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# Evaluation of Neutron Reactions for ENDF/B-VII: $^{232-241}$ U and $^{239}$ Pu

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We have completed new evaluations for several actinides in the ENDF/B-VII database and have extensively modified existing evaluations for several other actinides. We compare calculations using the new evaluations with critical assembly reaction rate measurements made at Los Alamos over the past 50 years, covering a range of reactions and differing neutron spectrum and fluence environments. The evaluations are for all neutron-induced reactions with uranium isotopes in the mass range A=232-241 as well as <sup>239</sup>Pu, and mostly cover the incident neutron energy range from keV energies to 30 MeV. We combined the results of these analyses with new evaluations of the resolved and/or unresolved resonance regions from Oak Ridge for <sup>233,235,238</sup>U and with modified ENDF/B-VI resonance evaluations for the other actinides to produce new neutron-induced evaluations spanning the incident neutron energy range from  $10^{-5}$  eV to 20 or 30 MeV. Major aspects of this analysis are: systematic accumulation of all relevant experimental data; re-normalization of the neutron data to modern standards; assessment of the applicability of several recent optical model potentials for actinide calculations; interpretation of the experimental results in terms of nuclear theory to allow interpolation and extrapolation of the data into unmeasured regions; and finally, assembly of the experimental and theoretical results into formal evaluated nuclear data files that can be processed for use in applied nuclear programs.

In this report we discuss the theoretical analysis and evaluation of all the evaluations, with emphasis on incident neutron energies in the range 10 keV to 20 MeV. We present detailed comparisons of critical assembly simulations with the measurements and include tables of the experimental results. The critical assembly measurements include reaction rates for (n,f),  $(n,\gamma)$ , and (n,2n) reactions obtained in the Godiva, Jezebel, Topsy, Bigten, and Flattop assemblies. The evaluations described here are on file at the National Nuclear Data Center at Brookhaven National Laboratory in the ENDF/B-VII database.

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## I. INTRODUCTION

The next generation evaluated nuclear data library, ENDF/B-VII, has recently been released by the U.S. Cross Section Evaluation Working Group (CSEWG) [1]. Extensive validation of the database, using radiation transport codes to simulate measured critical assemblies, indicate major improvements, a number of which relate to upgrades in the evaluated nuclear data for actinides. These improvements include: removal of the long-standing under prediction of criticality for low-enriched uranium thermal assemblies; removal of the  $^{238}$ U fast-system reflector bias; removal of the under prediction of fast criticality of  $^{233,235}$ U and  $^{239}$ Pu assemblies; and, more accurate prediction of intermediate spectrum critical assemblies.

We completed new evaluations for ENDF/B-VII of incident neutron reactions with the uranium isotopes having A=232-234, 236-241 over the incident energy range from  $10^{-5}$  eV to 30 MeV. Additionally, we modified and updated existing (ENDF/B-VI.8) evaluations for neutron reactions on  $^{235}$ U and  $^{239}$ Pu over the energy range  $10^{-5}$ eV to 20 MeV. This work is part of a systematic analysis of nuclear reaction data of actinides for Los Alamos National Laboratory (LANL) programs that has spanned a number of years. Previously we published reports describing our evaluations of  ${}^{233}$ U [2],  ${}^{232,234}$ U [3], and <sup>238</sup>U [4], as well as several Los Alamos internal reports, e.g., Ref. [5]. Those evaluations served as the starting point for our ENDF/B-VII evaluations, and some of the prior evaluation work was incorporated into our ENDF/B-VII evaluations. In most cases, the newer experimental data that are now available would not significantly alter the evaluations.

A summary of the work on several of these isotopes is included in the main ENDF/B-VII database publication [1] by CSEWG. The evaluated data files described here are identical to those discussed in Ref. [1]. The goal of the present paper is to provide a more detailed description of the  $^{232-241}$ U and  $^{239}$ Pu evaluations than is given in Ref. [1].

Our analyses mostly cover incident neutron energies from approximately 10 keV to 30 MeV, except for  $^{235}$ U and  $^{239}$ Pu, which only extend to 20 MeV. At low energies, we combine our results with resonance parameter evaluations, either new evaluations from Oak Ridge National Laboratory (ORNL) or existing evaluations from Release 8 of the ENDF/B-VI database, sometimes with modifications. This report focuses on the evaluations above 10 keV; the new resonance analyses, as well as the fission neutron spectra and delayed neutron evaluations, are described in more detail elsewhere, e.g., see Ref. [1].

There is a significant amount of experimental data available for neutron reactions on several of the actinides in this study. We obtained experimental data from the EXFOR/CSISRS database at the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory (BNL) and the Data Bank of the Nuclear Energy Agency in Paris. Much of the fission cross-section data and prompt neutron multiplicities from fission (nubar) are in the form of ratios to other accurately measured "standard" quantities. Nubar measurements are frequently relative to  $^{252}$ Cf nubar, which is very accurately

known ( $^{252}$ Cf nubar total =3.7692±0.125%). In the case of the fission cross section, the data are relative mostly to the well-known <sup>235</sup>U fission cross section. As part of the ENDF/B-VII evaluation activity by CSEWG, an international evaluation effort [6] was mounted to carefully re-evaluate all neutron standards data. This activity spanned several years, and in the course of it, corrections were made to many of the source measurements. In our evaluations of <sup>233,235,238</sup>U and <sup>239</sup>Pu data. all prompt nubar measurements were adjusted to conform to ENDF/B-VII standards, and all fission crosssection ratios were converted to absolute cross sections using the ENDF/B-VII <sup>235</sup>U(n,f) standard cross section. The experimental data available for <sup>234,236</sup>U were performed before ENDF/B-VII standards were available so were normalized to ENDF/B-VI nubar standards and to a modified version of the ENDF/B-VI (n,f) cross section standard [7], [8].

Our general procedure was to assess the experimental database for each isotope and to then combine theoretical analyses with the experimental data. In all cases we relied upon the theoretical analyses for at least part of the evaluation, the extent depending upon the amount of available experimental data. The theoretical models that we utilized were mainly coupled-channels optical models and Hauser-Feshbach statistical-plus-preequilibrium theory.

The optical model and reaction theory analyses are described below in Section II. The methodology used in combining the model calculations and the experimental data to produce the full evaluations is described in Sec. III. In Sec. IV and its subsections, the individual evaluations for each isotope are described and compared with other evaluations and experimental data. In Sec. V, we present comparisons of critical assembly measurements with calculations using the ENDF/B-VII evaluations. We close with some concluding remarks and suggestions for future work in Sec. VI.

#### **II. THEORETICAL ANALYSES**

The primary goal of the theoretical analyses was to provide consistent descriptions of all reactions over the energy range 10 keV to 30 MeV for all the isotopes. Our analyses consisted of developing suitable coupled-channels optical model potentials and carrying out Hauser-Feshbach/statistical, preequilibrium, and direct reaction calculations. The parameters in the various analyses were optimized so that the calculations matched the available experimental database as well as possible. There is an abundance of experimental data for several isotopes: <sup>233</sup>U, <sup>235</sup>U, <sup>239</sup>Pu and, in particular, <sup>238</sup>U. These data include total, fission, (n,xn), and radiative capture cross section data, elastic and inelastic scattering angular distributions, and prompt nubar measurements. However, there are many energy regions where data are lacking and sparse, and for several of the isotopes very little data exists at all. So, the specific use of the analyses was to provide magnitudes and shapes of cross-sections, as well as energy and angle dependencies in regions where experimental data were lacking. the calculations were particularly important for predicting unmeasured (n,n'),  $(n,\gamma)$ , and (n,xn) cross sections, angular distributions for elastic and inelastic neutrons, and correlated energy-angle distributions for continuum emitted neutrons. For the rare isotopes, fission cross section calculations were also important.

#### A. Optical model analysis

A critical requirement for analyses such as these is to have available reliable optical model potentials. Not only are optical model calculations needed for determining neutron cross sections and angular distributions where measurements are lacking, but they are also required for obtaining neutron transmission coefficients for the reaction theory calculations. Optical model calculations provide useful supplements to the experimental data for total and scattering cross sections and are essential for analvsis, interpretation, and prediction of (n,n') and (n,xn)reaction cross sections, angular distributions, and energy distributions. As part of our evaluation procedure, we assessed several recently derived optical model potentials and compared them to our analyses and to experimental data. In particular, because of the abundance of experimental data for <sup>238</sup>U, we performed a reasonably comprehensive analysis of optical model potentials for that isotope.

This work on  $^{238}$ U+n potentials is described in detail in our  $^{238}$ U report [4]. To summarize, we investigated the following coupled-channels potentials for our  $^{238}$ U+n analysis:

- 1. A new global actinide potential developed by Vladuca *et al.* [9] that spans the incident neutron energy range from 0.001 to 20 MeV.
- 2. A new potential by Maslov *et al.* [10] covering the energy range 1 keV-20 MeV, developed by fitting s-wave strength functions and experimental data. This potential was utilized by Maslov *et al.* in an evaluation of  $^{238}$ U+n cross sections to 20 MeV.
- 3. An earlier potential by Young and Arthur [11], which was utilized for ENDF/B-VI evaluations. This potential covers the incident neutron energy range to 30 MeV and is itself a modification of a potential derived at Bruyères-le-Châtel [12] that was developed for use to approximately 10 MeV.
- 4. A new <sup>238</sup>U+n potential developed by Ignatyuk *et al.* [13] covering the energy range 1 keV-150 MeV.
- 5. A new potential derived by Sukhovitskij *et al.* [14] by fitting  $^{238}$ U+n and  $^{238}$ U+p scattering angular distributions and neutron total cross sections up to 150 MeV.
- An extensive modification [4] of the earlier <sup>238</sup>U+n potential from LANL [11] mentioned in item (3) above.
- 7. A new potential developed by Maslov *et al.* [15] that covers the incident nucleon energy range from 0.001 to 200 MeV.

The optical model calculations were performed using the 1996 version of the ECIS coupled-channels optical model code by Raynal [16]. All calculations include coupling of the ground state rotational bands. For all of the potentials, we coupled the lowest 3 to 7 rotational states into the calculations. In most cases, we included compound nucleus competition from other uncoupled states plus a continuum of (n,n') states. The discrete levels were generally taken from the International Atomic Energy Agency (IAEA) RIPL-2 database [17]. We also used ECIS96 for DWBA calculations to estimate contributions from a selection of  $\beta$ - and  $\gamma$ -vibrational states between  $E_x=0.5$  and 4 MeV for certain of the target nuclei. More details are given below.

