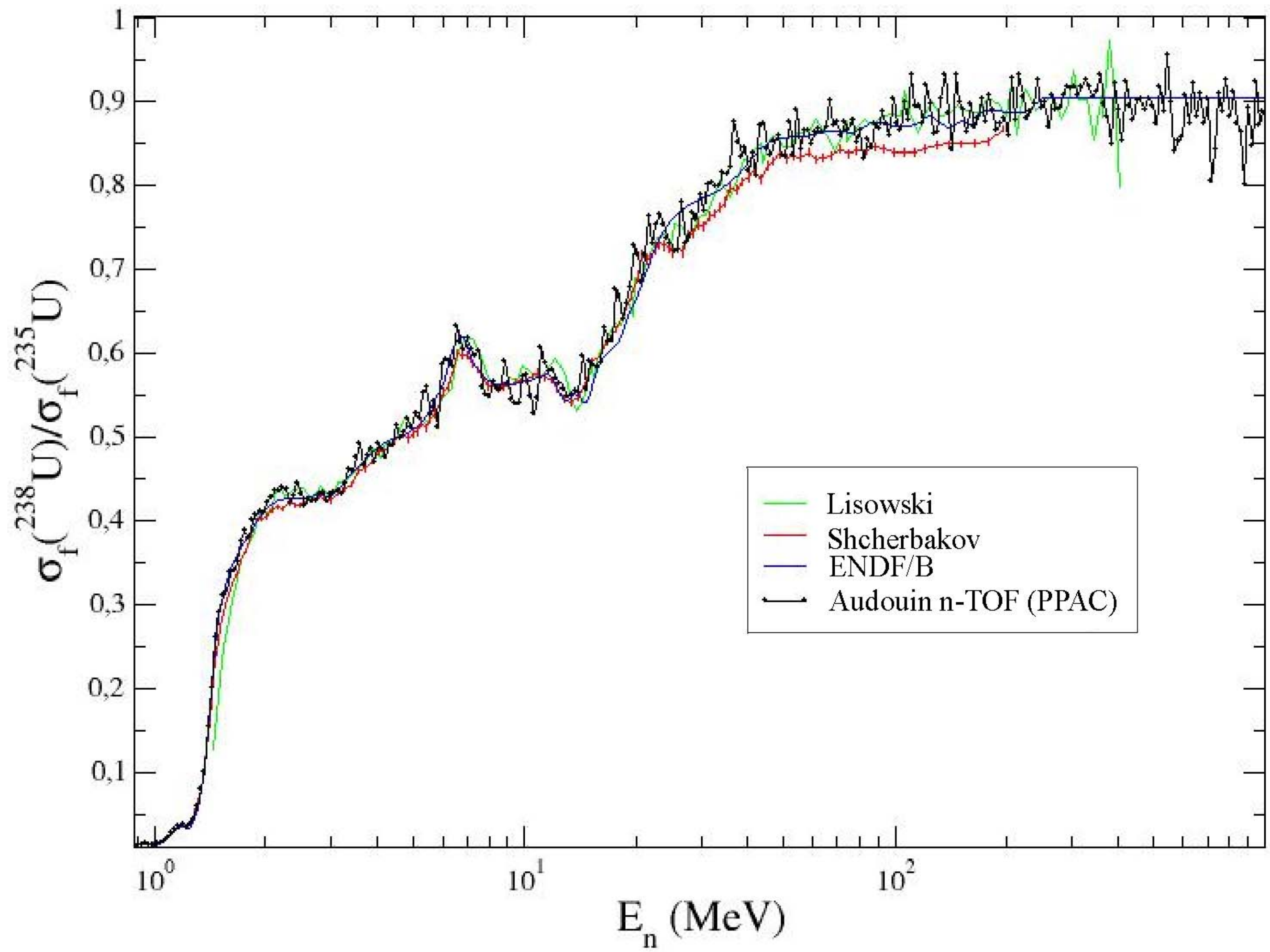
Comparison of Recent Measurements of the $^{238}U/^{235}U$ Fission Cross Section Ratio of Nolte With Other Work



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

•Measurements are expected on the ^{239}Pu(n,f) cross section in the MeV energy from a collaboration initiated by staff at LANL and LLNL. 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.

Conclusions

•Considerable experimental activity has occurred since the completion of the International evaluation of the standards. 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

•Additional work should be done in the high energy region on the ^{235}U(n,f) and ^{238}U(n,f) standard cross sections.