Database work for the new cross section standards evaluation

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Abstract. An effort is now underway to produce a new evaluation of the neutron standards. It is important to maintain experimental programs to increase the quality and extend the database for the neutron cross section standards in order to improve evaluations of them that will be used to convert cross section measurements made relative to those standards. Measurements have been made for most of the standard cross sections since the last evaluation of the standards. The improved database includes the cross sections for the H(n,n), ^{6}Li(n,t), ^{10}B(n,αγ), ^{10}B(n,α), C(n,n), Au(n,γ), ^{235}U(n,f) and ^{238}U(n,f) standard reactions and ratios among them. The database also includes the ^{238}U(n,γ) and ^{239}Pu(n,f) cross sections in addition to the standard cross sections. Those data were included since there are many ratio measurements of those cross sections with the standards and absolute data are available for them.

1 Introduction

There is a need for improved neutron cross section standards. These standards are the basis for the neutron reaction cross section databases. They are used by experimenters in converting measurements made relative to the neutron crosss section standards. They are also used by evaluators in similar situations. The standards are shown in Table 1. Only a few measurements can be made without the use of standards. They include neutron total cross sections and a number of absolute cross section measurements.

Table 1. Neutron Cross Section Standards

Reaction	Standards incident energy range
H(n,n)	1 keV to 20 MeV
^{3}He(n,p)	0.0253 eV to 50 keV
^{6}Li(n,t)	0.0253 eV to 1 MeV
^{10}B(n,α)	0.0253 eV to 1 MeV
^{10}B(n,$\alpha_1\gamma$)	0.0253 eV to 1 MeV
C(n,n)	10 eV to 1.8 MeV
Au(n,γ)	0.0253 eV, 0.2 to 2.5 MeV, 30 keV MACS
^{235}U(n,f)	0.0253 eV, 7.8 to 11 eV, 0.15 to 200 MeV
^{238}U(n,f)	2 MeV to 200 MeV

Work has been done on all the neutron cross section standards since the last standards evaluation [1] except the ^{3}He(n,p) reaction. In many cases the results of the new measurements are in good agreement with the standards values. Such data are still very valuable since they confirm the standards values and can possibly improve the uncertainty or covariance information. In addition to the experimental efforts, work has been done by Neudecker, *et al*., [2] on updating covariances of experiments in the neutron standards database. The initial updating was done on the ^{239}Pu(n,f) database. The work was focused on helping evaluators in identifying missing or suspiciously low uncertainties and missing correlations between uncertainties of the same and different experiments when estimating covariances for measurements entering their evaluations. Also work has been done on unrecognized sources of uncertainties [3] in experimental nuclear data. Inconsistencies in data have led to the speculation that for many (if not all) experiments of a given type there exist signicant unrecognized (unknown) experimentally related sources of uncertainty that cannot be eliminated by repeated measurements using the same analysis. Efforts are also underway for revisions of the thermal neutron constants [4]

2 Recent work on the neutron cross section standards database

There are a number of measurements of the neutron cross section standards that have been made since the last evaluation of the standards. Due to space limitations, only new measurements that will have an impact on evaluations will be shown here.

2.1 The H(n,n) cross section

This cross section is one of the most important neutron cross section standards. It is a primary standard. It is absolute. The total cross section is a standard and it is measured with a transmission measurement so it does not depend on a neutron fluence measurement. Angular distributions can be measured relatively and the integral of the differential data can be normalized to the total

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cross section. Thus it also is determined independent of fluence measurements. Many standard cross section measurements are made relative to the hydrogen standard. Thus they become absolute measurements since they are not dependent on a fluence measurement. Improvements of the hydrogen scattering cross section are important to increase the quality of this standard and also for a better understanding of the nucleon-nucleon interaction.
One of the first measurements of the total cross section of hydrogen in the MeV energy range was made by Bailey [5] during the Manhattan Project. Those data were used for the first time to make fission cross section measurements relative to hydrogen scattering.

