NIST Measurements and Standards Including Related Work at Other Facilities

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THE NEUTRON CROSS SECTION STANDARDS

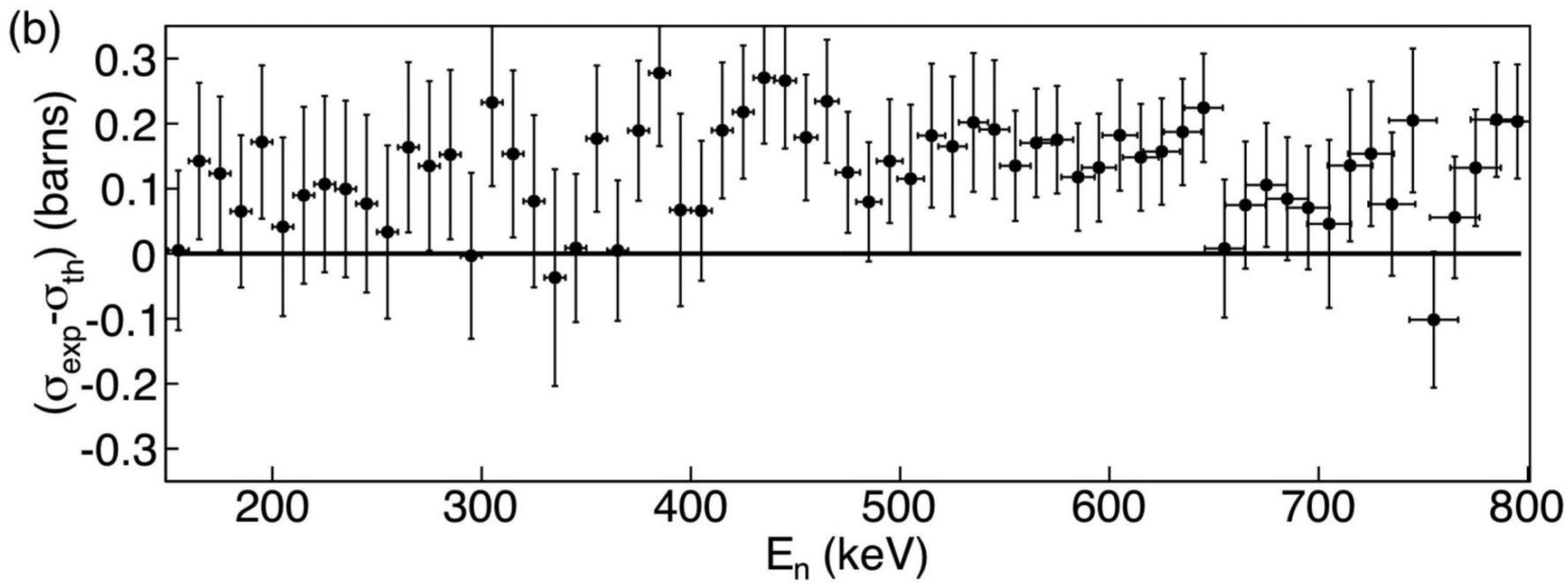
Reaction	Energy Range
H(n,n)	1 keV to 20 MeV
$^{3}He(n,p)$	thermal to 50 keV
$^{6}Li(n,t)$	thermal to 1 MeV
$^{10}B(n,\alpha)$	thermal to 1 MeV
$^{10}B(n,\alpha_1\gamma)$	thermal to 1 MeV
C(n,n)	thermal to 1.8 MeV
$^{197}Au(n,\gamma)$	thermal, 0.2 to 2.5 MeV
$^{235}U(n,f)$	thermal, 0.15 to 200 MeV
$^{238}U(n,f)$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

H(n,n)H Standard Measurements .

- Concerns about the hydrogen total scattering cross section at low neutron energies led to Van de Graaff work by Daub *et al.* from 150 keV to 800 keV. The results were systematically slightly larger than the ENDF/B-VII values but generally within their uncertainties of 1.1 to 2%. (Phys Rev C87, 014005 (2013)).

- Including these data in the
new hydrogen being done by Hale and Paris will cause a slight increase in the evaluated cross section. This would then lead to a somewhat better agreement with the Arndt Evaluation. Now the Arndt evaluation is larger than ENDF/B-VII by about 0.1% at low energies and about 1% at about 12 MeV.

