NIST Measurements and Standards Related Work at Other Facilities

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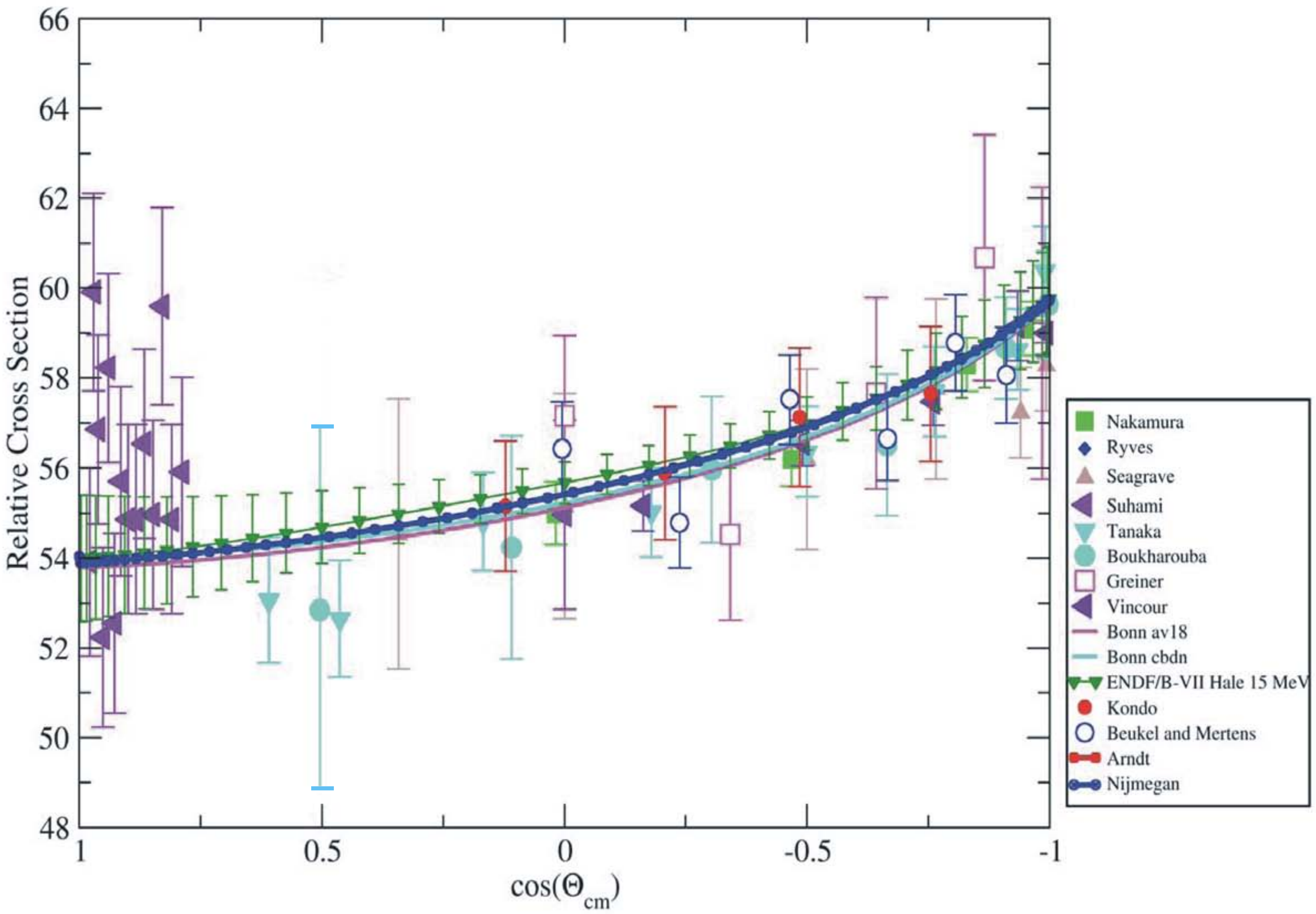
THE NEUTRON CROSS SECTION STANDARDS