The most recent measurement of the differential cross section for hydrogen scattering was done by Jiang *et al* [6]. The data extend over the energy range from 6 to 52 MeV with 23 energy points. They are relative measurements made with 10 ΔE-E detectors for the angular range from 70.0º-159.8º .The data were obtained using the China Spallation Neutron Source (CSNS). The

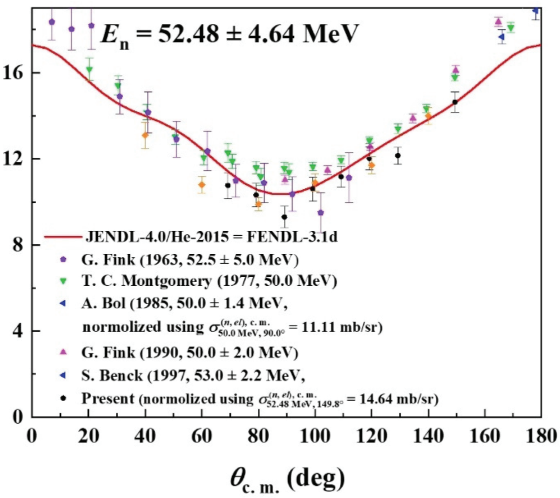

Fig. 1. H(n,n) angular distribution by Jiang *et al*. at the highest energy for their work.

angular distribution at the highest energy for the Jiang *et al* work is shown in Figure 1. The measurements agree well with existing measurements, evaluations and theoretical calculations. The hydrogen standard is limited to 20 MeV at the present time. The Jiang *et al.* data combined with the database being developed by Paris and Hale at LANL will allow an evaluation with an extended energy range to be produced. The present results of the LANL work extend up to 100 MeV with the objective of extending the evaluation to 350 MeV. There is interest in providing an extended energy range for this standard now. However complications with matching the new evaluation with the existing standard indicate it would be better if incremental increases in the hydrogen standards energy region not be made. Instead improvements will wait until the next version of the standards is done. Then a single R-matrix evaluation will be done for the full energy range possible; but it is important to ensure that the new cross section below 20 MeV agrees quite well with the previous standard values.

The final work on the hydrogen scattering angular distribution by the Ohio University collaboration has now been published [7]. The work emphasizes the small angles in the center-of-mass system at 14.9 MeV where very little data are available. This work required detection of the scattered neutrons in order to make measurements at small CMS angles. The scattering angle varied from 20 degrees to 65 degrees in the laboratory system in 5 degree incremental steps. The results are in excellent agreement with the latest standards evaluation but there is a slight trend toward lower values at small CMS angles.

2.2 The ^{6}Li(n,t) cross section

This standard is now limited to 1 MeV as the highest energy for which it can be used. An improved evaluation of this standard that extends to 2 or 3 MeV would allow a convenient overlap with the hydrogen standard.

Measurements were made by Bai *et al*. [8] at the CSNS of this cross section. The data extend from 1 eV to 3 MeV with 80 energy groups and angular distribution measurements at each energy group for 15 angles between 19.2 and 160.8 degrees. Those data were normalized to the present standard in the interval from 0.1 to 0.4 MeV. The data appear to be overall the most complete, and best-quality, set of relative differential cross sections for the ^{6}Li(n,t) reaction that presently exists at energies below 3 MeV. There are some complications with these data. The neutron energy spectrum was not measured at the position of the experiment. It is expected that this will affect the cross section values. It will not affect the angular distributions. There are deviations from an isotropic angular distribution in the eV energy region. Some of these problems may be due to the use of the ^{235}U(n,f) cross section for determining the neutron fluence in regions where it is not a standard and not smooth. Also the integrated cross sections are below the standard for energies above 0.5 MeV, but within uncertainties. The magnitude of the cross section at the resonance peak differs from expected values. The agreement with the standard in many regions is relatively good.

Preliminary measurements are being made by Anastasiou [9] of the ^{235}U(n,f)/^{6}Li(n,t) cross section ratio with the NIFFTE fission TPC. The expected energy range is from about 0.1 MeV up to 3 MeV (possibly 4 MeV). The data will impact evaluations of both the ^{235}U(n,f) and ^{6}Li(n,t) cross sections. Some results of this work were given by at this conference. The preliminary results agree with the standards evaluation and indicate a rise in the ratio above 1 MeV compared with the ENDF/B-VIII.0 evaluation.