Daub *et al.* Hydrogen Total Cross Section-ENDF/B-VII Evaluation



H(n,n)H Angular Distribution Measurements

- There is a problem with the quality of data at small CMS angles for hydrogen scattering. In order to improve the database of 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. Plans have also been made to do similar measurements for 10 MeV neutrons.

- To obtain the accuracy needed for this work, the neutron detector efficiency must be determined accurately.

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

- For our work, the detector efficiency is well known below about 6 MeV. For neutron detector efficiency determinations above that energy, a technique using reactions where the projectile and target are identical is being used. Because they are identical, the angular distribution **must** be symmetrical in the CMS. So the neutron yield at an angle Θ must be the same as that at 180- Θ in the CMS. But the energies of the neutrons are different in the LAB system. Thus in the LAB system, for a bombarding energy such that the backward portion of the angular distribution falls in the energy range below 6 MeV where the efficiencies are well known, we can deduce the efficiency for the higher energy group in the forward hemisphere.

- Our study of possible reactions indicated that the $^{6}Li(^{6}Li,n)^{11}C$ reaction would be the best for our use, however for the only suitable targets we successfully made, ^{6}LiF and $^{6}LiCl$, the backgrounds were very large. Measurements with C(C,n) were successful however the Q value of -2.6 MeV is a limitation. Targets are being made for a D(d,n) source. The Q value of 3.3 MeV will allow data to be taken at small angles for 10 MeV neutrons. Going to 14.9 MeV will require further study.

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

^{3}He(n,p) Measurements

- Progress continues on an experiment to measure the n-^{3}H coherent scattering length. This measurement is complementary to the n-^{3}He work. This measurement would constrain the fundamental nucleon-nucleon interaction models that underlie all of our cross section work. This work could help with Hale's R-matrix evaluation of the ^{3}He(n,p) cross section.

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

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

- A measurement has been completed of the $^{6}Li(n,t)$ cross section standard at ~ 4 meV neutron energy. This is the first direct and absolute measurement 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 $^{6}Li(n,t)$ cross section measurement is the mass uncertainty of the ^{6}Li target. The present mass uncertainty is about 0.25%. The deposits were made at IRMM. Studies have been made to compare the mass with the value obtained when it was characterized a number of years ago. Comparisons have also been made with a number of other deposits made at the same time at IRMM. It is expected that an ultimate 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.)

- 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. The ^{6}Li samples were supposed to be made by the end of October. They are using a digital data acquisition system for these experiments. Some data were obtained in June. GELINA was shut down July-October. Data taking was to resume in November. Six months of data taking are required.

- At the IRMM Van De Graaff facility Giorginis and Bencardino have made ^{6}Li(n,t) measurements at the IRMM Van De Graaff facility. They are using a one-dimensional 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 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.

^{6}Li(n,t) Measurements of Giorginis and Bencardino (cont.)

- Unfortunately Giorginis has retired (moved away from Geel) and Bencardino has accepted a permanent position with the European Commission. They are planning to return to IRMM for analysis of the data in November.

- With the TPC configuration used for the measurements, they could only determine the sum of kinetic energies of the reaction products. The two anodes of the twin 1D-TPC, were electrically connected so that they recorded only one energy signal. Angle information was thus suppressed in this way for the sake of simplicity.

- The thin LiF targets good separation between the fast and thermal neutron groups. Measurements with thinner targets to improve the separation could not be performed due to problems with the accelerator. For this reason some simulation work will be done to determine the the degree of overlap of the low energy tail of the fast neutron group with the thermal neutron group.

- They are hoping for a few percent accuracy for the cross section.