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

14 MeV Hydrogen Angular Distribution Data

Note
problem
near
zero
degrees



All data have been converted to 14 MeV

H(n,n)H Angular Distribution Measurements

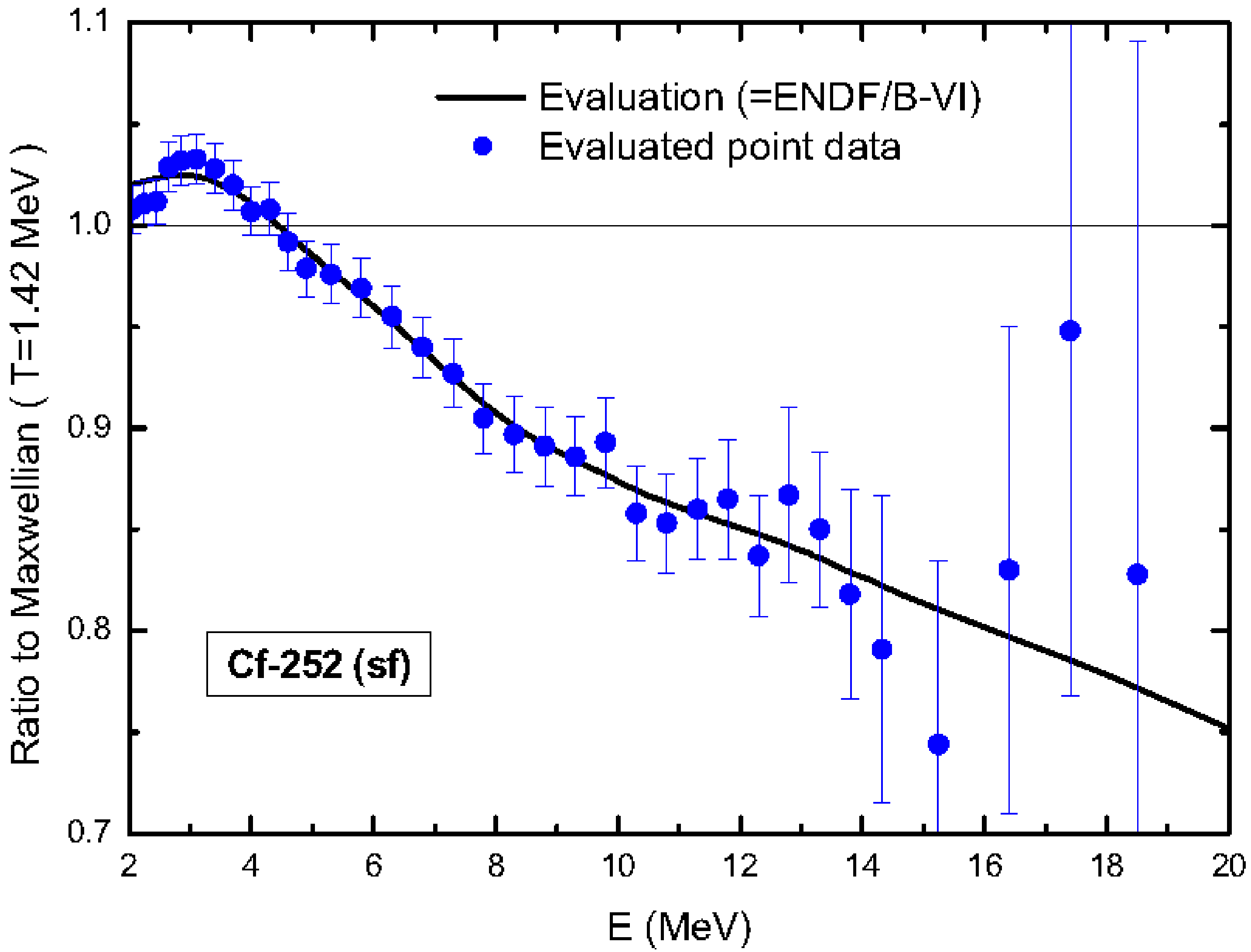
•In order to make measurements at smaller scattering angles an experiment has been designed where the primary objective is detection of the scattered neutron instead of the scattered proton.

•The work is being done at the Ohio University accelerator facility. 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 neutron energies below about 9 MeV ^{252}Cf spectra will be used.