#### 1. Calculated total, elastic, and nonelastic cross sections

As examples of our optical model analysis, in this section we make detailed comparisons of  $^{238}$ U experimental data with total, elastic, and nonelastic cross sections as well as elastic and inelastic scattering angular distributions predicted by the optical potentials of Vladuca *et al.* [9], Maslov *et al.* [10], Young and Arthur [11], Ignatyuk *et al.* [13], Sukhovitskij *et al.* [14], and Young *et al.* [4]. These comparisons are made below a neutron energy of 30 MeV, which is the maximum energy of our <sup>238</sup>U evaluation.

Comparisons of calculated neutron total cross sections from the various optical model potentials are given in Figs. 1 and 2. Figure 1 illustrates the  $^{238}$ U+n total cross section for  $E_n=0.06$ -8 MeV, and Fig. 2 covers the energy range 2-30 MeV. The experimental data of Poenitz *et al.* [18], Abfalterer *et al.* [19], Lisowski [20], and Shamu [21] are included for comparison with the optical model calculations. In each of these figures an expanded cross section scale is used, so the differences seen between the calculations and the optical calculations are generally quite small, usually within a few percent.

In Fig. 1, only the cross section from the Ignatyuk potential differs significantly from the others and that difference occurs mainly below 1 MeV. However, it should be noted that the Ignatyuk potential was developed primarily for use at higher energies. In Fig. 2, the Sukhovitskij and 2001 Young potentials give cross sections that overshoot the experimental data near 22 MeV; the Ignatyuk result is somewhat high above 25 MeV; and both the Vladuca and Maslov potentials produce cross sections that are lower than the data near 10 MeV. Only the older 1992 potential of Young and Arthur [11] agrees well with most of the experimental data at all energies. It is interesting to note that the newer Young potential [2], [4] was developed from the Young and Arthur potential, except that the newer one is relativistic whereas the older version is nonrelativistic. Similarly, the Sukhovitskij and Ignatyuk potentials are relativistic.

Similar comparisons for <sup>238</sup>U+n elastic scattering are given in Figs. 3 and 4, that is, between optical model calculations using these same potentials and experimental data for neutron elastic scattering cross sections. Experimental results from Murzin *et al.* [22], Barnard *et al.* [23]. Tsang and Brugger [24], Smith [25], Haouat *et al.* [12], Batchelor *et al.* [26], Smith and Guenther [27],



FIG. 1: Neutron total cross sections from 0 to 8 MeV calculated with various optical model potentials compared with experimental data.



FIG. 2: Neutron total cross sections from 2 to 30 MeV calculated with various optical model potentials and compared with experimental data.



FIG. 3: Calculated and measured elastic scattering cross sections between 0 and 4 MeV.



FIG. 4: Calculated and measured elastic scattering cross sections between 0 and 16 MeV. The calculated cross sections include excited levels to  $E_x \sim 0.2$  MeV.

Voignier [28], Shen *et al.* [29], Li Jingde *et al.* [30], Litvinskiy *et al.* [31], Grigorev *et al.* [32], Knitter *et al.* [33], Allen *et al.* [34], and Cranberg *et al.* [35] are included in the comparisons.

The comparisons in Fig. 3, which cover the incident neutron energy range 0-4 MeV, are for pure elastic scattering, that is, the resolution of the experiments was sufficient to resolve the ground state data from the excited states. In Fig. 4, covering the range 0-16 MeV, contributions from the first 4 excited states ( $E_x \sim 0.6$  MeV) are included with elastic scattering to approximate the resolution of the experimental data. For the curves in Figs. 3 and 4, we calculated the compound elastic and inelastic contributions for each potential with ECIS96, using the same level density parameters as were included in the GNASH calculations, that is, values resulting from mean level spacing data.

The agreement between the elastic scattering cross section measurements and the optical model calculations is generally good. There are some exceptions, of course. For example, in Fig. 4 the experimental data of Knitter et al. [33] above  $E_n=3$  MeV fall below all the calculated cross sections. Additionally, differences between the calculations and individual points occur in some cases. For instance, in Fig. 3 all the calculations lie below the Haouat et al. [12] point at 0.7 MeV by about 2 standard deviations and, similarly, all the calculations lie above the Haouat point at 3.4 MeV by at least one standard deviation. Overall, however, the agreement between the calculations and measurements is reasonable. Certainly most of the calculations below  $E_n=3$  MeV in Figs. 3-4 are consistent with the bulk of the experimental data, and in Fig. 4 all the calculations at  $E_n = 14$  MeV agree to within 4% and are consistent with the measurements.

We obtained nonelastic cross sections from each of the optical model potentials by subtracting the compound elastic cross section from the reaction cross section produced with each potential. We calculated the compound elastic for each potential with ECIS96, again using the same level density parameters as were included in the GNASH calculations. Of course, the nonelastic and reaction cross sections are essentially the same above a few MeV.

Comparisons of experimental nonelastic cross sections with the calculated nonelastic cross sections are given in Fig. 5. Because of the large amount of experimental data that exists, we only include a representative sampling of the available data. Figure 5 includes the experimental data of Bethe *et al.* [36], Degtyarev [37], Beyster *et al.* [38], Ennis [39], Cohen [40], Degtyarev and Nadtochu [41], Voignier [28], MacGregor *et al.* [42], Didier and Dilleman [43], and White [44].

There is a systematic over-prediction of the nonelastic cross section measurements below about 3 MeV. This is the energy range where compound elastic scattering is important, so perhaps a greater inaccuracy in the calculations occurs at these energies. Alternatively, the age of the measurements ranges from 36 to 53 years, and the differences in calculation and measurement below 3 MeV might reflect a systematic problem in the measurements. In support of this thesis is the reasonably good agreement of the calculated total cross sections below 3 MeV with the measurements shown in Figs. 1 and 2.

There is some disagreement among the experimental nonelastic cross section data above 10 MeV, with the differences being greatest near 20 MeV. The nonelastic cross section from the Maslov potential [10] generally follows the lower data in this energy range, whereas the other potentials are more consistent with the higher measurements. Of course, a reliable reaction cross section is essential for the calculated (n,f) and (n,xn) reactions.

#### 2. Elastic scattering angular distributions

Neutron elastic scattering angular distributions for  $^{238}$ U have been measured at a variety of incident neutron energies, covering the energy range from 0.075 to 14.2 MeV. Because of the large number of measurements, we refer the reader to Ref. [4], where extensive graphical comparisons of the optical model predictions [9], [10], [11], [13], [14] with the experimental data are included in Appendix A. We limit ourselves here to sample comparisons with the experimental data of Baba *et al.* [45] at  $E_n=2.03$  MeV (Fig. 6), and with the data of Haouat *et al.* [12] at  $E_n=3.4$  MeV (Fig. 7). In both cases reasonable agreement between the measurements and calculations is seen.

In general, all the potentials give results that are in reasonable agreement above about 0.3 MeV. At lower energies, the potential of Ignatyuk *et al.* [13] results in angular distributions that lie above the experimental data, similar to the total cross section in Fig. 1. Several of the potentials give angular distributions that are higher than the data at the diffraction maxima near  $\theta_{cm}=70^{\circ}$ , 100°, and 155° at neutron energies above about 5 MeV It appears that the Sukhovitskij *et al.* [14] potential gives the best overall agreement with the measured elastic distributions in the energy range 4-10 MeV.

Extensive comparisons are also given in Reference [4] of experimental and calculated (n,n') cross sections and angular distributions. The calculations were made with the ECIS96 code and include both direct reaction and compound nucleus effects, incorporating the same parameters



FIG. 5: Calculated and measured nonelastic cross sections between 0 and 20 MeV.



FIG. 6: Comparison of measured and calculated elastic scattering angular distributions at  $E_n=2.03$  MeV. Contributions from the first 2 excited states are included.

as were used in the GNASH calculations described in Sec. II.B below. The experimental data for members of the ground state rotational band are the most sensitive to the optical model potentials.

#### 3. Conclusions from optical model comparisons

In general, most of the optical model potentials that we have considered give reasonably good results over most of the incident neutron energy range from 10 keV to 30 MeV, and in our view no single potential greatly dominates over the others in these comparisons. Of course, certain of the potentials are better for particular reactions in limited energy ranges. For instance, if we limit our consideration to cross sections alone, the Young, 1992 potential [11] probably gives the best overall results for  $^{238}$ U. Notice in Figs. 1-2 that it closely reproduces the total cross section over the entire energy range from 60 keV to 30 MeV. Broadening our consideration to include elastic scattering angular distributions, we note from the exhaustive comparisons in Ref. [4] that the Sukhovitskii



FIG. 7: Comparison of measured and calculated elastic scattering angular distributions at  $E_n = 3.4$  MeV.

potential does exceptionally well in reproducing the angular distributions from 4 to 10 MeV. However, that potential does lead to a  $^{238}$ U nonelastic cross section that is at least 5% higher than the others near 14 MeV. To pursue this issue, we attempted to apply the Sukhovitskii potential to calculate the  $^{238}$ U(n,2n) cross section near 14 MeV. That is, we obtained transmission coefficients from this potential and adjusted the fission barrier parameters in our GNASH analysis (see Sec. 4 below) to reproduce the (n,f) cross section. However, in this very limited effort, we were unable to satisfactorily reproduce the (n,2n) experimental data. A more thorough analysis, in which other parameters are adjusted, would be useful.

Our conclusion of the analysis for  $^{238}$ U was to utilize the 1992 Young potential [11] in the ENDF/B-VII analysis. Not only did this potential reproduce most of the experimental data as well as, or better than, the other potentials, it also gives reasonable values for s- and p-wave strength functions and potential scattering radii and was used as the starting point for several of the other uranium potentials prior to our  $^{238}$ U analysis.