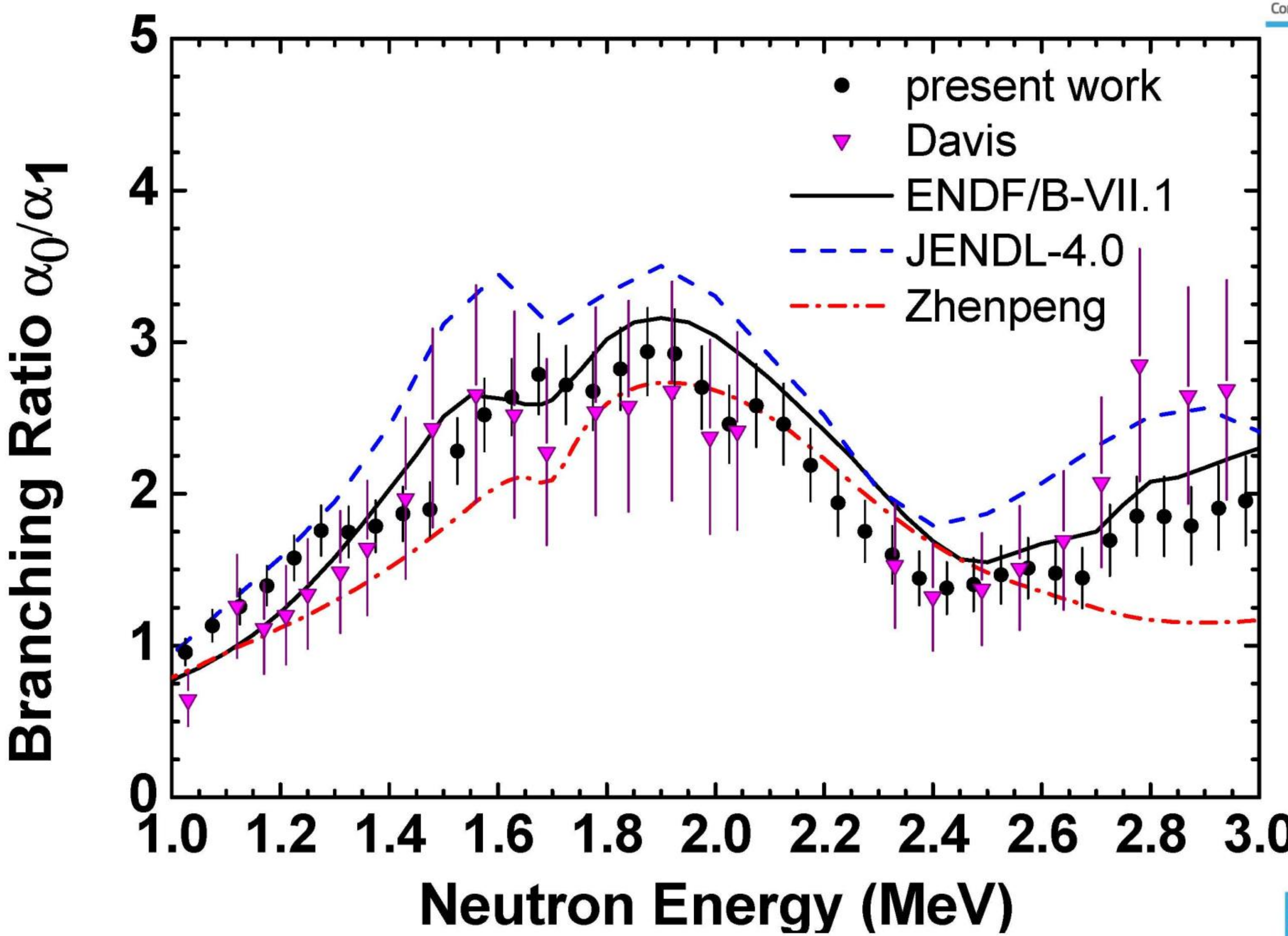
$^{10}B(n,\alpha)$ Measurements

- 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. He found problems with the branching ratio data from 1 – 2 MeV that he published in Nucl. Sci. Eng. 156 (2007) 111. He has taken improved data with very good statistics that cover that energy region.   The new branching ratio measurements in the 1-2 MeV energy region are now in better agreement with the ENDF/B-VI and ENDF/B-VII evaluations. That are presently analyzing the newly measured data.