Mumm reported on NIST measurements of the ^{6}Li(n,t) cross section at this conference [10]. This is the first direct and absolute measurement of this cross section for cold mono-energetic neutrons. A primary effort was focused on measuring the neutron fluence accurately. It was determined with an uncertainty of 0.06%. Most of the uncertainty in the cross section measurement is from the uncertainty in the ^{6}Li mass. Using the mass determination provided by IRMM led to a cross section determination with an uncertainty of

0.3% that is 1% lower than the standard's value. Concerns about the IRMM mass value has led to an effort to re-determine accurately the mass of that sample at NIST using sample intercomparisons and Isotope Dilution Mass Spectrometry. The pandemic has slowed down progress in this area.

2.3 Work on the $^{10}B(n,\alpha)^7Li/^6Li(n,t)^4He$ cross section ratio and ^{10}B+n cross sections

A very complete set of measurements of the $^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1)$ angular distributions was made at the CSNS by Jiang *et al.* [11]. The data cover the energy range from 1 eV to 2.5 MeV. For this experiment and the one by Bai *et al*. [8] on the $^6Li(n, t)$ cross section, the measurements were made at the same flight path. The experimental conditions for the two reactions were the same (same detectors, electronics, sample holder and neutron fluence). Thus the problems associated with the use of the $^{235}U(n,f)$ cross section for determining the fluence, which produced significant uncertainties due to the structure in that cross section below the region where it is a standard, were removed by taking a ratio [12] of the two sets of cross sections. It has been decided that the angular distribution data for

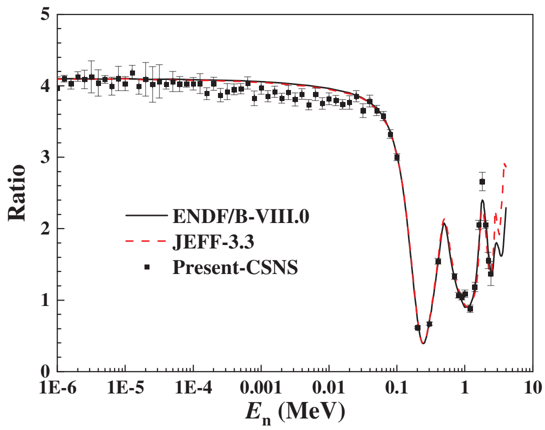

Fig. 2. Liu *et al.* ratios of the angle-integrated cross sections for $^{10}B(n, \alpha)^7Li$ divided by those of $^6Li(n, t)^4He$ vs energy.

these two experiments, unnormalized, will be analyzed using R-matrix techniques. The ratio data shown in Figure 2 will be analyzed using a Python [13] based analysis (based on the GMA analysis formerly used)

Massey *et al*. [14] measured differential cross sections for the $^{10}B(n,p_0)^{10}Be$, $^{10}B(n,p_1)^{10}Be$, $^{10}B(n,t_0)^8Be$, $^{10}B(n,t_1)^8Be$, $^{10}B(n,\alpha_2)^7Li$, and $^{10}B(n,\alpha_3)^7Li$ reactions for neutron energies from 2 to 20 MeV. The work was done at the LANSCE WNR facility where proton, triton and alpha particles were measured at four angles. Also several measurements of the $^{10}Be(p,n)^{10}B$ reaction were made by Massey and Jones-Aberty at Ohio University. The preliminary data include two angular distributions at 2.5 and 3.5 MeV. All of the Massey work involves the ^{11}B compound nucleus, thus it will have an impact on the boron standards.

Extension in the energy ranges to above 1 MeV of the $^6Li(n,t)$ and ^{10}B standards may be possible with the $^{235}U(n,f)/^6Li(n,t)$ cross section ratio work of Anastasiou, the CSNS measurements of Bai *et al*. and Jiang *et al*. and the Massey *et al*. data.

2.4 C(n,n) cross section

The most recent evaluation of the carbon standard was done by combining ^{12}C and ^{13}C R-matrix evaluations to obtain the elemental cross section, that is the standard. That evaluation is almost 2% higher than the previous standard at the highest energy where it is a standard. Danon at RPI made total cross section measurements in the 150 to 400 keV energy region. Those data with uncertainties from a fraction of a percent to about 1% are in better than 1% agreement with the earlier standard. The basic difference in the standards is due to the addition of ^{13}C data. New ^{13}C scattering measurements are now underway at the University of Kentucky by Vanhoy [15] in the standards energy region.