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

Evaluation of the ^{252}Cf spontaneous fission neutron spectrum at high energies



H(n,n)H Angular Distribution Measurements

•For neutron energies above 9 MeV, a technique using reactions where the projectile and target are identical will be used. Because they are identical, the angular distribution **must** be symmetrical in the CMS. Thus, for a bombarding energy such that the backward portion of the angular distribution falls in the energy range below 9 MeV where the efficiencies are well known, we can reduce these data to obtain cross sections for a given group in the backward hemisphere. Reflecting these data gives us the cross sections in the forward hemisphere which are the same. The center-of mass cross section would then be converted to lab cross sections. Analysis of the measured counts at the appropriate angles can then give us the efficiency for the 14 MeV neutron energy range.

•A study of possible targets indicated that the ^{6}Li(^{6}Li,n)^{11}C reaction is the best for our use. Neutrons could be used from the ground and two excited states for ^{11}C to give the desired neutron energies.

•Work has been done to try to evaporate a suitable target using lithium metal and then LiCl. Various backings and surface coatings were used with limited success. This is an ongoing project

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

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.

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

•There appears to be an inconsistency between NIST collaborative measurements of the total cross section by Keith *et al.* from 0.1 to 500 eV with uncertainties less than 1% with an R-matrix evaluation of the ^{3}He(n,p) standard cross section by Hale. 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 have been completed 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 was very accurate measurements of the fluence. The fluence (efficiency) has now been determined with an uncertainty of 0.05%.

• The limitation on the accuracy of the NIST $^{6}Li(n,t)$ cross section measurement is the mass uncertainty of the ^{6}Li target. The present uncertainty is about 0.25%. Further studies are being 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 0.2% 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.)

- Work is underway at IRMM on ^{6}Li(n,t) measurements.

- At the GELINA linac, 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. This work will extend from a few keV to about 3 MeV so the resonances at 0.25 and the weak one at about 2 MeV will be covered. They are investigating a digital data acquisition system for these experiments since they see many benefits from this approach compared to the traditional analogue electronics approach.

- At the IRMM Van De Graaff facility Giorginis and Bencardino are planning ^{6}Li(n,t) measurements at the IRMM Van De Graaff facility. They are using a Time Projection Chamber that was designed and fabricated at IRMM. They plan to obtain high cross section accuracy by determining all important parameters with the best possible precision: number of reaction events, number of monitor events, number of ^{6}Li atoms in the ^{6}LiF samples, and the number of ^{238}U atoms in the monitor. They are characterizing the ^{6}LiF samples with Thermal Neutron Depth Profiling. Two cross section measurement campaigns are scheduled at the Van De Graaff: the first was in October 2011 and the second in February 2012. They will be obtaining ^{6}Li(n,t) cross section data in the 2 MeV energy region. These data should overlap the GELINA data from 1 to 3 MeV. The ^{6}Li deposits for both the GELINA and Van De Graaff measurements were made at IRMM.

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

•Hambsch 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. This work is being done at the 60m station of GELINA at IRMM. Some of the data are being analyzed. He estimates results from the analysis will be available in early 2012.

$^{10}B(n,\alpha)$ 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. They found that the sample suffers almost a 40% loss in thicknesses in about 2 years' duration. They do not know if the loss is related to neutron beam bombardment.