IRMM Preliminary Measurements of the $^{10}B(n,\alpha)$ Branching Ratio

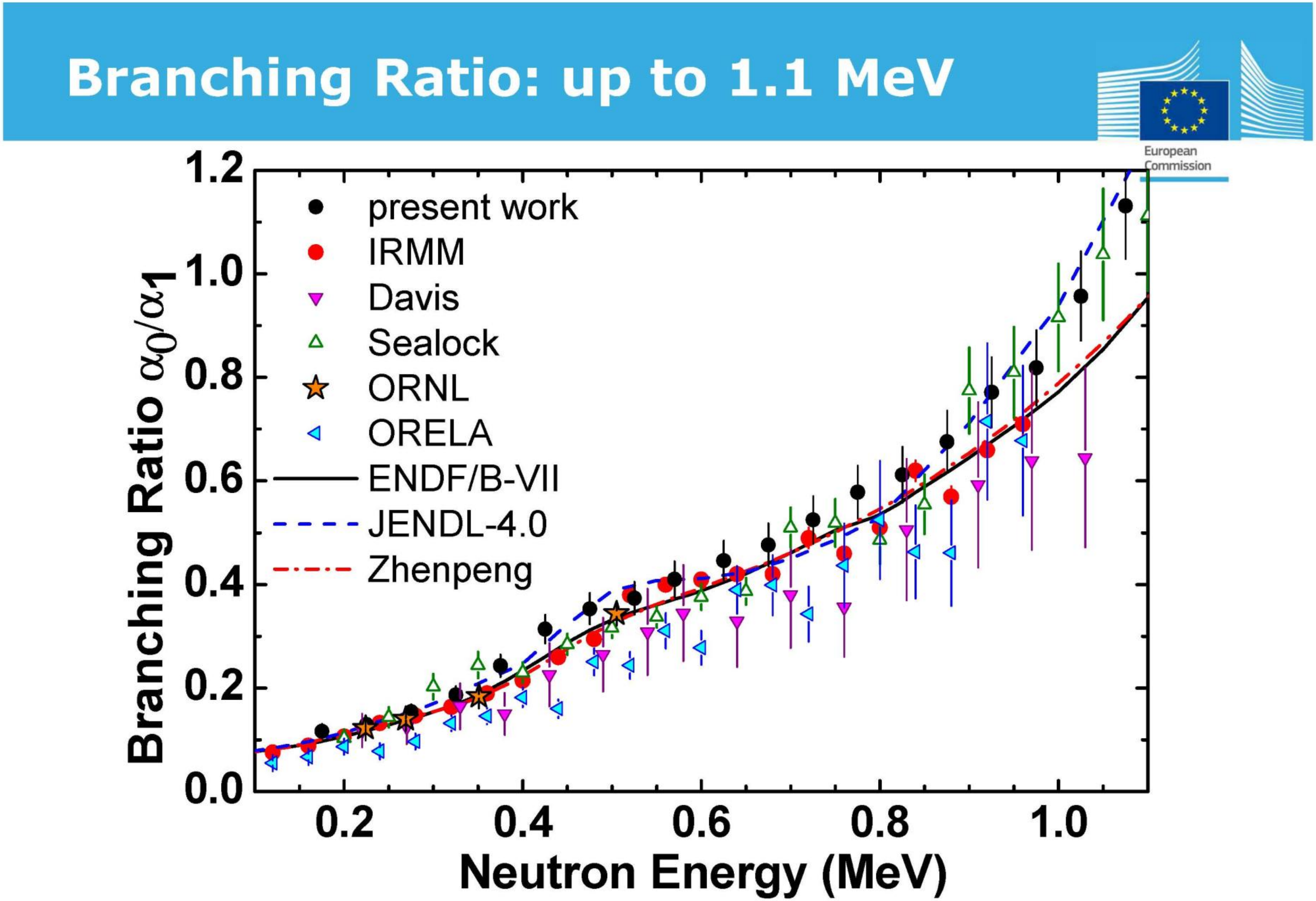
Branching Ratio: 1 to 3 MeV

European Commission



Joint Research Centre

IRMM Preliminary Measurements of the $^{10}B(n,\alpha)$ Branching Ratio



^{10}B+n Measurements

- Measurements have been made of the $^{10}B(n,\alpha_1)$, $^{10}B(n,\alpha_0)$, $^{10}B(n,p)$ and $^{10}B(n,t)$cross sections using four E-ΔE telescopes at WNR-LANL in a LANL-Ohio University collaboration. The neutron fluence was determined using a ^{238}U fission chamber.

