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NEUTRON STANDARD DATA

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Abstract: The neutron standards are reviewed with emphasis on the evaluation for ENDF/B-VI. Also discussed are the neutron spectrum of ^{252}Cf spontaneous fission, activation cross sections for neutron flux measurement, and standards for neutron energies greater than 20 MeV. Recommendations are made for future work.

[neutron standards, ^{6}Li(n,t), ^{10}B(n,α), ^{235}U(n,f), ^{197}Au(n,γ), ^{252}Cf sp. fission, H(n,n), ^{27}Al(n,α), ^{59}Co(n,2n), ^{93}Nb(n,2n)^{92m}Nb]

Introduction

Neutron standard data are important to neutron reaction studies because of the difficulties encountered in determining a flux of uncharged particles. To compensate, neutron experimenters have emphasized absolute measurements on a few "standard" cross sections that can be most reliably determined and "implemented" in simple instruments. Ideally, such instruments uniquely identify all the nuclear reactions corresponding to the cross section. Other cross sections can be measured relative to a standard by placing appropriate samples in the same unknown flux.

Standard cross sections have been remeasured and evaluated for decades with slowly changing best estimates of values and uncertainties. Table 1 lists the neutron reaction cross sections accepted as standards by both the International Nuclear Data Committee (INDC) and the Nuclear Energy Agency Nuclear Data Committee (NEANDC);[1] most are considered as standards only for restricted incident energy regions within which they are smooth and have well-known values.

These criteria have been met for the light-element standards by fitting parameters of applicable theory to experimental data. For the heavy-element standard reactions ^{197}Au(n,γ) and particularly for ^{235}U(n,f), theory has played only a minor role in the determination of best cross section values. These cross sections are considered as standards at energies high enough for fluctuations to be unimportant. These important reactions, with others such as ^{238}U(n,γ) and ^{239}Pu(n,f) that are not considered as standards, have been measured using a remarkable variety of absolute and relative techniques. Direct evaluation using data plots is certain to lose information.

The present paper covers the process used for evaluating standard cross sections for ENDF/B-VI, and shows some results though full documentation is not yet available. This new evaluation is under consideration as a possible international standard. Recent progress on the ^{252}Cf spontaneous fission prompt neutron spectrum is described. Standard activation cross sections that have become important for neutron dosimetry are then discussed. Finally, extension of the reference cross section concept to energies higher than 20 MeV is considered.

Table 1. Neutron Reactions Having Cross Sections Accepted As Standards By The NEANDC And The INDC[a]

H(n,n)H	
^{6}Li(n,t)^{4}He	
^{10}B(n,α)^{7}Li	
the 2.2 km/s cross sections of major actinides	
^{235}U(n,f)	^{197}Au(n,γ)
^{238}U(n,f)[b]	^{27}Al(n,α)[b]

[a]The C(n,n) cross section is also a standard, but is not considered in this paper.
[b]The cross sections for these reactions are not considered as standards by the US Cross Section Evaluation Working Group (CSEWG).

Global Evaluation Of Standard Cross Sections

Background

A traditional approach to standards evaluation within the US Cross Section Evaluation Working Group (CSEWG) was to establish the hierarchy of cross sections shown in Table 1.[2] The cross sections on each line in the table were taken as more nearly absolute than those on the next; this assumption allows the data base to be unfolded. In evaluating the fission cross section of ^{235}U, for example, one could combine absolute measurements on that cross section with the results of ratio determinations to any of the standards higher on the list. The evaluations of the higher-level cross sections were not affected; the hierarchical evaluation strategy suffered from this logical inconsistency. For another example, combining absolute measurements of the $\sigma_{nf}(^{239}Pu)$ cross section together with ratios of $\sigma_{nf}(^{239}Pu)$ to $\sigma_{nf}(^{235}U)$ could not lead to improved values of $\sigma_{nf}(^{235}U)$.

The difficulties with the hierarchical evaluation strategy and the successes already realized using comprehensive objective data combination techniques[3] led to selection of a more global approach for ENDF/B-VI than had been used earlier. In such "objective" techniques one relies on least-squares or similar procedures to combine the input data consistent with experimental uncertainties. Each experiment must be evaluated in detail to represent it fairly in the combination program.

The CSEWG sought an evaluation method for ENDF/B-VI standard cross sections that could accept the full information content of the data base.[2] The method should: a) evaluate standards and other well-known cross sections with the same procedure; b) include absolute and ratio data on the same basis as they were measured; c) retain fits to theory where possible [H(n,n), ^{6}Li(n,t), and ^{10}B(n,α)] to assure smoothness and consistency and to include pertinent data from charged-particle reactions; d) use average cross sections over selected intervals, at energies too low for the heavy-element cross sections to be sufficiently smooth, to take advantage of data sets that extend down to thermal energies; e) incorporate a completed "thermal" (2.2 km/s) cross sections evaluation; f) provide output covariance data consistent with a cross section evaluation that weights input data with the inverse of its variance-covariance matrix; g) combine if possible the evaluation at thermal energies with resonance evaluations containing data as a function of energy.