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

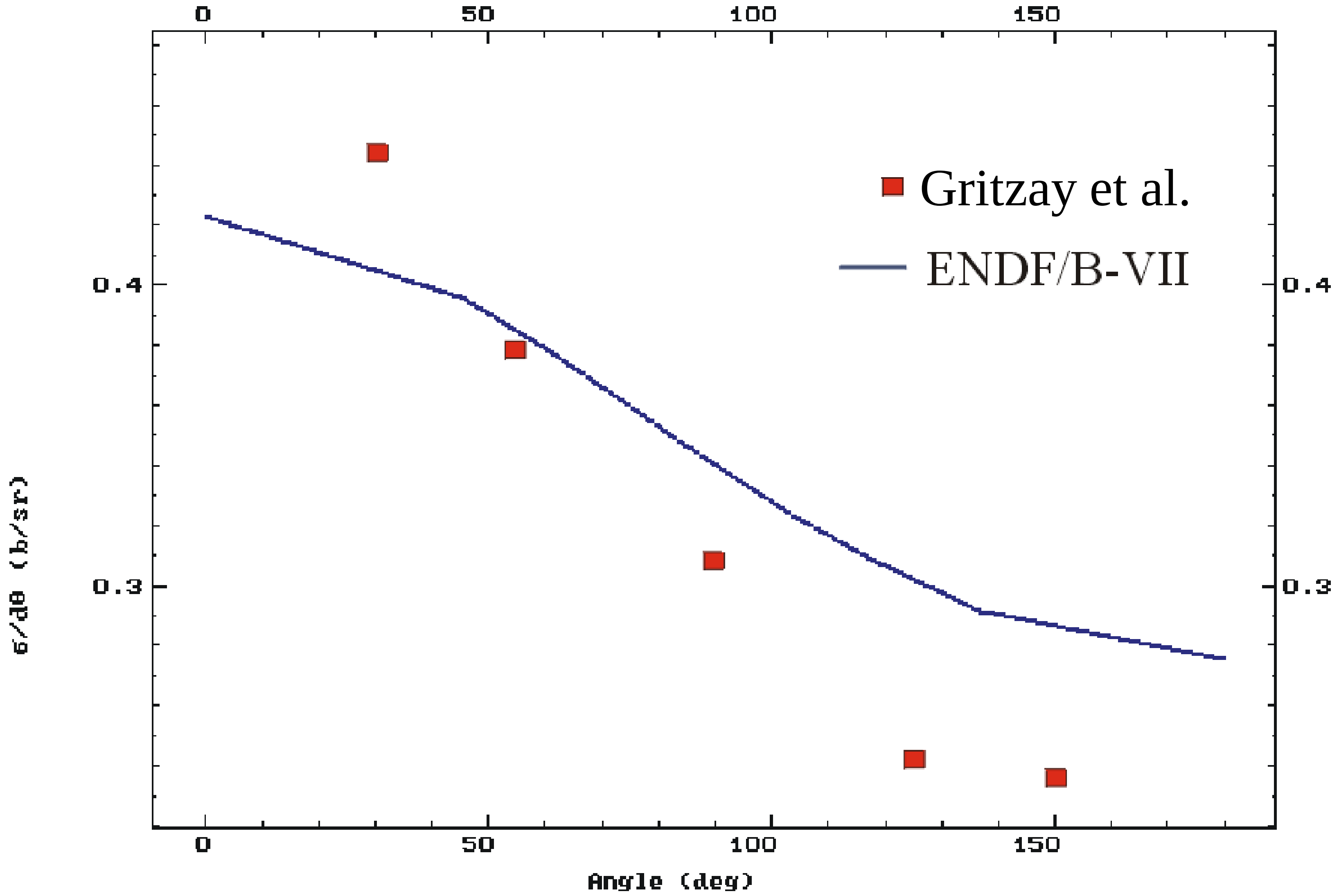
•NIST has also noted a problem with loss of ^{10}B from evaporated deposits. Plans for making $^{10}B(n,\alpha)$ measurements at low neutron energies are being delayed while work is being done to investigate these losses

C(n,n) data

• Linac measurements have been made of the carbon differential cross section at RPI for neutron energies from 0.5 to 20 MeV. The lab angles measured were 26, 52, 72, 90, 107, 119, 140, and 154º. The measurements are probably not of the accuracy that will impact a new evaluation. They can be used for quasi-differential benchmarking.

• Gritzay et al. data were shown at the last CSEWG Meeting. they have angular distribution data for 2, 59 and 133 keV. The data were taken at the Kyiv reactor using filered beams. The measurements were made at 30, 55, 90, 125 and 150º. They were measured relative to lead scattering but the shape should still be relatively good anyway. The measurements at 133 keV are shown in the next plot. The results differ from the carbon standard. In her last correspondence with me she indicated she was continuing this work and also looking at the 152.9 keV resonance seen in the carbon total cross section. Her previous work indicated that the resonance has a much larger neutron width than previously thought.

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.)