Because this work spanned many years, identical optical potentials were not used for all evaluations. As implied above, the various potentials produce similar results in most cases. The same potential [11] was used for the  $^{236,238,240}$ U+n analyses and is given in Table I. A similar potential [3] that utilizes different imaginary surface derivative terms for even and odd isotopes and that has no imaginary volume term (compensated for with the imaginary surface-derivative term) was used for the  $^{232,234,237,239,241}$ U+n analyses, listed in Table II. For  $^{235}$ U and  $^{239}$ Pu, very similar potentials [11] were used, and these are given in Tables III and IV, respectively. Finally, for the  $^{233}$ U+n analysis, we chose a potential developed for the neutron energy range 0 to 200 MeV [2], [4], and it is given in Table V.

#### B. Hauser-Feshbach/Statistical theory calculations

In addition to the optical model calculations with ECIS96 [16], Hauser-Feshbach statistical calculations were performed both with ECIS96 and with the GNASH

TABLE I: Non relativistic optical model potential [11] used in the Los Alamos evaluations of n +  $^{236,238,240}$ U reactions. Energies are in MeV, radii and diffusivities are in fm, E<sub>n</sub> is the incident neutron energy, and  $\eta$ =(N-Z)/A, where N, Z, and A are the neutron, proton, and atomic mass numbers for the target nucleus.

		$E_n$	$\mathbf{r}$	a
$V_V$	$= 49.83 - 0.275 E_n - 16n$	$\eta = 0-30$	1.26	0.63
$W_V$	= 0	0-7	1.26	0.63
	$= -1.4 + 0.175 E_n$	7-30		
$W_D$	$= 4.995 + 0.400 E_n - 8n$	$\gamma = 0-8$	1.26	0.52
	$= 8.563 - 0.046 E_n - 8\eta$	8-30		
$W_{SO}$	= 6.20	0-30	1.12	0.47
Defor	mation parameters:	<sup>236</sup> U $\beta_2 = 0.1$ <sup>238</sup> U $\beta_2 = 0.1$ <sup>240</sup> U $\beta_2 = 0.1$	197 $\beta_4 = 0.0$ 198 $\beta_4 = 0.0$ 206 $\beta_4 = 0.0$	)66 )57 )51

TABLE II: Non relativistic optical model potential [3] used in the evaluations of  $n+^{232,234,237,239,241}$ U reactions. Energies are in MeV, radii and diffusivities are in fm,  $E_n$  is the incident neutron energy, and  $\eta=(N-Z)/A$ , where N, Z, and A are the neutron, proton, and atomic mass numbers for the target nucleus.

			$E_n$	$\mathbf{r}$	а
$V_V$	= 50.328 - 0.30E	$n-18.194\eta$	0-30	1.26	0.63
$W_V$	= 0		0-30	1.26	0.52
$W_{SO}$	= 6.20		0-30	1.12	0.47
EVEN A					
$W_D$	$= 5.642 + 0.4E_n$	$-9\eta$	0-10	1.26	0.52
	= $9.253$ - $9\eta$		10-30		
ODD A					
$W_D$	$= 5.253 + 0.4E_n$	$-9\eta$	0-10	1.26	0.52
	$= 9.253$ - $9\eta$		10-30		
Deformat	ion parameters:	$^{232}$ U $\beta_2 = 0.$	190 $\beta_4$ =	=0.078	
		$^{234}$ U $\beta_2 = 0.$	197 $\beta_4$ =	=0.071	
		$^{237}$ U $\beta_2 = 0.$	197 $\beta_4$ =	=0.066	
		$^{239}$ U $\beta_2 = 0.$	205 $\beta_4$ =	=0.056	
		$^{241}$ U $\beta_2=0.$	206 $\beta_4$ =	=0.046	

TABLE III: Non relativistic optical model potential [11] used in the Los Alamos evaluation of n  $+^{235}$ U reactions. Energies are in MeV, radii and diffusivities are in fm, En is the incident neutron energy, and  $\eta$ =(N-Z)/A, where N, Z, and A are the neutron, proton, and atomic mass numbers for the target nucleus.

		$E_n$	r	a
$V_V$	$= 49.87 \cdot 0.300 E_n \cdot 16\eta$	0-30	1.26	0.63
$W_V$	= 0	0-7	1.26	0.63
	$= -0.7 + 0.100 E_n$	7 - 30		
$W_D$	$= 5.036 + 0.400 E_n - 8\eta$	0-8	1.24	0.50
	$= 8.604 \cdot 0.046 E_n \cdot 8\eta$	8-30		
$W_{SO}$	= 6.20	0-30	1.12	0.47

Deformation parameters: <sup>235</sup>U  $\beta_2=0.215$   $\beta_4=0.075$ 

TABLE IV: Non relativistic optical model potential [11] used in the Los Alamos evaluation of  $n+^{239}$ Pu reactions. Energies are in MeV, radii and diffusivities are in fm,  $E_n$  is the incident neutron energy, and  $\eta=(N-Z)/A$ , where N, Z, and A are the neutron, proton, and atomic mass numbers for the target nucleus.

	$E_n$	r	а		
$V_V = 49.61 - 0.300 E_n - 16\eta$	0-30	1.26	0.63		
$W_V = 0$	0-7	1.26	0.63		
$= -0.7 + 0.100 E_n$	7-30				
$W_D = 5.007 + 0.450 E_n - 8\eta$	0-8	1.24	0.50		
$= 8.975 - 0.046 E_n - 8\eta$	8-30				
$W_{SO} = 6.20$	0-30	1.12	0.47		
Deformation parameters: <sup>239</sup> Pu $\beta_2=0.205 \beta_4=0.075$					

TABLE V: Relativistic optical model potential [2] used in the Los Alamos evaluation of  $n+^{233}$ U reactions. Energies are in MeV, radii and diffusivities are in fm,  $E_n$  is the incident neutron energy, and  $\eta=(N-Z)/A$ , where N, Z, and A are the neutron, proton, and atomic mass numbers for the target nucleus.

		$E_n$	r	a
$V_V$	$= 49.61 - 0.300 E_n - 16\eta$	0-10	1.26	0.63
	$= 52.06400.4333E_n - 16\eta$	10-25		
	$= 46.0485 - 0.1927 E_n - 16\eta$	25 - 80		
	$= 81.7903 - 0.6395 E_n - 16\eta$	80-90		
	$= 35.5303 - 0.1255 E_n - 16\eta$	90-200		
$W_V$	= 0	0-7	1.26	0.63
	$=-0.7+0.1000E_n$	7-75		
	$= 2.48 + 0.0576E_n$	75-200		
$W_D$	$= 4.995 + 0.4000 E_n - 8\eta$	0-8	1.26	0.52
	$=8.8970.0878E_{n}-8\eta$	8-80.7		
	=0	80.7-200		
$V_{SO}$	=6.20	0-10	1.12	0.47
	$= 6.35790.01579E_n$	10-200		
$W_{SO}$	=0	0-10	1.12	0.47
	$=0.1026  0.01026E_n$	10-200		
Defor	rmation parameters: <sup>233</sup> U	$\beta_2 = 0.223 \ \beta$	$_4 = 0.076$	3

statistical/preequilibrium theory code [46] using the same optical potential and level density parameters. The GNASH code includes a double-humped fission barrier model with uncoupled oscillators for the barrier representation, as described by Arthur [47]. Each compound nucleus formed in the calculations is permitted to decay through the fission channel by neutron and gamma-ray emission.

Neutron transmission coefficients for the Hauser-Feshbach calculations were obtained from the coupledchannel optical model calculations. For all the uranium isotopes, three states from the ground-state rotational band were coupled in the calculations; for <sup>239</sup>Pu, seven states were coupled. Gamma-ray transmission coefficients were obtained from gamma-ray strength functions calculated with a form of the generalized Lorentzian model of Kopecky and Uhl [48]. Transmission coefficients for fission are calculated from the fission model summarized here and detailed in ref. [46]. Competition from fission was included in results from the ECIS96 compound nucleus calculations by scaling the calculated cross sections so that they summed to the reaction cross section.

Phenomenological level density functions from Gilbert and Cameron [49] were used to represent continuum levels at ground-state deformations, appropriately matched to available experimental structure data at lower excitation energies. Level density parameters for the  $^{232-238}$ U and <sup>238–240</sup>Pu compound systems were obtained from the measured s-wave mean level spacing,  $\langle D_0 \rangle$  [17]; systematics were used for the remaining isotopes. Multiplicative factors were applied to the level density functions to account for enhancements in the fission transition state densities at the fission barriers due to increased asymmetry conditions, and the continuum level densities are matched to the discrete fission transition states at each barrier. The discrete fission transition state spectra were calculated from bandhead information developed from calculations and compilations by Britt [50].

Default parameters for preequilibrium were used in the GNASH calculations. For example, the matrix element normalization constant that describes the competition between precompound particle emission and internal transitions to higher exciton states in preequilibrium emission was typically fixed at a value of 150 MeV<sup>3</sup>. Similarly, the nuclear single-particle state densities were set to A/13 MeV<sup>-1</sup> in the asymptotic limit where shell effects are washed out. Gamma-ray strength functions were normalized to experimental information [17] on  $2\pi\Gamma_{\gamma}/D_0$ , or systematics when experimental data were absent. Small renormalizations were made in some cases to optimize calculated (n, $\gamma$ ) cross sections with experimental data, when available.

Initial values of fission barrier parameters also were taken from the work of Britt [50], which were then optimized by comparing calculated fission cross sections from GNASH with experimental data. While GNASH calculations of fission cross sections are not used directly in most of the evaluations, it is important to match the cross section well in the calculations so that the competition to (n,n') and (n,xn) reactions is properly represented. In our calculations of the (n,n'continuum), (n,2n), (n,3n), and (n,4n) reactions, we utilize Kalbach [51] angular distribution systematics to obtain correlated energy-angle distributions for continuum reactions.

Limited use was also made of the COMNUC reaction theory code [52], primarily to provide GNASH with width-fluctuation correction factors and compound nucleus angular distributions, and to fit first-chance fission cross section measurements as described below.

#### 1. Fission theory calculations

Substantial experimental (n,f) cross section data exist for  $^{233-236}$ U,  $^{238}$ U, and  $^{239}$ Pu, and there are limited data for  $^{232,237}$ U. Wherever the (n,f) cross section data were adequate, we utilized those data for our evaluations. However, in order to have confidence in our predicted values for other unmeasured cross sections and energy/angle distributions, particularly above 1-2 MeV, we attempted to fit the measured (n,f) cross section data reasonably well with the GNASH code. The fission barrier parameters were adjusted to optimize agreement with measured data for each isotope that was analyzed. This allowed the competing (n,n') and (n,xn) channels to be calcu-

lated with reliability.