The generalized least squares technique, in the GMA program already demonstrated by Poenitz,[3] offered assurance that all criteria except c) and g) could be met. Earlier applications by Hale[5] of his R-matrix code EDA to the light-element standards indicated that the theoretical fits could be obtained if a way could be found properly to include ratio data among cross sections of different nuclides. Goal g) was finally abandoned for ENDF/B-VI.

Approach for ENDF/B-VI

For ENDF/B-VI, the CSEWG Standards Subcommittee retained the hierarchical strategy to the extent that measurements relative to the n-p scattering cross section were treated as if they were absolute. It was believed that the uncertainties in the n-p scattering cross sections would not be important. A nucleon-nucleon cross section evaluation of Dodder and Hale[6] was later adopted to represent n-p scattering for ENDF/B-VI.

A joint evaluation was undertaken for the reactions listed in Table 2. In principle, goals a) through f) could be met using a hypothetical grand fitting program that would use all experimental data involving these reactions. The output for the ^{7}Li and ^{11}B compound systems would be R-matrix parameters, while average cross sections at many energies would be output for the heavy-element cross sections. A grand fitting program was not implemented; it seemed infeasible to combine the GMA and EDA programs.

It was noted[7] that, if independent data segments were input to the EDA and GMA programs, the equivalent of the above grand combination could be achieved using arrays obtained from these programs. Calculations that required transfer of large data files among the installations of the three participants were awkward at the time. Therefore, the initial estimates of the output variables would have to be sufficiently close that a single iteration would suffice.

Table 2. Cross Sections Included In The ENDF/B-VI Combined Evaluation.[a]

^{6}Li(n,t)^{4}He and ^{6}Li(n,n)
^{10}B(n,α_0)^{7}Li, ^{10}B(n,α_1)^{7}Li*, and ^{10}B(n,n)
^{197}Au(n,γ)[b]
^{238}U(n,γ) and ^{238}U(n,f)
^{235}U(n,f)
^{239}Pu(n,f)
^{233,235}U and ^{239,241}Pu 2.2 km/s parameters
$\bar{\nu}$ of ^{252}Cf

[a]The light-element standards were represented by R-matrix parameters.
[b]The 2.2 km/s ^{197}Au(n,γ) cross section was not a variable in the Axton work[8] from which most of the thermal data were drawn.

ENDF/B-VI Implementation of a Global Approach

The multilab task group that performed the evaluation has reported previously.[2,4] Experimental data of all types[3,4] were divided into two independent segments; data in Segment 1 were not correlated with data in Segment 2. Segment 1 included independent subsets for the ^{7}Li and for the ^{11}B compound systems, each of which was fit by G. Hale using the R-Matrix program EDA[5] to obtain parameters that give the neutron cross sections well beyond the standards region. The data of Segment 2, in two independent subsets, were fit together by W. Poenitz using his data combination code GMA mentioned above. The output thermal parameter set from the thoroughly documented evaluation of Axton[8] comprised one input subset. The other subset was a pointwise representation of essentially all other average cross section absolute and relative measurements on the reactions in Table 2, including some data sets involving n+^{6}Li and n+^{10}B. The fission cross sections were included through 20 MeV. Altogether about 9300 data points were fit with 109 R-matrix parameters and 935 pointwise average cross sections, 565 of these for other than the boron and lithium reactions.

For the combination process, the fitting variables in the least-squares minimization were small changes in the R-matrix parameters (ε_{LR} and ε_{BR}) for the lithium and boron reactions and small relative cross section changes (ε_P) for the heavy elements. For simplicity in writing the equations below, the Axton set is not explicitly recognized and only the lithium R-matrix fit is represented. The least-squares equation[9] can be written for this case in terms of submatrices:

$$\left[\begin{pmatrix} Q_{1L} & 0 \\ 0 & 0 \end{pmatrix} + S^t\, Q_2\, S\right]\begin{pmatrix} \varepsilon_{LR} \\ \varepsilon_P \end{pmatrix} = S^t\, R_2 \quad . \qquad (1)$$

The matrix Q_{1L} is the inverse of the R-matrix parameter covariance matrix for the Segment 1 lithium data,

$$R_2 = \begin{pmatrix} G_{2L}{}^t \\ G_{2P}{}^t \end{pmatrix} V_2^{-1}\, \eta_2, \quad S = \begin{pmatrix} S_L & 0 \\ 0 & 1 \end{pmatrix} ,$$

and

$$Q_2 = \begin{pmatrix} G_{2L}{}^t \\ G_{2P}{}^t \end{pmatrix} V_2^{-1}\, (G_{2L},\ G_{2P}) \quad .$$