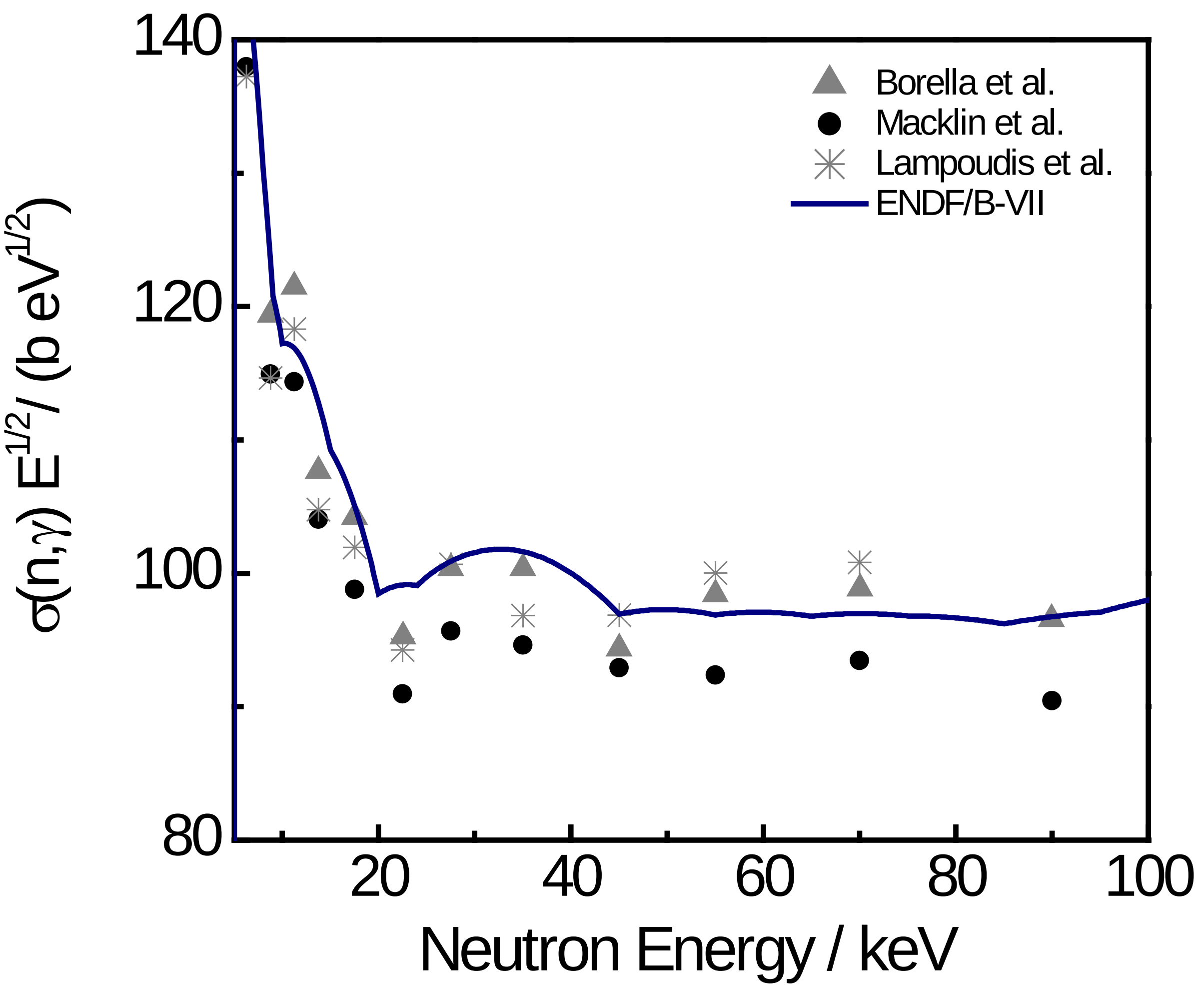
- New experiments on the $^{197}Au(n,\gamma)$ cross section

  - Wallner et al. using AMS with samples irradiated in a simulated Maxwellian neutron source spectrum of 25 keV mean energy obtained a ratio to the standards evaluation for gold capture of 1.05 ± 0.06 (obtained using his $^{238}U(n,\gamma)/Au(n,\gamma)$ cross section ratio and the $^{238}U(n,\gamma)$ cross section from the standards evaluation)

  - Lederer et al. reanalyzed n_TOF gold capture data of Massimi et al. and folded a simulated Maxwellian neutron source spectrum of 25 keV mean energy into that data. It agrees with the standards evaluation. The result with an uncertainty of 3.6% is smaller than the standards evaluation by 1%. It is 4.7% higher than the Ratynski evaluation.