- Due to the thickness of target, there was a problem separating the alpha groups. Also it may not be possible to separate the proton and triton groups. Analysis is being done now to see if the separation can be improved.
It is possible that only the $^{10}B(n,\alpha)$ cross section and the $^{10}B(n, p+t)$ cross section will be obtained from the new analysis The data extend to 5 MeV.

- It is not clear what impact this work may have on an R-matrix evaluation of the standards.

- A paper on this work, by Massey et al., shown as preliminary, was given at the ND2013 conference.

C(n,n) Data

- Gritzay *et al.* measured the carbon total cross section 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, with 1-2% uncertainties, at the lower energies their results are somewhat low and at 148 keV their result is about 5 standard deviations higher. They suggest that the resonance in ^{13}C at 152.9 keV may cause this increase. Further work is being done on this using modified filters.

However

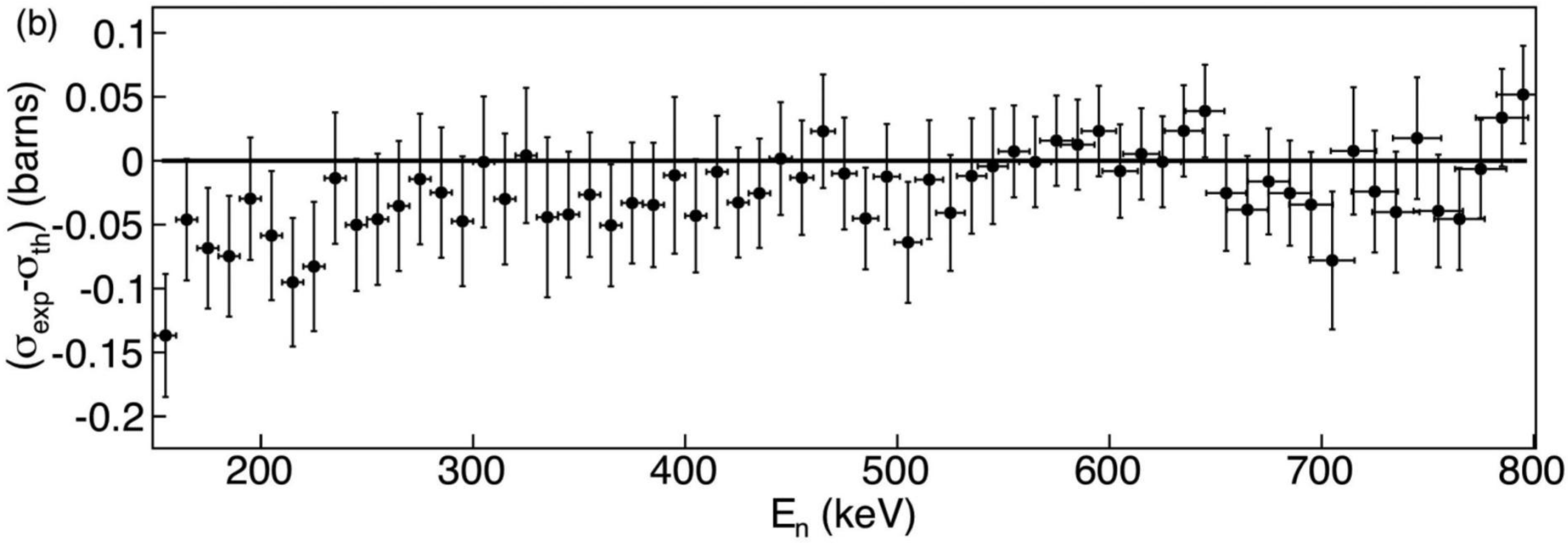
- Danon *et al.* made very accurate measurements of the carbon total cross section using an iron filtered linac neutron beam. The data were obtained for 19 peaks from 24.3 to 945 keV. This method provided very low backgrounds. The results obtained with an accuracy of better than 1% were in excellent agreement with the ENDF/B-VII evaluation.

- Anh *et al.* made total cross section measurements with reactor filtered beams at 54 and 148 keV that agree with the ENDF/B-VII.0 evaluation. The results were given at the ND2013 Conference.