The matrix V_2 is the variance-covariance matrix of the Segment 2 input data. The elements of G_{2L} and G_{2P} are the partial derivatives of the approximation equations, corresponding to each Segment 2 reduced input datum, with respect to relative changes in the pointwise cross section parameters. The reduced data vector η_2 contains the differences between the experimental data, reduced to a fixed energy grid, and the initial estimates derived from the zero-order parameter values. Finally, the elements of S_L are the logarithmic derivatives of the pointwise interpolated cross sections for the ^{7}Li system with respect to its R-matrix parameters; these were obtained from the R-matrix equations at the Segment 1 solution point.

Equation (1) was solved for the 674 elements of ε. The output covariance matrix propagating the input data uncertainties and correlations is the inverse of the matrix on the left side. The equivalents of the matrices Q_{1L}, S, Q_2, and R_2 in Eq. 1 were obtained from the EDA and GMA programs for their respective data segments. The lithium and boron results from the Segment 1 fits and the Axton output thermal parameters were used as initial estimates in the final Segment 2 cycle.

Since the R-matrix formulations were non-linear for some of the parameter refinements, the final R-matrix parameters were selected to fit the cross sections implied by the solution to the linearized equations.

Summary of Identified Problems

An unusual problem in the present implementation was the inability to iterate the combination of the R-matrix and simultaneous pointwise evaluations of the independent data segments. For an early data set a second iteration was performed by obtaining the R-matrix parameter covariance matrix for the parameters corresponding to the output of the first iteration. This matrix had one negative eigenvalue, but the iteration could proceed formally. The resulting cross section changes were substantially smaller than those in the first iteration, but the output data covariance matrix had many negative eigenvalues and the results were considered unusable. The underlying problem was that the R-matrix fits were quite nonlinear in some parameters over intervals comparable to the iteration increments, though the development of the combination equations and the tentatively quoted output uncertainties assume linearity. The one-pass combination results were accepted regardless of this inconsistency because they seemed to represent the input data.

Few experimenters report their known experimental uncertainties with sufficient clariy to remove the ambiguities that face an evaluator in quantifying the required input data covariance matrix,[4,10] though techniques are emerging.[11] This problem interacted with the other difficulties inherent in reducing input data sets to cross sections and covariance data on a standard energy grid for the evaluation.[3]

Since some experimental uncertainties are unrecognized or underestimated, inconsistencies among input data commonly occur. The tentative uncertainties in the ENDF/B-VI standards were expanded in some cases to compensate inconsistencies, yet they still appear small to reviewers.[12] The uncertainties apply to the average values over intervals equal to the energy grid spacing.

The values obtained directly from the GMA or combination equations for the heavy element standards in some cases showed fluctuations that seemed unreasonable based on expectations from the theory of average cross sections. In these cases some smoothing was performed. Significant fluctuations can occur, for example, if not all the output points in a neighborhood reflect the same input data sets and if unrecognized uncertainties existed.

Results

The ENDF/B-VI standards[13] are hard to judge pending full documentation. Of interest are the impacts of the combination process, the amount of change from the ENDF/B-V,[14] the extent to which the results agree with key input data sets, and the estimated uncertainties.

Table 3 shows some of the results for thermal energies including those for which there was significant change from Axton's values caused by the energy-dependent data. The change in the value for ^{235}U fission should be considered in the light of the differences between the combination results and the results of Derrien et al. for average cross sections in the resonance range.[17]

Figure 1 illustrates the effects of the data combination on the ^{6}Li(n,t) cross section. Few experimental data sets for this cross section, primarily ratio data, were retained in data Segment 2 analyzed using GMA. The two data segments do not appear to yield results within their uncertainties. The results from this combination are recommended for use as a standard up to 1 MeV. Figure 2 shows the effect of the combination on results for the ^{235}U(n,f) cross section. All values are referenced to the initial estimates for the final GMA run. The effect of including the Segment 1 data is to reduce the uncertainties and in some cases to shift the values.