  - GELINA Au(n,γ) cross section measurements by Borella et al. and Lampoudis et al. support the standards evaluation.

Au(n,γ) cross section measurements by Borella et al., Macklin et al. and Lampoudis et al. compared with the ENDF/B-VII evaluation



Au(n,γ) at low energies (cont.)

- New experiments on the $^{197}Au(n,\gamma)$ cross section (cont.)

    - Independently measurements for the $^{7}Li(p,n)^{7}Be$ neutron spectrum at Ep= 1912 keV at IRMM by Feinberg *et al*. using a proton beam energy spread of 1.5 keV showed consistent results with the original findings of Ratynski and Käppeler and of Lederer *et al*. These authors also confirmed, using a proton beam energy spread of 1.5 keV, the spectrum averaged Au(n,γ) cross section within the 1.4% uncertainty of Ratynski and Käppeler. They also made measurements using a proton beam energy spread of 15 keV and the same average proton energy. The spectrum averaged Au(n,γ) cross section for these measurements agrees with the results of the standards evaluation. The apparent inconsistency may be due to the different angular acceptances in the 1.5 keV measurements compared with the 15 keV measurements. These cross section results were only recently reported.

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, neutron irradiation data were obtained for this 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 keV FWHM) energy spread. That ratio, 0.99± 0.04, compared with the standards evaluation is in excellent agreement.

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

$^{235, 238}$U(n,f) and ^{239}Pu(n,f) Measurements

•There has been no new measurement activity since the last CSEWG meeting for these fission cross sections. Analyses of the two independent measurements of the ^{238}U(n,f)/^{235}U(n,f) cross section ratio by Calviani et al. and Audouin et al. made at the n_TOF facility are underway. Both sets of measurements tend to support the Lisowski *et al.* data somewhat better than the Shcherbakov *et al.* data. Lisowski has been investigating the hydrogen data used in converting his various ratio measurements to absolute cross sections. This work is on-going.

•The measurements of the ^{239}Pu(n,f) cross section by Tovesson and Hill at the WNR facility at LANL have been published. The data are relative to the ^{235}U(n,f) cross section. In the MeV energy 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.

^{239}Pu(n,f) Measurements

- Additional work on the ^{239}Pu(n,f) cross section in the MeV energy is expected from a collaboration initiated by staff at LANL, LLNL and INL 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.

Iron sphere measurements

•Work done in an Ohio University, NIST and University of Florida collaboration that was completed some time ago is now being published in Nuclear Science and Engineering. The work was done to provide information on the quality of the iron nonelastic cross section (which is dominated by the inelastic cross section).

•For spherical shell transmission measurements, if the source produces neutrons that have nearly the same energy and intensity at all angles, then the non-elastic cross section can be easily determined. Unfortunately, a source reaction with these properties does not exist.

•Neutron source studies led to the $^{15}N(p,n)^{15}O$ and $D(d,n)^{3}He$ reactions as the most suitable.

•The measurements were made with the Ohio University tandem accelerator. Spherical shell transmission data were obtained using time-of-flight techniques.

Iron sphere measurements (cont.)

•For the work with the $^{15}N(p,n)^{15}O$ source, measurements were made with a proton energy of 5.1 MeV. The neutron energy at zero degrees was 1.37 MeV.