We used the results of these analyses along with simpler analyses of measured first-chance fission data with the COMNUC code to estimate the systematics of the fission barrier heights. These results were used to calculate cross sections for the unmeasured uranium targets such as  $^{240}$ U and  $^{241}$ U. The inner and outer fission barrier heights obtained in the GNASH and COMNUC analyses of the uranium isotopes are shown in Fig. 8.

As an example of results from our analysis, our calculated  $^{238}$ U(n,f) cross section is compared to the measurements of Lisowski [53] and Behrens [54] between neutron energies of 0 and 30 MeV in Fig. 9. Our evaluated ENDF/B-VII  $^{238}$ U(n,f) cross section is also included in Fig. 9 for comparison. As described below, the evaluated curve is based on the ENDF/B-VII standard cross section analysis [6], which has very small uncertainties.

Because the fission barriers in GNASH are uncoupled, the rapid rise of the first-chance fission cross section near  $E_n=1.5$  MeV is not exactly reproduced. Similarly, there is a slight energy-shift between the calculated and experimental cross sections near the onset of second-chance fission at  $E_n \sim 6.5$  MeV. At all other energies, however, the calculation falls within  $\sim 5\%$  of the mean of the data and is better in most regions. We judged this GNASH result to be satisfactory for describing competition of the fission channel. Of course, improved fission and level density models (e.g., see Ref. [55]) could improve our fission cross section calculations, particularly at lower energies.

#### 2. (n,xn) Cross sections

As (n,xn) examples, the results from our GNASH calculations of the  $^{238}$ U(n,2n) cross section is compared to measurements and to our ENDF/B-VII evaluation in Fig. 10, and a similar comparison is given for the  $^{238}$ U(n,3n) cross section in Fig. 11. Because the neutron transmission parameters were determined from the optical potential, the fission barrier parameters by fits of the (n,f) cross section, the level density parameters from measurements of  $\langle D_0 \rangle$ , and the preequilibrium parameters from default values, no *ad hoc* parameter adjustments were made prior to the (n,xn) calculations.

The experimental  $^{238}U(n,2n)$  and (n,3n) data from Pepenik et al. [56], Kornilov et al. [57], Barr et al. [58], Frehaut et al. [59], [60], Veeser and Arthur [61], Karius et al. [62], Raics et al. [63], Konno et al. [64], Golovnya et al. [65], Filatenkov et al. [66], Mather et al. [67], Allen et al. [68], White [44], Mather and Pain [69], and Knight et al. [70] are compared to the GNASH calculations and to our evaluated ENDF/B-VII cross sections in Figs. 10 and 11. The calculated (n,2n) cross section in Fig. 10 agrees well with the data of Knight et al. between threshold and 10 MeV, but the Knight data are somewhat higher than the other measurements at  $E_n=9-10$  MeV. We decided to follow the higher Knight et al. data for the evaluation in the threshold region, both because of the GNASH prediction and because of its consistency with the integral critical assembly data testing for the (n,2n) reaction rate discussed in Sec. V. Additionally, the (n,2n) calculations appear a little higher than the data between 15 and 20 MeV. Near threshold and at most energies to 15 MeV,



FIG. 8: Fission barrier heights for uranium isotopes obtained from the GNASH analysis.



FIG. 9: Measured and calculated fission cross section from 0 to 30 MeV.

however, the calculation agrees closely with the experimental data. The (n,3n) cross section over predicts the experimental data near 22 MeV but is in good agreement with the measurements from threshold to 18 MeV.

#### 3. Radiative capture cross section

We used a value of  $2\pi\Gamma_{\gamma}/D_0=0.007$  for our <sup>238</sup>U calculations, determined from experimentally inferred values of  $\Gamma_{\gamma}$  and D<sub>0</sub> [17], to normalize the gamma-ray strength function in the Kopecky and Uhl [48] generalized Lorentzian model utilized by GNASH. Our calculated  $(n,\gamma)$  cross section is compared to experimental data and to our evaluated ENDF/B-VII result (see Sec. IV.G.5) between  $E_n = 0.01$  and 30 MeV in Fig. 12. The experimental data included in Fig. 12 are from the measurements of Drake et al. [71], Kazakov et al. [72], Panitkin and Tolstikov [73], [74], Rimawi and Chrien [75], Block et al. [76], Poenitz et al. [77], Lindner et al. [78], Ryves et al. [79], Davletshin et al. [80], [81], and Mc-Daniels et al. [82]. In general, the calculation agrees well with most of the measurements, especially those of Lind-



FIG. 10: Measured and calculated  $^{238}\mathrm{U(n,2n)}$  cross section from threshold to 20 MeV.



FIG. 11: Measured and calculated  $^{238}\mathrm{U}(\mathrm{n},3\mathrm{n})$  cross section from threshold to 20 MeV.



FIG. 12: Measured and calculated  $^{238}{\rm U}({\rm n},\gamma)$  cross section from 10 keV to 20 MeV.

ner, Block, Davletshin, Kazakov, and Poenitz below 3 MeV, indicating that the  $(n,\gamma)/(n,n')$  competition in the discrete level region is handled reasonably. At higher energies, however, the calculation is about a factor of 2 higher than the Drake *et al.* and McDaniels *et al.* measurements over the approximate energy range  $E_n \sim 8-14$  MeV.

#### 4. Neutron emission spectra

The two major reactions that lead to neutron emission spectra in the actinides are the (n,xn) and (n,ynf) reactions, where x can be 1, 2, 3, or 4 and y can be 0, 1, 2, 3, or 4 for incident neutron energies up to 30 MeV. Neutrons from both sources are calculated for all isotopes. The calculations are described in the sections below.

a. Neutrons from fission : Prompt fission neutron spectra were calculated for the major actinides  $(^{235,238}\text{U}$  and  $^{239}\text{Pu})$  using the Los Alamos model (LAM) developed by Madland and Nix [83]. The fission neutron spectra for the remaining actinides utilize Maxwell distributions with parameterizations obtained from various sources or, in the case of  $^{233}\text{U}$ , an energy-dependent Watt spectrum.

The LAM is based upon classical nuclear evaporation theory and utilizes an isospin-dependent optical potential for the inverse process of compound nucleus formation in neutron-rich fission fragments with energy-dependent compound nucleus formation cross sections for inverse processes. The model accounts for the physical effects of (a) the motion of the fission fragments emitting the neutrons, (b) the distribution of fission-fragment residual nuclear temperature that results from the initial distribution of fission-fragment excitation energy, (c) the energy dependence of the cross section for the inverse process of compound-nucleus formation, and (d) the effects of and competition between first-, second-, third-, and fourth-chance fission, wherein the neutrons emitted prior to fission in multi-chance fission are included in the total prompt fission neutron spectrum [1], [83].

Semi-direct (preequilibrium) reactions are not currently included in the LAM. We believe the best way to incorporate such reactions is to use a Hauser-Feshbach approach in calculating the spectrum, which would guarantee the conservation of scattering flux. However, a full Hauser-Feshbach approach requires that the partition of the fissioning compound nucleus excitation energy into the light and heavy fragments be done in a physically correct manner, which has yet to be accomplished. Once that is done, however, the Hauser-Feshbach approach will also allow more reliable calculation of (n,ynf) reactions. Currently, the "yn" neutrons for (n,ynf) reactions from the LAM are evaporation spectra calculated at the average excitation energies of each successive fissioning nucleus in multi-channel fission at each incident neutron energy.

The exact formulation of the LAM was utilized for  $^{235,238}$ U and  $^{239}$ Pu. The lowest incident neutron energy for a measured fission cross section for  $n+^{238}$ U is just under 2 eV with a value of about 5 microbarns. Both  $^{233,235}$ U and  $^{239}$ Pu undergo fission at thermal neutron energies, so the prompt fission spectrum calculations

for these isotopes were carried to low energies. Average prompt neutron multiplicities from multiple-chance fission were calculated simultaneously and, in reproducing experiment, were important in determining the fission spectrum matrices. Until more experimental data become available, spectra for incident neutron energies above 20 MeV are roughly approximated by using the 20-MeV spectrum.

b. Neutrons from (n,xn) reactions : At lower excitation energies, where excitation energies, spins, and parities are known for discrete states, we used coupledchannels, DWBA, and Hauser-Feshbach calculations with the ECIS code [16] to determine cross sections and angular distributions of discrete (n,n') reactions. These calculations could typically be used for states up to several hundred keV in excitation energy for the odd-A isotopes and to somewhat higher energies for the even-A nuclides, at least in cases where the structure is understood.

We used DWBA calculations to estimate cross sections for vibrational states in  $^{235}$ U and  $^{239}$ Pu at excitation energies between 0.5 and 1.1 MeV. While such contributions are small in terms of the overall neutron spectrum, they do occur in an important part of the neutron spectrum. Cross sections of vibrational states at these excitation energies also have been calculated for  $^{238}$ U(n,n') reactions [84], and such contributions should be included for  $^{238}$ U and other U isotopes in the next update of the ENDF/B-VII evaluation.

At higher excitation energies (*i.e.*, between  $E_x=1$  and 4 MeV), where the level spacing is so dense that we usually cannot identify individual states, neutron emission spectra observed for  $n+^{238}U$  reactions are significantly higher than can be accounted for by conventional compound-nucleus or preequilibrium calculations. Similar effects were observed by Marcinkowski *et al.* [85] in measurements of neutron emission spectra from tungsten isotopes near 14 MeV. To explain the inability to account for the measurements assuming only compound nucleus and preequilibrium reactions, Marcinkowski inferred the existence of collective states in the spectrum of states at these excitation energies.

The evidence for such states in the case of <sup>238</sup>U+n comes from the neutron emission spectrum measurements of Baba *et al.* [45] at  $E_n = 14$  MeV. As with  $^{184}\mathrm{W}{+}\mathrm{n}$  reactions, it is not possible to reproduce Baba's data by assuming only compound nucleus and preequilibrium reactions. Therefore, we have postulated the existence of a series of  $J^{\pi}=3^{-}$  and  $2^{+}$  collective states at excitation energies in the range  $E_x=1$  and 4 MeV. We used DWBA calculations of the assumed states with ECIS96 at  $E_n = 14$  MeV to get an excitation energy-dependent shape, which we normalized to roughly match Baba's data. The deformation parameters that resulted from this normalization are given in Table VI for each assumed excitation energy, spin and parity. (No attempt was made to ensure that the postulated states obey energyweighted sum rules). The angle-integrated spectrum obtained at  $E_n=14$  MeV is compared in Fig. 13 to Baba's measurement [45] and to other evaluations. The calculated and evaluated spectra in Fig. 13 include neutron emission from fission as well as (n,xn) reactions.