Table 3. Selected Thermal Constants from the Data Combination. Values are at room temperature.[a]

React.	This Work	Axton[8]	Divadeenam[15]	ENDF-V[16]
U3nf	531.1±1.3	530.7±1.3	529.1±1.2	528.4[a]
U5nf	584.3±1.2	582.8±1.2	582.6±1.1	583.5
Pu9nf	748.0±1.7	747.6±2.0	748.1±2.0	741.7
Pu1nf	1013. ±7.	1012. ±7.	1011. ±6.	1015.
U5nn	15.5±1.1	16.0±1.1	14.0±0.5	14.7
U5$\bar{\nu}_t$	2.432±.004	2.433±.004	2.425±.003	2.437
Pu9$\bar{\nu}_t$	2.882±.005	2.882±.005	2.877±.006	2.891
Cf2$\bar{\nu}_t$	3.768±.005	3.768±.005	3.768±.004	3.766
Li6nt	941.0±1.3	-	-	936
B10nα0	241.3±0.5	-	-	244
B10nα1	3598.±6.	-	-	3592

[a]The values for ENDF/B-V are as given there. The pointwise files are often interpreted as being evaluated at 0.K. If they are Doppler broadened to room temperature, slightly high values result (by <0.1% for the fission cross sections).

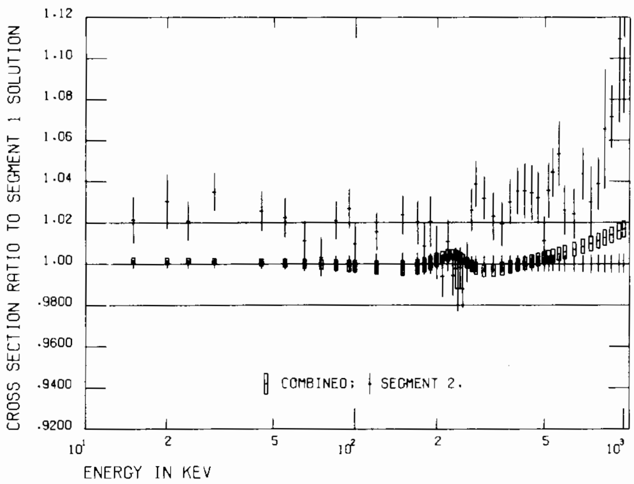

Fig. 1. The combined output for the $^{6}Li(n,t)$ cross section, the rectangles, as a ratio to the R-matrix fit to Segment 1 data. The error bars along the unit ratio line are the uncertainties from that fit. The points with simple error flags reflect the fit to the Segment 2 data sets. All uncertainties are tentative. The lines at ratios of 0.98 and 1.02 are eye guides.

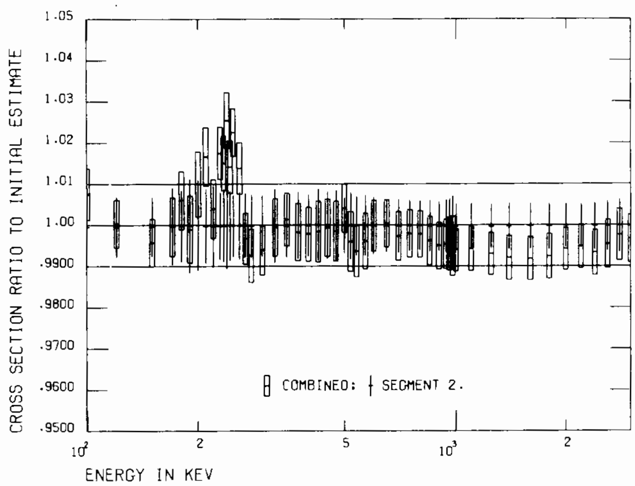

Fig. 2. The combined output for $^{235}U(n,f)$, the rectangles, relative to initial estimates for the final iteration of the Segment 2 data in GMA. The values shown are prior to smoothing. The points with simple error flags represent the fit to the Segment 2 data sets. Uncertainties are tentative. Lines at 0.99 and 1.01 are eye guides.

Figures 3 to 5 illustrate the ratios between ENDF/B-VI and ENDF/B-V standards for $^{6}Li(n,t)$, $^{10}B(n,\alpha)$, and $^{235}U(n,f)$. The changes are larger than the previously quoted uncertainties for the light element standards, but are of similar size for $^{235}U(n,f)$. The large change for the $^{10}B(n,\alpha_0)$ reaction in Fig. 4 reflects changes in the input data rather than in the model. The tentative uncertainties shown on the output values in these figures reflect the evaluated input uncertainties compensated for most of the inconsistencies among the data sets within each data segment.

Figure 6 compares some absolute $^{235}U(n,f)$ data against the ENDF/B-VI and ENDF/B-V standards data. The figure represents a tiny share of the extensive and diverse data base, but reminds one of the difficulties in deriving an evaluation without use of a comprehensive data combination method.