Daub *et al.* Carbon Total Cross Section

- In addition to their work on the hydrogen total cross section, Daub *et al.* also made very accurate measurements of the carbon total cross section from 150 keV to 800 keV. The results were systematically very slightly lower than the ENDF/B-VII values but generally within their uncertainties of 1.1 to 2%. These data have already been put into the carbon evaluations being done by Hale and Young.

Daub *et al.* Carbon Total Cross Section – ENDF/B-VII Evaluation



C(n,n) Angular Distribution Data

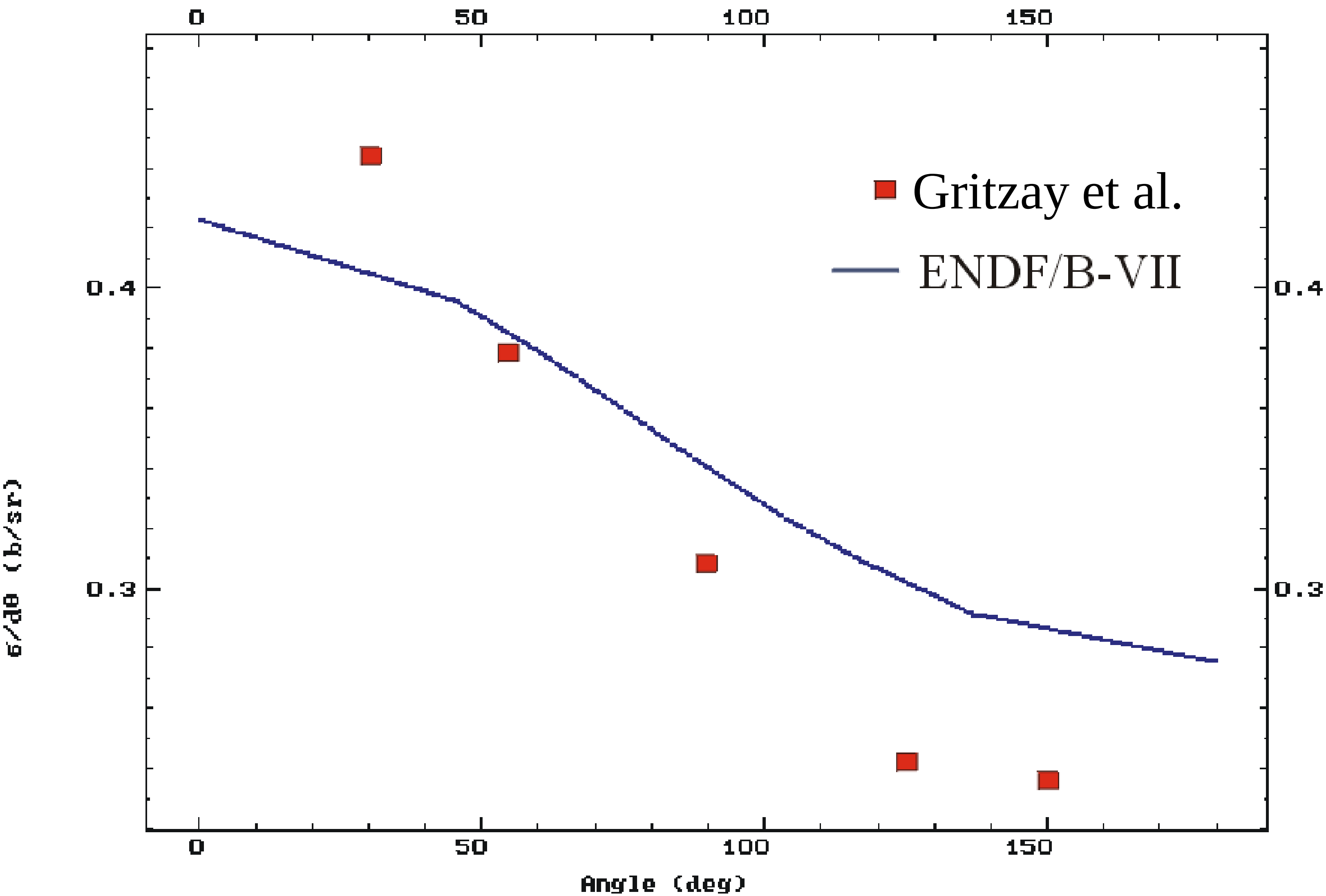
- Gritzay et al. data were shown at the last CSEWG Meeting. they have angular distribution data for 2, 59 and 133 keV. The data were taken at the Kyiv reactor using filered beams. The measurements were made at 30, 55, 90, 125 and 150º. They were measured relative to lead scattering but the shape should still be relatively good anyway.