We also used the DWBA calculations to obtain angular

TABLE VI: Beta deformation parameters obtained by matching  $n+^{238}U$  14-MeV neutron emission data.

Ex (MeV)	J	$\pi$	Beta
1.170	3.0	-1	3.8087 E-02
1.250	2.0	+1	3.0175E-02
1.440	3.0	-1	5.6001E-02
1.590	3.0	-1	3.8111E-02
1.750	3.0	-1	3.9460E-02
1.850	3.0	-1	3.5265E-02
1.950	3.0	-1	4.0750E-02
2.150	3.0	-1	4.7400E-02
2.300	3.0	-1	5.3002E-02
2.390	4.0	+1	8.8154E-03
2.490	2.0	+1	2.5122E-02
2.940	2.0	+1	2.7150E-02
3.189	2.0	+1	2.5287 E-02
3.388	2.0	+1	2.5070E-02
3.538	2.0	+1	1.5390E-02
3.637	2.0	+1	1.6125E-02
3.737	2.0	+1	1.6472E-02
3.837	2.0	+1	1.4293E-02
3.909	2.0	+1	1.5091E-02

distributions for the collective states. These assumptions lead to significantly improved neutron emission spectra from  $^{238}$ U (see Sec. IV.G.10 below), as well as in improved simulations of time-of-flight neutron distributions from pulsed-sphere experiments [86] in calculations with the MCNP Monte Carlo code [87].

Comparisons of the calculated and measured spectra for  $n+^{238}$ U are given in Fig. 14 for  $E_n=4.25$  MeV,  $\theta_n=45^\circ$ ; in Fig. 15 for  $E_n=14.05$  MeV,  $\theta_n=90^\circ$ ; and in Fig. 16 for  $E_n=18.0$  MeV,  $\theta_n=120^\circ$ . In addition to Baba's data in Figs. 14 and 15, Fig. 16 contains experimental data from Matsuyama *et al.* [88]. It should be noted that a Gaussian resolution function of 7.1%, which approximates the experimental resolution, has been folded into the evaluated spectra, and neutron emission from fission is included in the figures.

A slight under-calculation of the 4.25-MeV spectrum at emission energies corresponding to excitation energies between 0.5 and 1.1 MeV is seen in Fig. 14, presumably due to not including direct reactions at those energies, as mentioned above.

The <sup>238</sup>U(n,n'continuum) cross section threshold occurs at  $E_n=1.12$  MeV. Therefore, an underlying compound-nucleus-plus-preequilibrium continuum is present in emission spectra calculated with the above collective state cross sections. The GNASH cross sections and energy-angle distributions were used directly for the (n,n'continuum) reactions for all isotopes, also utilizing Kalbach angular distribution systematics [51].

#### 5. Delayed neutron multiplicities and spectra

The 1989 work of England and Brady [89] produced fission-product nuclide inventories along with their individual contributions to production and spectra of delayed neutrons (DN) at a range of times following fission. The temporal inventories were calculated for each of the fission product yield sets present in the ENDF/B-VI actinide evaluations for thermal-, fast-, and/or high-energy



FIG. 13: Comparison of  $n+^{238}U$  angle-integrated neutron emission spectra from evaluations with the measurement of Baba *et al.* at  $E_n = 14.05$  MeV.



FIG. 14: Double-differential neutron emission spectra from the  $n+^{238}$ U reaction at incident neutron energy  $E_n = 4.25$  MeV with an emission angle of  $45^{\circ}$ .



FIG. 15: Double-differential neutron emission spectra from the  $n+^{238}$ U reaction at incident neutron energy  $E_n = 14.05$  MeV with an emission angle of 90°.



FIG. 16: Double-differential neutron emission spectra from the  $n+^{238}$ U reaction at incident neutron energy  $E_n = 18.0$  MeV with an emission angle of  $120^{\circ}$ .

neutron-induced fission. The temporal DN production was fit accurately with a traditional sum of six exponential terms. The historical interpretation of this series, numerically equivalent to six simply-produced fission products that decay only by DN emission, is that the six exponentials are viewed as groupings of DN precursors by decay constants of the six "groups". Six group fractions and decay constants were produced by the fits. Then the spectra of each group were constructed from fractional contributions of the nuclides. Each nuclide's spectrum was apportioned to groups with neighboring decay constants. The resulting delayed neutron multiplicities and spectra were included in the ENDF/B-VI.8(Release 8) evaluation.

New DN 6-group parameters obtained from summation calculations with the CINDER'90 [90] code have been incorporated into the ENDF/B-VII evaluations. These calculations use Pfeiffer-Kratz-Moller [91] updated (measured) half-life and/or  $P_n$  data, supplemented with calculated data from their QRPA-FFS (first-forbidden statistical) model [92]. These parameters were used to calculate new delayed neutron multiplicities and decay constants, and these were incorporated into our evaluation in sections MF=1, MT=455 and MF=5, MT=455. New multigroup spectra have not yet been calculated, however, so the older six-group spectra from the ENDF/B-VI.8 evaluation are carried over and used in our ENDF/B-VII evaluation, regardless of the inconsistency between the older and newer group decay constants.

#### **III. EVALUATION METHODOLOGY**

Our procedure in performing the data evaluations was to combine theoretical analyses with the available experimental data for each isotope. The first step in each analysis was to perform coupled-channels optical model and Hauser-Feshbach statistical-plus-preequilibrium theory calculations, optimized to whatever data were available as described above in Section II. The model calculations were utilized in all the evaluations, but the extent varied according to the amount of experimental data that were available. The individual evaluations are described in more detail and compared to experimental data in Section IV below.

#### A. Cross sections and neutron multiplicities

Because of the abundance of experimental cross section data for  $n+^{238}$ U reactions, we relied significantly on measurements for that evaluation, both directly and in normalizing calculations. On the other hand, for isotopes such as  $^{237,239-241}$ U, model calculations were used almost exclusively for the evaluations. For the remaining isotopes, model calculations were used to varying extents, usually with model parameters optimized to experimental data. In all cases experimental data for fission cross sections were utilized directly at energies where the data were regarded as reliable. In the evaluations of all isotopes, either relative or absolute model calculations of excitation cross sections of the (n,n'), (n, $\gamma$ ), and (n,xn) reactions were used over at least part of the energy ranges.

Overall characteristics of several reactions among the various isotopes are described here. The total cross sections for the uranium isotopes are compared in Fig. 17. It is seen that the cross sections do not vary significantly among the various isotopes, except in the minima near 2 and 12 MeV, and near 20 MeV. These effects come in part from the isospin dependence of the optical model potentials that were used in the calculations. Experimental data for the total cross section are mainly limited to  $^{233,235,238}$ U, so the other isotopes rely heavily on the systematics of the optical potentials. The neutroninduced fission cross sections for the various U isotopes are compared in Fig. 18 for neutron energies between 0 and 20 MeV. The cross sections generally decrease with increasing A, consistent with the trend of increasing barrier height with increasing A seen in Fig. 8. The curves shown for <sup>233–236</sup>U and <sup>238</sup>U were determined primarily from direct neutron measurements. The  $^{232}$ U curve is based on GNASH calculations and limited experimental data, whereas the  $^{237}$ U and  $^{239}$ U fission cross sections rely to a large extent on surrogate (t,pf) fission probability measurements together with GNASH calculations. The remaining  $^{240,241}$ U evaluations are based entirely on GNASH calculations with extrapolated model parameters. More details are given in Section IV below.

The inelastic scattering cross sections for the U isotopes are illustrated in Fig. 19. Here the effect of adding neutrons to the uranium core is clearly seen, with the cross section systematically increasing with increasing A. This effect is demonstrated even more dramatically in Fig. 20, where the (n,2n) cross sections are shown for the U isotopes. The cross section for the <sup>240</sup>U(n,2n) cross section is roughly an order of magnitude higher than the <sup>232</sup>U(n,2n) cross section.

The  $(n,\gamma)$  cross sections for the various U isotopes are compared in Fig. 21. In this case the cross sections generally decrease with increasing A above the (n,n') threshold. That is, the isotopes with higher neutron emission cross sections have lower  $(n,\gamma)$  cross sections. Below the (n,n') thresholds the behavior of the  $(n,\gamma)$  cross sections is less systematic, but the heavier even-A isotopes generally have smaller cross sections, whereas this effect is



FIG. 17: Comparison of the total cross sections of the various uranium isotopes between 0 and 20 MeV.

somewhat reversed for the odd-A isotopes. Again, more details of the evaluations for the individual isotopes are given below. As a final overall comparison, Fig. 22 shows the average neutron multiplicities from prompt fission (nubar) of the U isotopes. As would be expected, the multiplicities generally increase as neutrons are added to the U core. An exception to this is nubar for  $^{232}\mathrm{U}$  (and possibly  $^{237}$ U), which is seen to be generally higher than the nubar curves for the heavier isotopes. This effect is thought to be spurious because the  ${}^{232}U$  nubar curve was taken over unchanged from the ENDF/B-V evaluation. which in turn is based on an older measurement. More recent evaluations of  $^{232}$ U nubar are consistent with the trend of the other U isotopes. This problem will be corrected in the first revision of ENDF/B-VII.

#### B. Angle and energy distributions

For the evaluations of all the isotopes, model calculations were utilized for angular distributions of elastic and inelastic neutrons, and for energy-angle correlated neutron emission spectra from (n,n') and (n,xn) continuum reactions, as described in Sec. II above. In some cases (for example, <sup>238</sup>U+n), minor renormalizations based on experimental data were implemented. The elastic and low-lying inelastic scattering angular distributions were



FIG. 18: Comparison of the fission cross sections of the various uranium isotopes between 0 and 20 MeV.

determined by combining compound elastic contributions with shape elastic and direct reaction calculations from ECIS96 [16] using the coupled-channels optical model potentials in Tables I-V. The compound nucleus contributions were calculated either with COMNUC [52], with GNASH [46], or with ECIS96. Contributions from direct reactions at  $E_x=1-4$  MeV were approximated in most cases by direct use of our <sup>238</sup>U results (Sec. II). Preequilibrium angular distributions were used to approximate direct components for higher excited states in some cases. For all isotopes, neutrons from fission reactions are assumed to be isotropic at all incident energies.