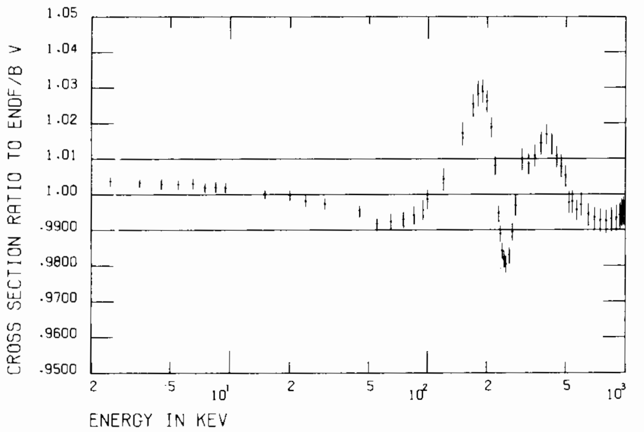

Fig. 3. Ratio of the ENDF/B-VI $^{6}Li(n,t)$ cross section to that for ENDF/B-V. The uncertainty bars are tentative. Lines at 0.99 and 1.01 are eye guides.

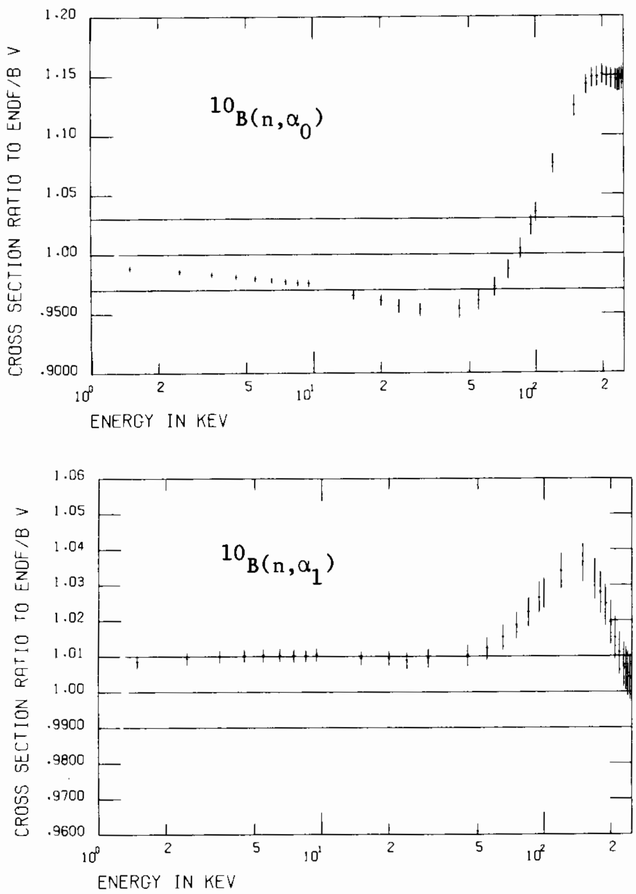

Fig. 4. Ratio of the ENDF/B-VI $^{10}B(n,\alpha)$ cross sections to those for ENDF/B-V. The upper figure is for the ground state reaction, and the lower for the excited state. Uncertainty bars are tentative. Lines are eye guides at 0.97 and 1.03 in the upper figure and at 0.99 and 1.01 in the lower figure.

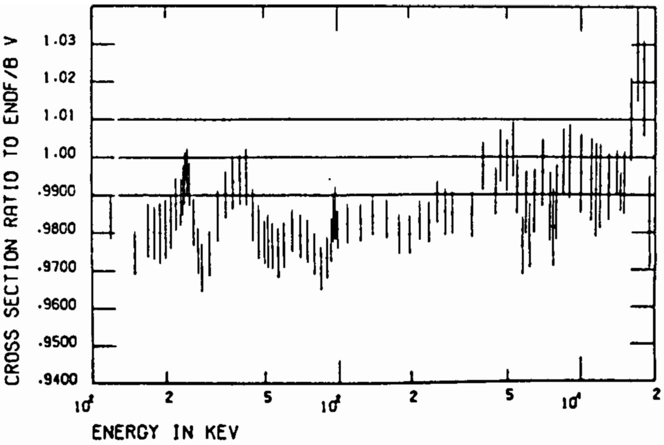

Fig. 5. Ratio of the ENDF/B-VI $^{235}U(n,f)$ cross section to that for ENDF/B-V. Uncertainty bars are tentative. Lines at 0.99 and 1.01 are eye guides.