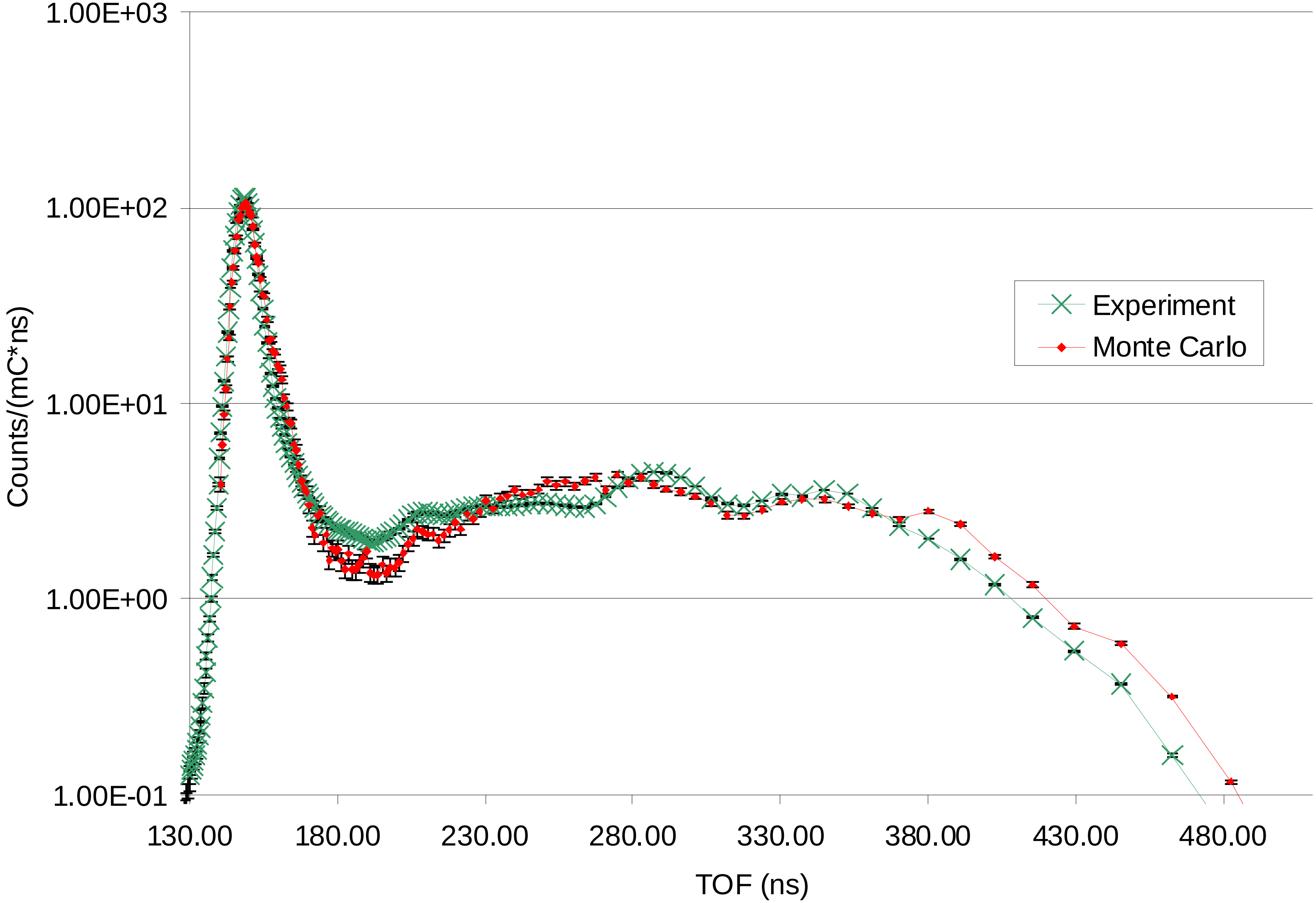
•For the work with the $D(d,n)^{3}He$ source, the measurements were made with deuteron energies of 3, 5 and 7 MeV. The respective zero degree neutron energies were 6.06, 8.13 and 10.08 MeV.

•For both source reactions, the angular range of the measurements was as large as 15 to 135 degrees. Two iron shell thicknesses (3 and 8 cm thick) were used.