Legendre polynomials were used for all isotopes at all energies to represent discrete inelastic scattering angular distributions. Legendre polynomials also were utilized to represent elastic scattering angular distributions, but elastic angular distributions were sometimes tabulated above 10 MeV to prevent problems with the limitation on the maximum order of Legendre expansions permitted under earlier ENDF-6 rules. In all cases, energy-angle distributions in ENDF-6 File 6 format are used to represent neutrons from (n,n'continuum), (n,2n), (n,3n), and (n,4n) reactions. The energy distributions are obtained from the GNASH calculations. The angular distributions are specified using Kalbach systematics [51] with the ENDF-6 format LAW=1, LANG=2 Kalbach-Mann option.



FIG. 19: Comparison of inelastic scattering cross sections for the various uranium isotopes between 0 and 20 MeV.

#### C. Gamma-ray production

Virtually all gamma-ray production data for ENDF/B-VII were adopted from the previous ENDF/B-VI.8 evaluations.

#### IV. EVALUATION DETAILS

In this section we describe in more detail the evaluations of neutron-induced reactions on the isotopes of U for A=232-241 and <sup>239</sup>Pu. We place particular emphasis on comparing our ENDF/B-VII evaluations above the resonance region with experimental data and with additional evaluations. The other evaluations to which we will compare are the previous version of the U.S. evaluated data system, ENDF/B-VI, Release 8; either the previous or present version of the European Joint Evaluated data file, JEFF-3.0 or JEFF-3.1; and the present version of the Japanese Evaluated Nuclear Data Library, JENDL-3.3.



FIG. 20: Comparison of the (n,2n) cross sections for the various uranium isotopes between threshold and 20 MeV.

# A. $n+^{232}U$ evaluation

#### 1. $^{232}U$ summary

The  $n+^{232}U$  evaluation above the resonance region is based mainly on the model calculations described in Secs. II and III.

#### 2. <sup>232</sup> U resonance region

The resolved resonance region for the n +  $^{232}$ U evaluation extends from 10<sup>-5</sup> to 194 eV, and the unresolved region covers the range 194 eV to 2 keV. Both these evaluations are from MOD 2 of ENDF/B-VI [93]. The resolved resonance parameters utilize the Reich-Moore formalism, with parameters obtained from the compilation of Mughabghab [94]. The unresolved resonance evaluation also utilizes Mughabghab's parameters.

#### 3. $^{232}U(n,f)$ cross section

The only  $n+^{232}U$  reaction for which significant experimental data exist is fission. The total fission cross section in our evaluation at lower energies is based on the



FIG. 21: Comparison of the  $(n, \gamma)$  cross sections for the various uranium isotopes between 0.1 and 20 MeV.

experimental data of Fursov [95] and follows closely the ENDF/B-VI.8 evaluation [93] to a neutron energy of 7 MeV. For the energy range 7-30 MeV, the (n,f) cross section is taken from the GNASH analysis. Our results below 4 MeV are compared to the other evaluations and to our GNASH calculations in Fig. 23.

The fission barrier and level density parameters used for the  $n+^{232}U$  GNASH calculations were taken from our combined analysis of uranium target isotopes from A=232 to A=238, and no effort was made to specifically optimize the parameters for  $^{232}U$ . Consequently the match between theory and experiment is somewhat poor below 2 MeV. At higher energies, however, the calculated cross section from GNASH is satisfactory and appears reasonable out to 30 MeV. In Fig. 24 we compare the experimental data, the various evaluations, and the calculation from 4 to 30 MeV.

## 4. Other $n+^{232}U$ reactions

The evaluated data for all reactions other than fission are based entirely on nuclear model calculations. These reactions include the neutron total, elastic, (n,n'), (n,2n), (n,3n), (n,4n), and  $(n,\gamma)$  cross sections. Additionally, the GNASH calculations were utilized to distribute the (n,f)cross section among the (n,nf), (n,2nf), (n,3nf) multi-



FIG. 22: Comparison of prompt nubar for the various uranium isotopes between 0 and 20 MeV.



FIG. 23: Evaluated and measured  $^{232}\mathrm{U}(n,f)$  cross section from 2 keV to 4 MeV.

chance fission channels. Our evaluated  $n+^{232}U$  total cross section is based on the coupled-channels calculations described in Sec. II.A. It is compared with other evaluations in Fig. 25. The various evaluations agree well except for JEFF-3.1, which is approximately 10% higher at most energies.



FIG. 24: Evaluated and measured  $^{232}\mathrm{U(n,f)}$  cross sections from 4 to 30 MeV.

Our evaluated <sup>232</sup>U(n,2n) cross section is taken directly from the GNASH analysis and is compared to the other evaluations in Fig. 26. The ENDF/B-VI.8 evaluation was obtained from JENDL-3.2, which is the same as JENDL-3.3. The present result is lower than the other evaluations, and the JEFF-3.1 evaluation is a factor of 10-30 higher than the other evaluations. Our evaluated <sup>232</sup>U(n,3n) cross section also is lower than the other evaluations; the JEFF-3.1 evaluation of the (n,3n) cross section is a factor of ~100 higher than the other evaluations.

Direct components of the (n,n') reactions to the first three excited states of  $^{232}$ U were obtained from the ECIS96 calculations. Compound-nucleus contributions for all discrete (n,n') excitation cross sections were obtained from the GNASH and ECIS96 calculations, as was the (n,n'continuum) cross section. Direct cross section components for the excitation energy range 1-4 MeV were taken from the ENDF/B-VI (Release 5) evaluation [96] of  $^{238}$ U. As described in Sec. II.4.a above, these  $^{238}$ U direct cross sections are based on ECIS96 calculations, normalized to be consistent with  $^{238}$ U(n,xn) neutron spectrum measurements near 14 MeV [45].

The  $^{232}$ U inelastic cross section that results from summing all the individual (n,n') components is compared to the other evaluations in Fig. 27. The present result lies between the JEFF-3.1 and ENDF/B-VI.8/JENDL-3.3 evaluations.

Our calculated  $^{232}$ U(n, $\gamma$ ) cross section is compared to the other evaluations in Fig. 28. Additional uncertainty is introduced into the (n, $\gamma$ ) cross section due to the poorer fit to the (n,f) cross section below 2 MeV. However, the present result, which was obtained from the GNASH analysis, is similar to and consistent with the JEFF-3.1 evaluation.

# 5. $n+^{232}U$ angular and energy distributions

The neutron angular distributions and  $^{232}U(n,xn)$  emission spectra were obtained from the calculations, as described in Sec. III.B.

The fission neutron spectra and prompt nubar were



FIG. 25: Evaluated neutron total cross sections for  $^{232}\mathrm{U}.$ 



FIG. 26: Evaluated  $^{232}$ U(n,2n) cross section from threshold to 30 MeV. Note that the JEFF-3.1 curve has been divided by a factor of 10.



FIG. 27: Evaluated integrated  $^{232}U(n,n')$  cross section from threshold to 30 MeV.



FIG. 28: Evaluated  $^{232}\mathrm{U}(\mathrm{n},\gamma)$  cross section from  $10^{-5}$  eV to 30 MeV.

adopted directly from the ENDF/B-VI (MOD 2) evaluation [93] with linear extrapolation of the data to 30 MeV. Nubar for  $^{232}$ U is discussed above in Sec. III.A. As stated there, the nubar curve is unreasonably high considering the trend of the systematics and disagrees with more recent evaluations. The present nubar evaluation will be reexamined in the first revision of ENDF/B-VII.

#### B. $n+^{233}U$ evaluation

#### 1. $^{233}U$ summary

In 2003 we completed a new analysis of cross sections for neutron reactions on  $^{233}$ U for neutron energies between 10 keV and 30 MeV [2]. Since that time, a new set of standards for cross section and other nuclear data was developed for the ENDF/B-VII nuclear database [6]. We therefore undertook the present revision to ensure that our ENDF/B-VII evaluation is consistent with the standards database. Most of the remaining data are taken from our 2003 evaluation.

The most important reactions affected by the revised neutron data standards are the fission cross section and the average multiplicity of prompt neutrons from fission reactions. Other quantities, while usually dependent on standards, are not measured to sufficient accuracy that small changes in the standards have significant impact. We obtained the experimental data for  $^{233}$ U(n,f) and nubar from the EXFOR/CSISRS database at the NNDC. Most of the  $^{233}$ U fission cross-section data and prompt neutron multiplicities from fission are in the form of ratios. As described earlier, most of the fission cross section data are relative to the well known  $^{235}$ U fission cross section, and likewise most of the  $^{233}$ U nubar data are relative to  $^{252}$ Cf nubar. All relative nubar and (n,f) measurements were normalized to ENDF/B-VII standards.

Because of the large quantity of fission cross section and nubar data available, we performed a covariance analysis of these experimental data using the Oak Ridge code GLUCS, developed by Hetrick and Fu [97]. This analysis combined all the experimental data, including uncertainties and correlations, and output the results on a pre-selected energy grid. Results are presented below.

The other significant new feature of the  $n+^{233}$ U evaluation comes from our incorporation of the results from our modern theoretical analysis, as summarized in Sec. II. We utilized default parameters for level densities and preequilibrium in our GNASH calculations. Gamma-ray strength functions were normalized to experimental information on  $2\pi\Gamma_{\gamma}/D_0$ , with a slight renormalization to optimize calculation of the <sup>233</sup>U(n, $\gamma$ ) cross section with the experimental data of Hopkins *et al.* [98].

#### 2. <sup>233</sup> U resonance parameters

Below 40 keV, we combined our results with a recent evaluation by Leal *et al.* [99] from ORNL of the resolved and unresolved resonance regions, which resulted in a complete, ENDF-6 formatted evaluation covering the energy range from  $10^{-5}$  eV to 30 MeV. The resonance parameter evaluation was performed using the multilevel R-matrix analysis code SAMMY [100]. The resolved resonance evaluation spans the energy range from 0 to 600 eV. The unresolved resonance region evaluation covers the energy range from 600 eV to 40 keV. Details of the evaluation are given in Ref. [99].