- In her last correspondence she indicated she was planning on continuing this work. But her immediate effort is developing a new method for measuring the carbon total cross section in the 90 – 160 keV energy region that encompasses the 152.9 keV carbon resonance. Her previous work indicated that the resonance has a much larger neutron width than previously thought. The method she is using is called modified filtered beams. It involves making measurements with many different types of filters and analyzing the results. A paper on this work was given at the NPAE-2012 conference in Kiev.

- The measurements at 133 keV are shown in the next figure. The results differ from the carbon standard.

- Hale will be checking to see what effects the 152.9 resonance due to ^{13}C would have on this angular distribution measurement.

C(n,n) E_n =133 keV



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

- He had hoped to have the data finalized by now but he has had some setbacks. He plans to have the data available soon for use in the standards evaluation.

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

- Collaborative measurements have been made recently at GELINA and n_TOF using the same sample.

- At GELINA, Lampoudis And Gunsing made measurements using a C_6D_6 detector. Data were obtained from 10 keV to 1 MeV. The data are being analyzed.

- At n_TOF, measurements were made with a C_6D_6 detector by Mingrone et al. from thermal to about 500 keV. Data were also obtained with 40 BaF_2 detectors, (the Total Absorption Calorimeter, TAC), by Wright from about 0.3 eV to 100 keV. They anticipate that average values will be available from 20 keV to 1 MeV for that detector.

- Initial work by this collaboration was reported at the ND2013 conference. At the CIELO meeting this November, they reported TAC results up to 10 keV and C_6D_6 results up to 3 keV.