2.5 Fission cross section measurements

Progress on absolute measurements of the $^{235}U(n,f)$ cross section relative to hydrogen scattering by the n_TOF collaboration were reported at this conference. Plans are for results to be eventually available from 20 MeV to about 1 GeV. The analysis of the data from 20 MeV to 200 MeV was discussed by Pirovano *et al*.[16]. These results appear to agree with the standards. The author expressed some concerns about corrections for some of the detectors. The systematic uncertainties are estimated to be 3-5%. The data analysis above 200 MeV up to 500 MeV were given by Manna *et al*. [17]. The preliminary results shown are in fairly good agreement with the high energy $^{235}U(n,f)$ reference cross section [18]. Improved modelling is underway. Further campaigns with ^{235}U are planned with the aim to improve the statistical accuracy and extend the energy range to higher energy. A limitation for their work using hydrogen scattering at higher energies is how to handle hydrogen inelastic scattering due to pion production since both elastic and inelastic neutrons are present. The present $^{235}U(n,f)$ cross section standard is limited to 200 MeV. There is a strong need for an extension to higher neutron energies that may be possible with these data.

Preliminary measurements, relative to the hydrogen scattering standard of the $^{235}U(n,f)$ and $^{238}U(n,f)$ cross sections from 10 to 66 MeV have been made at the CSNS by Chen [19] *et al.*. The data were shown as measurements normalized to the $^{235}U(n,f)$ standard at 14.5 MeV at this conference. They plan to have absolute data eventually. The present results are from 10 to 66 MeV with plans to extend the enery range to 100 MeV. They express some concern as to what evaluated hydrogen scattering cross section should be used for converting their ratio data. Both sets of data are generally in good agreement with the standards results with possible differences in the 20 MeV energy region.

Absolute measurements of the $^{238}U(n,f)/\ ^{235}U(n,f)$ cross section ratio were made by Wen *et al.* [20] at the CSNS for neutron energies from 1 to 20 MeV. They agree with the standards results within their uncertainties. The uncertainties are rather large from 1

MeV to 1.4 MeV where the ^{238}U(n,f) cross section is changing very rapidly.

The Casperson *et al.*, [21] NIFFTE collaboration, measurements at LANSCE of the ^{238}U(n,f)/^{235}U(n,f) cross section ratio extend to 30 MeV. They were normalized at 14.5 MeV to the present standards values. The agreement is quite good with the standard except in the region between 2 and several MeV where their results are approximately 1% low compared with the standard but generally within it's uncertainties.

The original ^{239}Pu(n,f)/^{235}U(n,f) cross section ratio measurements by Snyder *et al*. [22] made at LANSCE by the NIFFTE collaboration are higher than the standards evaluation by about 2%. They agree in shape with the standards evaluation. They have recommended that these data be used as ratio shape data. New measurements [23] with an improved sample by this collaboration were discussed at this conference. Though the normalization of these data has not been defined, the ratio shape results are close to their previous result.

Also measurements [24] have been made of the ^{239}Pu(n,f)/^{6}Li(n,t) cross section ratio with the NIFFTE fission TPC. These data will impact evaluations of both the ^{239}Pu(n,f) and ^{6}Li(n,t) cross sections. At the lower energies these measurements may help define the normalization of the shape of the ^{239}Pu(n,f) cross section and give information about the 2% difference between the NIFFTE and standard's results for the ^{239}Pu(n,f) /^{235}U(n,f) cross section. These data are not finalized.

An analysis by Neudecker [25] was done to compare two GMA evaluations differing only by the addition of the ^{238}U(n,f)/^{235}U(n,f) [21] and ^{239}Pu(n,f)/^{235}U(n,f) [22] data sets to one evaluation. Except for changes below 1.5 MeV for ^{238}U(n,f) at the 0.5% level, the only significant changes were observed above 10 MeV for the ^{239}Pu(n,f) cross section and ^{239}Pu(n,f)/ ^{235}U(n,f) cross section ratio which were as large as 2% lower. This change is still within the GMA uncertainties. This indicates that the fission TPC data using an entirely new technique validates the results of the existing database.

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