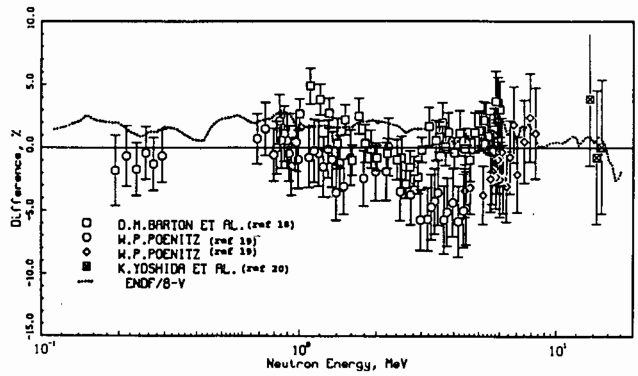

Fig. 6. Selected input data for the $^{235}U(n,f)$ cross section relative to the ENDF/B-VI standard. (Figure courtesy of W. P. Poenitz)

Recommendations

The following tentative recommendations seem appropriate concerning future use of global evaluation techniques for the standard neutron cross sections:

a) Highest priority should be assigned to untangling the data base to resolve discrepancies prior to data combination, since data combination may highlight new discrepancies but cannot eliminate known ones. The input data evaluation for the most important data sets should be reviewed. To facilitate such a review, it would be helpful if the ENDF/B evaluators could somehow tabulate an importance index for the various data sets.

b) The ENDF/B-VI evaluation strategy should be reviewed to check whether additional reactions should be included in the global evaluation process, and whether it is desirable to combine light and heavy element fits as was done. If so, means of setting up the calculation within one computer should be found or some other combination strategy devised that would allow multiple iterations to convergence.

c) A way should be sought to take full advantage of the theory of average neutron capture cross sections.[21]

d) The values of cross section integrals in the resonance region obtained in the data combination appear not to have been useful.[17] More work is needed if such data are to provide any guide for resonance-region evaluations.

Prompt Fission Neutron Spectrum of ^{252}Cf

The neutrons from the spontaneous fission of ^{252}Cf can be used for energy calibration of neutron detectors in the MeV region if the shape of the neutron spectrum is well known. It was also recommended by the IAEA/AGM on "Nuclear Theory for Fast Neutron Nuclear Data Evaluation," Beijing, October 12-16, 1987, that the present experimental differential data base for the spontaneous fission of ^{252}Cf should be used as a benchmark for testing theoretical fission model calculations.

An overall consensus between experiments and calculations using the Complex Evaporation Model and other statistical model approaches has been reported by Märten.[22] The overall agreement between the recent evaluation by Mannhart,[23] which is based only on experimental data, and theoretical calculations is good in the whole energy range. Small deviations are still seen in the energy range below 0.2 MeV (3-6%) and between 1.5 and 2.5 MeV (~3%).

Compared to a Maxwellian spectrum with T = 1.42 MeV which was earlier accepted as a standard, there is a positive deviation reaching a maximum of 3% at about 3 MeV followed by a negative deviation increasing continuously with energy and becoming about 20% at 20 MeV. For most practical applications it has been shown by Froehner[24] that a fit to a Watt spectrum is accurate enough. The recent experimental data are very well fitted by a Watt distribution with the only exceptions above 20 MeV.

Standard Activation Cross Sections

Energy-dependent activation cross sections have received wide application in neutron dosimetry studies designed to determine or verify the absolute neutron flux spectra at locations where neutron irradiation effects may be important. These cross sections are often measured as ratios to each other.

The NEANDC Standards Subcommittee has recommended the cross section for the $^{27}Al(n,\alpha)$ reaction as a primary standard activation cross section, and the $^{59}Co(n,2n)^{58}Co$ and the $^{93}Nb(n,2n)^{92m}Nb$ reaction cross sections as secondary standards around 14 MeV. The produced activities of the $^{59}Co(n,2n)^{58}Co$ and $^{93}Nb(n,2n)^{92m}Nb$ reactions have very convenient half-lives (71 days and 10 days, respectively) to serve as neutron flux monitors for long irradiations. Furthermore, their decay properties are very well known and suited for accurate absolute measurements.

The $^{27}Al(n,\alpha)^{24}Na$ Reaction

The evaluations of the $^{27}Al(n,\alpha)$ cross section by Hale et al.[25] for ENDF/B-V and by Tagesen and Vonach,[26] adopted for the INDC/NEANDC standards file, are in agreement within the given errors. Except for the low threshold region from 8 to 9 MeV, the accuracy of the Tagesen-Vonach evaluation was stated to be better than 5%. In particular, an accuracy of about 0.5% was indicated for the 14-MeV region.

In addition, an evaluation has been made by Kornilov et al.[27] Except for the low threshold region from 5.5 to 8.5 MeV, the uncertainty was well below 5%. However, a structure was obtained for the cross section in the energy region from 6.5 to 8 MeV in disagreement with the Vonach and Tagesen evaluation.

New measurements have been made in a collaboration between PTB, Braunsweig, and IRK, Vienna, in the energy region 8 to 11 MeV. A new evaluation is in progress at IRK.[28]

A simultaneous evaluation at 14.4 MeV of nine activation cross sections, two fission cross sections, and the H(n,n) scattering cross section has recently been made by Ryves.[29] The evaluated $^{27}Al(n,\alpha)$ cross section was (112.7 $\pm$ 0.5) mb which is in good agreement with the evaluated data by Tagesen and Vonach (113.1 $\pm$ 0.5) mb.