#### 3. $^{233}U(n,f)$ cross section

Several important newer measurements of the fission cross section were available for our evaluation. Included among these are results from Kanda et al. [101], Shpak and Koroljov [102], and Bergman et al. [103] below 7 MeV, and new measurements of the  $^{233}\mathrm{U}/^{235}\mathrm{U}$  fission cross section ratio near 14.7 MeV by Meadows [104] and Zasadny et al. [105]. In addition to his precision measurement of  $^{233}$ U, Meadows also measured ratios of  $^{230}$ Th,  $^{232}$ Th,  $^{234}$ U,  $^{236}$ U,  $^{238}$ U,  $^{237}$ Np,  $^{239}$ Pu and  $^{242}$ Pu relative to <sup>235</sup>U, which links the fission cross section at 14.74 MeV for most of the major actinides. None of these measurements were included in the ENDF/B-VI.8 evaluation, which in fact was carried over from an older (1978) ENDF/B-V data file. As described above, we utilized a covariance analysis that took account of the entire database, including several absolute (n,f) cross section measurements.

Most of the newer measurements below 7 MeV are in reasonable agreement with one another and consistent with the bulk of older measurements. We chose to emphasize these newer measurements in our evaluation, as well as the 1974 data of Meadows [106]. This occurred naturally by utilizing the results of the covariance analysis for our evaluation. The new 14.7-MeV measurements of Meadows [104] and Zasadny [105] are consistent and point to a higher fission cross section than is given in the ENDF/B-VI.8 evaluation. We utilize directly the GNASH calculation for the fission cross section between 6.5 and 16 MeV.

We compare our evaluated  $^{233}U(n,f)$  cross section to the other evaluations (upper half) and to a sampling of experimental data (lower half) between 0.04 and 2 MeV in Fig. 29. We also include the results of our covariance



FIG. 29: Evaluated <sup>233</sup>U(n,f) cross sections for  $E_n=30$  keV to 2 MeV compared to our covariance analysis (upper) and to experimental data (lower).

analysis in the upper part of Fig. 29. Similarly, Fig. 30 compares the evaluated and measured fission cross section data between 2 and 30 MeV. In addition to the newer data by Meadows [104] and Kanda *et al.* [101], we include the older measurements by Meadows [106], Carlson and Behrens [107], Behrens *et al.* [54], and Pfletschinger and Käppeler [108] in Figs. 29 and 30.

#### 4. Neutron multiplicity from <sup>233</sup> U prompt fission

Our evaluation of prompt nubar is based entirely on experimental data, and all results were normalized to ENDF/B-VII standards. As described earlier, most of the measurements are relative to spontaneous fission of  $^{252}$ Cf, which has a standard value of nubar=3.7692±0.12%. In addition, we used the value of nubar for  $^{233}$ U at thermal neutron energy that was recommended for the ENDF/B-VI thermal constants, in particular, total nubar (thermal)=2.4968 ± 0.14%. Much of the experimental data base is fairly old. We did utilize all the available data but tended to emphasize the more recent data in our analysis. In particular, we emphasized the measurements of Gwin *et al.* [109], Nurpeisov *et al.* [110], Boldeman and Walsh [111], Nurpeisov *et al.* [112], and Gwin *et al.* [113] in the incident neutron energy



FIG. 30: Evaluated  $^{233}$ U(n,f) cross sections for E<sub>n</sub>=2 to 30 MeV compared to our covariance analysis (upper) and to experimental data (lower).

range of 0 to 10 MeV. All the data at 14 MeV are quite old, but we chose to emphasize the results of Smirenkin *et al.* [114] and Flerov and Talyzin [115].

Our evaluated nubar prompt values are compared to our covariance analysis of the experimental data and to the ENDF/B-VI.8, JEFF-3.1, and JENDL-3.3 evaluations in Figs. 31 and 32. Figure 31 covers the energy range from 1 keV to 2 MeV, and Fig. 32 shows the data from 2 to 20 MeV. Also included in both figures is a sampling of experimental data.

The various evaluations are reasonably consistent up to about 6 MeV. Above 6 MeV, however, the differences among the evaluations are larger and, especially above 10 MeV, the JENDL-3.3 evaluation deviates significantly from both the experimental data and the other evaluations.

# 5. $n + {}^{233}U$ total cross section

Our evaluation of the n +  $^{233}$ U total cross section between 0.2 and 13 MeV is taken directly from the ENDF/B-V.2 evaluation, which in turn is based on the measurements of Poenitz *et al.* [18], Foster and Glasgow [116], and Green and Mitchell [117]. Above 13 MeV, our



FIG. 31: Evaluated  $n+^{233}$ U prompt nubar for  $E_n=1$  keV-3 MeV compared to our covariance analysis (upper frame) and to experimental data (lower frame).

evaluated total cross section is the result of our coupledchannels optical model calculation using the Young potential [2], [4], which agrees well with the Foster data. Below 0.2 MeV, the ENDF/B-VI.8 total cross section was adjusted downward by approximately 1% to better agree with the 1981 experimental data of Poenitz *et al.* [18]. Note that the only new data on the total cross section since the ENDF/B-V.2 evaluation is the 1983 measurement of Poenitz and Whalen [118].

Figures 33 and 34 illustrate the <sup>233</sup>U+n total cross section for  $E_n = 0.04$ -4 MeV and 4-30 MeV, respectively. The experimental data of Poenitz *et al.* [18], Foster and Glasgow [116], Poenitz and Whalen [118], and Green and Mitchell [117] are included for comparison with the various evaluations and the optical model calculation. Note that the JEFF-3.1 evaluation is taken from JENDL-3.3. In each of these figures an expanded cross section scale is used, so the differences seen between the measurements, the evaluations, and the optical model calculation are quite small, typically within a few percent.

There is a discrepancy between the measurements of Foster and Glasgow [116] and those of Poenitz [118], especially in the 8-12 MeV region. Because the Young potential is more consistent with the Foster data, we chose to utilize it and the resulting optical calculations for the ENDF/B-VII evaluation at energies above 13 MeV.



FIG. 32: Evaluated <sup>233</sup>U(n,f) prompt nubar for  $E_n=2-30$  MeV compared to our covariance analysis (upper) and to experimental data (lower).

# 6. $n+^{233}U$ elastic and inelastic scattering

The only available experimental data on neutron elastic and inelastic scattering are angular distribution measurements at  $E_n=0.7$  and 1.5 MeV by Haouat *et al.* [12]. Fortunately, these measurements are reasonably accurate and provide a good test for the optical model potentials at these energies. The energy resolution in the experiment was adequate to resolve scattering to the ground-, first- and second-excited states of <sup>233</sup>U. We examined several optical model potentials for  $n + {}^{233}U$  scattering but found that the potential given in Table V [2], [4] consistently matched the experimental data quite well. This potential was used to calculate the elastic and inelastic scattering angular distributions at all energies. The <sup>233</sup>U(n,n') calculated cross sections were used directly in our evaluation. The elastic cross section was determined by subtracting the sum of all the nonelastic reaction cross sections from the total cross section. Because both the total and fission cross sections are determined from experimental data, the resulting elastic cross section is not identical to the coupled-channels optical model calculation but is reasonably close.

The evaluated elastic scattering angular distribution at 1.5 MeV is compared with the measurement of Haouat et



FIG. 33: Measured and evaluated neutron total cross section from 0.04 to 4 MeV.



FIG. 34: Measured and evaluated neutron total cross section for n +  $^{233}{\rm U}$  from  ${\rm E}_n{=}4$  to 30 MeV.

al. [12] and with other evaluations in Fig. 35. Also shown in Fig. 35 is the optical model result, which is essentially the same as the evaluation. The calculated results agree reasonably with the experimental data, especially considering that no adjustment has been made to the potential that was derived from  $^{238}$ U measurements [4].

The evaluated elastic cross section that resulted from our subtraction procedure is shown in Fig. 36, together with the other evaluations, the optical model calculation, and the experimental results obtained by integrating the angular distribution measurements of Haouat *et al.* The difference between the evaluation and the optical model calculations results from the subtraction method used to determine the evaluated cross section.

The evaluated angular distributions for the <sup>233</sup>U(n,n') reactions to the 40-keV and 92-keV rotational states of <sup>233</sup>U at  $E_n=1.5$  MeV are compared to the experimental data of Haouat *et al.* and to the ENDF/B-VII, ENDF/B-VI.8, and JENDL-3.3 evaluations in Fig. 37. Again, note that the JEFF-3.1 evaluation is the same as JENDL-3.3. The present results agree significantly better with experi-



FIG. 35:  $^{233}\mathrm{U(n,n)}$  Elastic Scattering Angular Distribution at  $\mathrm{E}_n{=}1.5$  MeV.

ment than the previous evaluations, especially ENDF/B-VI.8, which utilizes simple isotropic angular distributions for all (n,n') reactions. The angle-integrated cross sections for (n,n') reactions to these states are compared to Haouat's data and the various evaluations for neutron energies up to 30 MeV in Fig. 38.

As summarized earlier, these results come from ECIS96 calculations, which were also used to obtain the (n.n') cross sections and angular distributions for the other coupled states at  $E_x=155$ , 229, 315, and 411 keV. The (n,n') cross sections to the remaining uncoupled states were obtained either from GNASH calculations normalized for consistency with Haouat's data and with the ECIS96 results, or from ECIS96 DWBA calculations. The total inelastic cross section was determined by summing the (n,n') cross sections to individual states with the continuum (n,n') cross section obtained from the GNASH analysis. The total (n,n') cross section summed over all states is compared to the ENDF/B-VI.8 and JENDL-3.3 (JEFF-3.1) evaluations in Fig. 39. The pronounced peak in the inelastic cross section near  $E_n \sim$ 0.2 MeV results naturally from the ECIS96 calculation of the 40-keV, first-excited state excitation function.

#### 7. $n+^{233}U$ radiative capture cross section

The only measurement of the <sup>233</sup>U(n, $\gamma$ ) cross section above 40 keV is by Hopkins and Diven [98]. As described above, we utilized the GNASH calculation of the (n, $\gamma$ ) reaction at all energies, after a 20% adjustment of the normalization for better consistency with the Hopkins and Diven data. The original gamma-ray strength function normalization was based on  $2\pi\Gamma_{\gamma}/D_0$ . The (n, $\gamma$ ) cross section that results is compared to the Hopkins and Diven measurement and to the other evaluations in Fig. 40.