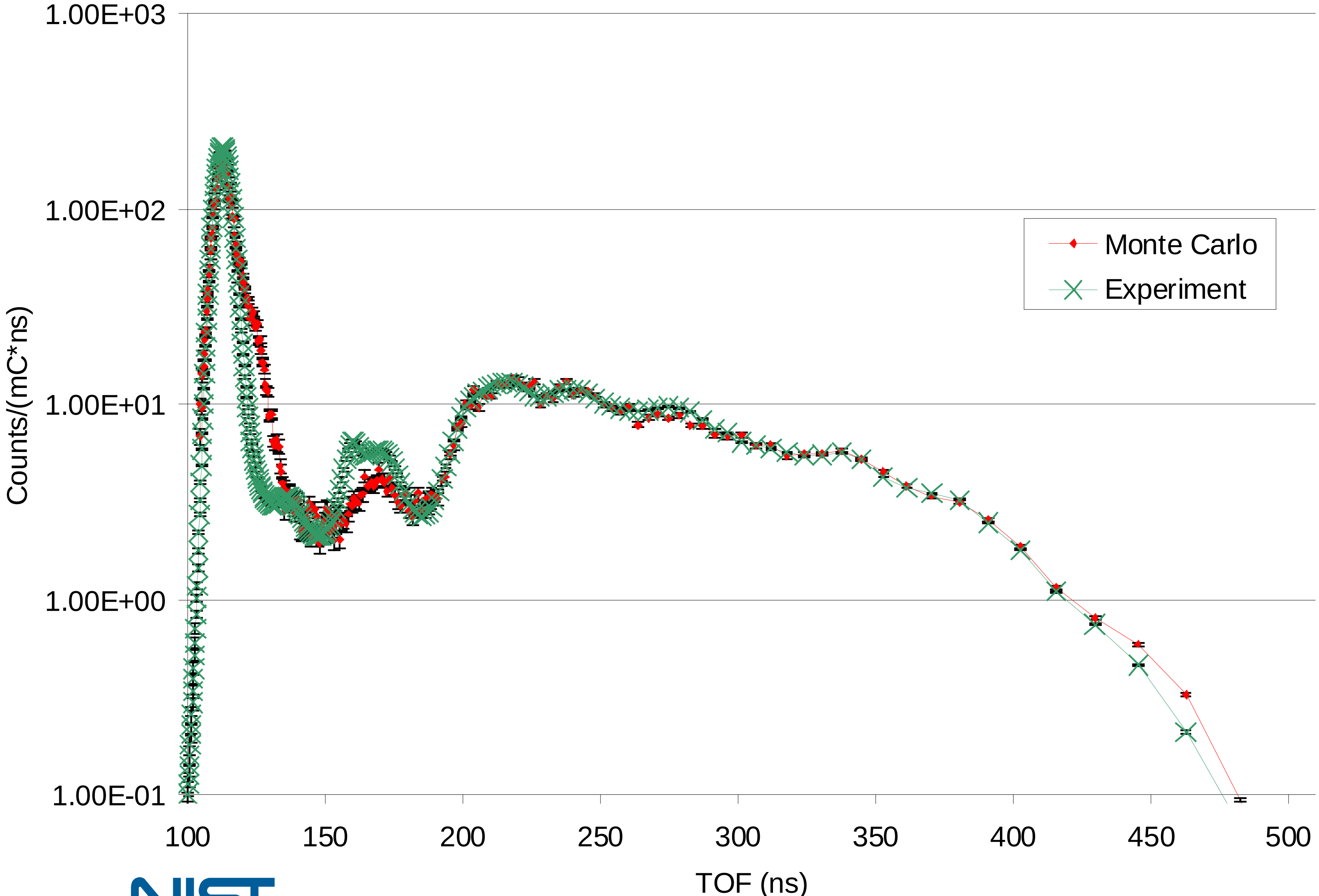
•From these data, iron total cross sections were determined for the energy intervals from 6.15 to 6.20 MeV and 8.16 to 8.21 MeV. They both agreed within a percent with the ENDF/B-VII evaluation.

•Comparisons were made between Monte Carlo predictions and the experimental data.

Comparison of 3 MeV D(d,n) Monte Carlo calculations and experimental data for the zero degree angle with the large iron shell



Comparison of 7 MeV D(d,n) Monte Carlo calculations and experimental data for the zero degree angle with the large iron shell



Iron sphere measurements (cont.)

- The experimental data can be used as benchmark data for comparison of iron cross section evaluations

- A crude attempt to improve the agreement between measurement and calculation was made by changing the inelastic cross section. To do this it was assumed that the difference between the spectra was due entirely to the inelastic cross section. The ^{56}Fe inelastic cross section was changed to improve agreement between the measured and calculated 3, 5 and 7 MeV D(d,n) zero degree spectra with the large sphere.

- The results suggest that the inelastic cross section should be changed by:

  -21% for neutrons near 6 MeV

  -29% for neutrons near 8 MeV

  -35% for neutrons near 10 MeV

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

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 .