It has been proposed by Smith,[30] that the ratio $^{235}U(n,f)/^{27}Al(n,\alpha)$ should be measured at 14 MeV to verify that the desired accuracy (1% in the ratio) of these two cross sections at this important energy has been achieved.

$^{59}Co(n,2n)^{58}Co$ Cross Section

The $^{59}Co(n,2n)$ reaction leads to the ground state of ^{58}Co(^{58g}Co) and to an isomeric state ^{58m}Co at an excitation of about 25 keV in ^{58}Co. The isomeric production ratio is about 2 at 14 MeV. The half-life of the isomer is 9.15 $\pm$ 0.10 h and it ultimately decays to the 70.87 $\pm$ 0.07 d half-life ground state. The isotopic abundance of elemental cobalt is 100% ^{59}Co.

The total $^{59}Co(n,2n)$ cross section is the sum of the ^{58m}Co and ^{58g}Co production. The total yield can be measured if several days are allowed for the ^{58m}Co activity to die away. Cobalt-58 decays by positron emission and electron capture to levels in ^{58}Fe. The characteristic 0.811-MeV gamma ray follows in 99.44 $\pm$ 0.02% of all ^{58}Co decays.

Competing reactions are the $^{59}Co(n,\alpha)^{56}Mn$ and the $^{59}Co(n,p)^{59}Fe$. The ^{56}Mn decays with a half-life of 2.6 h emitting 0.846 MeV gamma rays while the ^{59}Fe activity has a half-life of about 44 d emitting 1.099 and 1.291-MeV gamma rays.

The stated accuracies in recent 14-MeV measurements of the $^{59}Co(n,2n)^{58m+g}Co$ cross section[31-34] are as low as 1% with a spread in the cross section values of more than 2%. Ryves[29] as recently measured the 14-MeV cross sections for the reactions $^{59}Co(n,2n)^{58m+g}Co$, $^{59}Co(n,p)^{59}Fe$ and $^{59}Co(n,\alpha)^{56}Mn$ relative to the $^{56}Fe(n,p)^{56}Mn$ reaction. Accuracies of about 1% were achieved for the (n,α) reaction and 2% for the others. Both the $^{59}Co(n,p)$ and $^{59}Co(n,2n)$ cross sections were significantly higher than most previous measurements and he suggested that more measurements should be done to establish the values.

The accuracy claimed for the $^{59}Co(n,2n)$ cross section in the International Reactor Dosimetry File (IRDF) at 14 MeV is about 6%. The evaluation of Evain et al.[35] states an accuracy of 2% at 14 MeV but the value is low by more than 4% compared with recent measurements. New evaluations are reported to be in progress for the $^{59}Co(n,2n)$ cross section by D. L. Smith and A. B. Smith[36], and by Vonach.[28]

The $^{93}Nb(n,2n)^{92m}Nb$ Cross Section

The ^{92m}Nb-isomer produced in the $^{93}Nb(n,2n)$ reaction has a half-life of 10.15 $\pm$ 0.03 d. The isomer decays by positron emission to excited levels in ^{92}Zr. Gamma rays with an energy of 0.934 MeV are produced in more than 99% of the decays.

Several recent measurements have been made of the cross section for the $^{93}Nb(n,2n)^{92m}Nb$ reaction in the 14-MeV region.[31,37-40] Good agreement is obtained within the stated accuracies of typically a few percent. The cross section of the $^{93}Nb(n,2n)$ reaction is fairly flat over the energy region around 14 MeV. However, more experiments are needed outside the 14-MeV region to establish the shape of the excitation curve.[41]

The ENDF/B-V evaluation of Philis and Young[41] gives a value of 483 $\pm$ 50 mb at 14.7 MeV while the recent simultaneous evaluation by Ryves[29] gives 460 $\pm$ 5 mb. The BOSPOR library[43] which is referred to in the IAEA Handbook of Nuclear Activation Data gives a cross section value of 483 $\pm$ 5% mb at 14 MeV.

Neutron Standard Cross Sections Above 20 MeV

Neutron cross section standards in the energy region above 20 MeV have not yet been agreed upon internationally. There is a considerable interest in medium energy neutron data because of applications to radiation therapy, fusion, isotope production, radiation damage, accelerator shielding, etc.

The most obvious choice as a primary neutron standard up to several hundred MeV is the H(n,n)H cross section. This cross section can be used as a standard neutron scattering cross section relative to which other scattering cross sections can be measured. It can also be used for neutron flux determination. A common method is to detect proton recoils from hydrogeneous foils; this involves the cross section at backward c.m. angles.