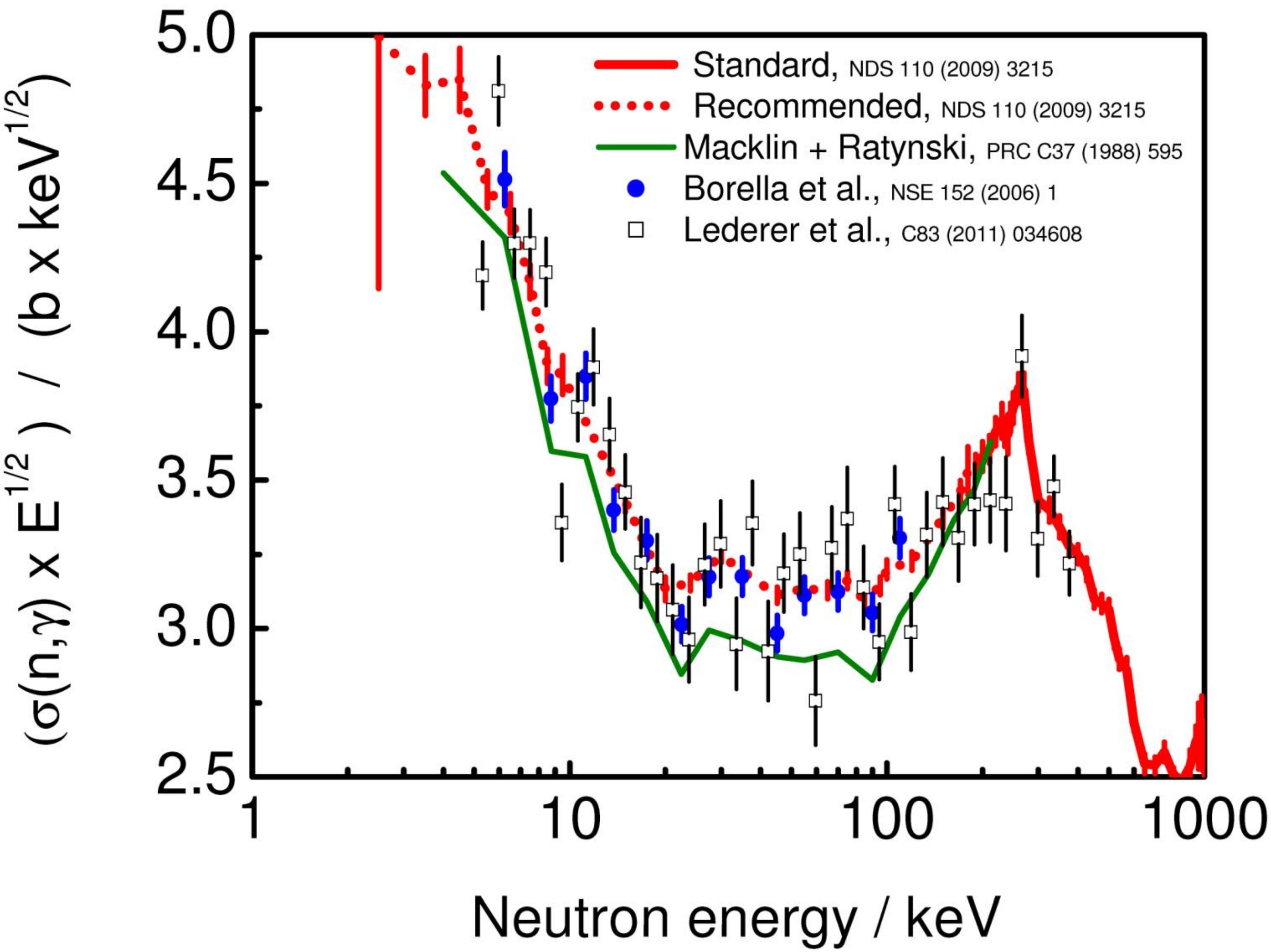
Additional Standards Work

- In order to improve the standards on a continuing basis, an IAEA Nuclear Data Development Project “Maintenance of the Neutron Cross Section Standards” was initiated.
  - This project has pursued improvements in the experimental database, considered additional standards, maintained evaluation codes and will periodically update the standards so they are available for new versions of data libraries. In addition to the conventional standards:
    - Work has been done on the gold cross section at energies below where it is considered a standard.
    - Reference cross sections for prompt gamma-ray production in fast neutron-induced reactions have been studied and the best candidates have been suggested.
    - An effort was directed at improvements in the evaluations of the ^{252}Cf spontaneous fission neutron spectrum and the ^{235}U thermal neutron fission spectrum

Au(n,γ) Data at Low Neutron Energies

- Au(n,γ) reference cross section for capture cross section measurements for astrophysics (below the standards energy region)
  - The measurements cited below all support the results of the standards evaluation. They indicate the Ratynski and Käppeler results are low by about 5-7% from 15 to 25 keV.
    - 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
    - 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.

Low Energy Au(n,γ) Cross Section Measurements and Evaluations



Prompt Gamma-Ray Production Reference Cross Sections

- Reference cross sections for measurements of prompt gamma-ray production cross sections.
  - Many nuclides and reactions were considered
    - ^{nat}Ti with large yields of two gamma-lines, 984 keV from ^{48}Ti(n,n'γ) and 160 keV from ^{48}Ti(n,2nγ) and ^{47}Ti(n,n'γ) reactions appears to be one of the most suitable for use as a reference cross section. More work needs to be done to improve the experimental database.
      - New measurements by Nelson using GEANIE have been made and are being analyzed.
      - An improved evaluation by Simakov has been done.
    - Li(n,n'γ) also appears to be a reasonable candidate
      - New measurements have been made by Nelson with GEANIE
      - There is little high quality data at higher neutron energies except the Nelson work

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 in the 10-15 MeV energy region.

  - H(n,n) at intermediate and high energies where data are sparse and typically not available for a large angular range.

  - 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 .

  - More work should be done on prompt gamma-ray reference cross sections and the gold capture cross section at low energies.

- The standards should be at the forefront, producing high accuracy cross sections including energy regions that may shortly require improved standards. It is short sighted to not have quality standards whenever/wherever they may be needed.