The n-p total cross section has been measured to a good accuracy ($\lesssim$1%) at least below 200 MeV. The recent measurements by Larson[44] and the nucleon-nucleon phase shift analysis by Arndt[45] show agreement to better than 1% in the energy region 2-80 MeV. The LAMPF n-p total cross section results by Lisowski et al.[46] have a different shape and normalization from much of the older data in the energy range above 200 MeV. The deviation amounts to a maximum of 6%. Below 200 MeV the values agree in general with the data of Brady et al. (25-60 MeV),[47] Groce and Sowerby, (20-80 MeV)[48] and Measday and Palmieri (90-150 MeV).[49]

The differential n-p scattering cross section is in general not adequately known at energies >20 MeV. The uncertainty in the degree of anisotropy and assymmetry around 90^o in n-p scattering is sensitive at low energies (<50 MeV) to P-wave phases, particularly $\delta(^1P_1)$. The phase shift parameters obtained from the two analyses by Bohannon et al.[50] and Arndt et al.[45] at 25 MeV are in agreement but the large uncertainties on the values of $\delta(^1P_1)$ of -5.18 $\pm$ 0.47^o (Bohannon) and -4.49 $\pm$ 0.94^o (Arndt) indicate that more differential scattering data are needed over a wide angular range. These values of $\delta(^1P_1)$ are also in reasonable agreement with those of -4.90 $\pm$ 0.48^o and -4.61 $\pm$ 0.08^o obtained from the Yale and Livermore (constrained) analyses, respectively, on which the Hopkins and Breit[51] analysis (ENDF/B-V) was based.

Data on the 180^o cross section for n-p scattering between 23 and 27 MeV have been reported by Drosgh[52] who measured 5.7 $\pm$ 3.3% lower values than those calculated from the recommended Yale phase shifts. Furthermore, discrepancies between different experimental data sets of the order of 20-30% have been obtained in measurements of backward (180^o) n-p differential cross sections in the energy region above 100 MeV.[53]

There are numerous n-p polarization data that can also be used to demonstrate the problems with systematic errors in the n-p data base, particularly in the energy range above 100 MeV.

In summary, more n-p differential scattering data are needed to solve problems of systematic errors above 100 MeV. Precision angular measurements are also needed between 20-100 MeV to improve on $\delta(^1P_1)$. Spin parameters should also be measured in the energy range 150 to 300 MeV where relatively few experiments exist.

A potential candidate as a reference neutron scattering cross section in the energy region above 20 MeV is the carbon differential elastic scattering cross section. Pure material is easy to obtain. The differential cross section is relatively smooth as a function of angle and remains fairly large up to at least 90^o lab. The first excited level is at 4.4 MeV and the angular integrated cross section has a smooth energy dependence above 20 MeV. However, at present accurate measurements exist only below 30 MeV and at some spot energies above. Good agreement has been obtained between recent differential scattering measurements between 20-30 MeV at Ohio[54] and Studsvik[55] within the stated errors of a few percent. The total neutron cross section for carbon has also recently been measured with good accuracy up to 200 MeV by Lisowski et al.[56]

The fission cross section of ^{235}U could be a useful standard in connection with measurements using white neutron sources because it covers the full entire energy range above 0.1 MeV. The same cross section of ^{238}U might be a better choice for monoenergetic intermediate neutron energy sources because it discriminates against slow neutrons. Measurements of the $^{235}U(n,f)$ cross section between 3-35 MeV at the LANL WNR facility by Carlson et al.[57] are reported to this conference.

Conclusions

The standard cross sections have evolved over the recent years both because of new measurements and because of improvements in data combination capability. A property of computer-based data combination techniques is that new data or new evaluations of older influential data can be included with a relatively small expenditure. This capability should be employed to upgrade standards files at intervals shorter than those between issuance of major general purpose evaluated data sets.

There is increasing interest in the magnitude and representation of the uncertainties in standards. While final uncertainty and covariance data have not yet been released for the ENDF/B-VI standards, it is safe to predict that further clarification of technique and results will be required for future evaluations. While it appears that many of the accuracy goals for standards have been met, the task is not complete until the basis for the small uncertainties is fully accepted.

The experimental data base that underlies the standard cross sections has definite inadequacies. The $n+^{10}B$ data base is both sparse and inconsistent. The data for the ^7Li system are somewhat better, but there is evidence for distortion of the neutron data around the 0.25-MeV resonance. There is need for some extension of standard cross section files into the ~100 MeV energy range, or at least as high an energy as neutrons may be present in radiotherapy applications. The best prospects are for the n-p scattering cross section and fission in ^{235}U and ^{238}U.

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