FIG. 36: n +  $^{233}\mathrm{U}$  elastic scattering cross section from 0 to 30 MeV.

#### 8. $^{233}U(n,xn)$ cross section

The evaluated  $^{233}$ U(n,2n) cross section is compared to other evaluations in Fig. 41. Similarly the  $^{233}$ U(n,3n) cross section is shown in Fig. 42 with the other evaluations. Both the (n,2n) and (n,3n) ENDF/B-VII curves are based entirely on calculations with the GNASH code.

#### 9. $n+^{233}U$ angular and energy distributions

The neutron angular distributions and  $^{233}$ U(n,xn) emission spectra were obtained from the calculations with the ECIS96 [16] and GNASH [46] codes, as described in Sec. III.B.

The fission neutron spectra are carried over from the previous ENDF/B-VI (Release 8) evaluation. That evaluation utilizes an energy-dependent Watt spectrum, which has an average energy for thermal neutrons of 2.073 MeV, and is based on ratio data with  $^{235}$ U and  $^{239}$ Pu.

#### C. $n+^{234}U$ Evaluation

#### 1. <sup>234</sup> U Summary

Major improvements were made to the  $n+^{234}$ U evaluation above the resonance region. In addition to a modern theoretical analysis over the range 0.01 to 20 MeV, new experimental data were available for the  $^{234}$ U(n, $\gamma$ ) reaction, and improved delayed neutron and prompt nubar data were incorporated, the latter based on experimental data.

#### 2. $^{234}U$ resonance parameters

The resolved and unresolved resonance region data in the previous version of the ENDF/B-VI.8 evaluation [119] for  $^{234}$ U are adopted in the present work, with



FIG. 37: <sup>233</sup>U(n,n') inelastic scattering angular distributions for the 40- and 90-keV states at  $E_n=1.5$  MeV.

some modification of the unresolved parameters to enhance agreement with experiment. In the ENDF/B-VI.8 evaluation, the resolved resonances are taken from James et al. [119] with the bound level parameters modified to fit BNL-325 Vol. 1 thermal and resonance integral cross sections. The resolved resonance region covers the incident neutron energy range from  $10^{-5}$  eV to 1.5 keV.

The unresolved resonance region covers the energy range from 1.5 to 100 keV. The unresolved parameters were obtained originally by fitting the averaged (n,f) cross section data of James *et al.* and ENDF/B-IV radiative capture cross sections from 1.5 to 100 keV. In our evaluation we changed  $\langle \Gamma_{\gamma} \rangle$  from 25 meV to 20 meV in order to improve agreement with new experimental data for the <sup>234</sup>U(n, $\gamma$ ) reaction from the LANSCE facility at Los Alamos by Rundberg [121].

# 3. $n+^{234}U$ radiative capture

The  $^{234}$ U(n, $\gamma$ ) measurement from LANL [121] was also important for our evaluation above the unresolved resonance region, as it extended to  $E_n=45$  keV. Prior to that measurement, we relied on the binned experimental data



FIG. 38:  $^{233}\mathrm{U}(\mathrm{n,n'})$  cross sections from threshold to 4 MeV for the 40- and 92-keV levels.



FIG. 39: The  $^{233}$ U(n,n') cross section integrated over all final states for  $E_n$ =threshold to 30 MeV.

of Muradyan et al. [122], which extended to near the top of the unresolved resonance region. For the present evaluation we utilized the shape of the  $(n,\gamma)$  cross section from our GNASH calculation but renormalized it (slightly) for better agreement with the experimental data of Rundberg. Our ENDF/B-VII results are compared to the experimental data and to other evaluations in Fig. 43. The



FIG. 40: Measured and evaluated cross sections for the  $^{233}{\rm U}({\rm n},\gamma)$  reaction.



FIG. 41: Evaluated  $^{233}\mathrm{U}(\mathrm{n},2\mathrm{n})$  Cross Section from threshold to 30 MeV.



FIG. 42: Evaluated  $^{233}\mathrm{U}(\mathrm{n}{,}3\mathrm{n})$  Cross Section from threshold to 30 MeV



FIG. 43: Evaluated  $^{234}\mathrm{U}(\mathrm{n},\gamma)$  cross section from 0.01 eV to 1 MeV

Rundberg data are seen to lie somewhat below the Muradyan et al. results.

# 4. $^{234}U(n,f)$ cross section

The fission cross section experimental data for  $^{234}$ U that we utilized are relative to <sup>235</sup>U, appropriately normalized to a reference cross section based on ENDF/B-VI standards below 14 MeV [7] and new higher energy data [8] above 14 MeV. The total fission cross section is based on the experimental data of White et al. [123] at neutron energies below  $\sim 0.6$  MeV. From 0.6 to 30 MeV, the evaluation primarily follows the experimental data of Behrens and Carlson [124]. The Behrens data cover most of the energy range of our evaluation and appear reasonably consistent with the measurements of Fursov et al. [125], Meadows [126], Kanda et al. [101], Meadows [104], and Goverdovskij et al. [127]. Our results below 4 MeV are compared to the experimental data and to the other evaluations in Fig. 44. Similarly, in Fig. 45 we show the various evaluations and experimental data from 4 to 30 MeV. The largest differences among the various evaluations occur in the energy range above 10 MeV, where ENDF/B-VII is higher, following the measurements of Behrens and Carlson.

# 5. Neutron multiplicity from <sup>234</sup> U prompt fission

Our ENDF/B-VII evaluation of prompt nubar is taken from the evaluation of Maslov et al. [128]. The various evaluations are compared to the measurement of Mather *et al.* [129] in Fig. 46. The various evaluations are in good agreement below 15 MeV.

# 6. Other $n+^{234} U$ reactions

The evaluated data for all reactions other than fission and radiative capture are based entirely on our nuclear model calculations. These reactions include the neutron



FIG. 44: The  $^{234}\mathrm{U}(\mathrm{n,f})$  fission cross section from 0 to 4 MeV.



The  $^{234}$ U(n,f) fission cross section from 4 to 30 MeV.

total, elastic, (n,n'), (n,2n), (n,3n), and (n,4n) cross sections. The optical model parameters used in the coupledchannels calculations are given in Table II. GNASH calculations were utilized to obtain the reaction cross sections and to distribute the (n,f) cross section among the (n,nf), (n,2nf), (n,3nf) multichance fission channels.

The  ${}^{234}$ U(n,2n) cross sections from the various evaluations are compared in Fig. 47. Similarly, the  ${}^{234}$ U(n,3n) cross sections are compared in Fig. 48. The differences among the various curves simply reflect the spread in the model calculations used for the evaluations.

The  $n+^{234}$ U inelastic cross sections from the different evaluations are given in Fig. 49, and the  $^{234}$ U neutron total cross sections are compared in Fig. 50. Large discrepancies are seen among the inelastic cross section evaluations, and the largest differences occur for the ENDF/B-VI.8 evaluation. The relatively large inelastic cross section above  $E_n \sim 10$  MeV results from the collective reactions included in the calculations, particularly from the ground-state rotational band. The total cross sections are much more consistent, reflecting the greater reliability of deformed optical model calculations. Again, the most prominent outrider in the data is the ENDF/B-VI.8



FIG. 46: Prompt fission nubar for  $n+^{234}U$  reactions.



FIG. 47: The  $^{234}\mathrm{U}(\mathrm{n,2n})$  cross section from threshold to 30 MeV.

evaluation.

#### 7. $n+^{234} U$ angular and energy distributions

The neutron angular distributions and  $^{234}$ U(n,xn) emission spectra were obtained from the GNASH [46] calculations, as described in Sec. III.B.

Neutron emission spectra from prompt fission of  $^{234}$ U were taken from the evaluation of Maslov et al. [128]. With Maslov's model, the prompt fission neutron spectra are the sum of two Watt distributions, one each for the light and heavy fragments. Physical parameters are utilized, plus two empirically adjusted parameters optimized by fitting measured spectra for several actinides. Contributions to the spectra from pre-fission (n,xnf) neutrons are included using a Hauser-Feshbach model. It should be noted that this procedure introduces a minor inconsistency in that the (n,xnf) cross sections from the GNASH calculations are not the same as those from Maslov's analysis.



FIG. 48: The  $^{234}\mathrm{U}(\mathrm{n}{,}3\mathrm{n})$  cross section from threshold to 30 MeV.



FIG. 49: The  $\rm n+^{234}U$  inelastic cross section from threshold to 30 MeV.

# D. $n+^{235}U$ evaluation

## 1. $^{235}U$ summary

The maximum energy of the evaluation remains at 20 MeV, the same as ENDF/B-VI.8. The total, fission, and radiative capture cross sections are based mainly on experimental data, complimented by nuclear model calculations. As usual, model parameters for the calculations were obtained by optimization with experimental data. The neutron total and (n,f) cross section revisions include new experimental data that were not included in the ENDF/B-VI.8 <sup>235</sup>U analysis.

The present evaluation utilizes some data from the ENDF/B-VI.8 evaluation, in particular, discrete inelastic scattering data for levels below an excitation energy of 1.1 MeV. These earlier evaluated data are based on nuclear theory/model code calculations with the ECIS70

[130] coupled-channels optical model code and with the GNASH [46] and COMNUC [52] Hauser-Feshbach codes, with model parameters optimized to experimental data. The GNASH calculations also include preequilibrium contributions. The coupled-channels optical model



FIG. 50: The  $n+^{234}U$  total cross section from 0 to 30 MeV.

potential used for the  $^{235}\mathrm{U}$  calculations is given in Table III [11].

DWBA calculations for the ENDF/B-VI.8 evaluation were performed with the DWUCK code [131] for several vibrational levels, using B(El) values inferred from (d,d') data on  $^{234}$ U,  $^{235}$ U,  $^{238}$ U, as well as Coulomb excitation measurements. A weak coupling model [132] was used to apply the  $^{234}$ U and  $^{238}$ U results to states in  $^{235}$ U.

An updated <sup>235</sup>U analysis was performed with the ECIS94 [16] and GNASH codes for the present ENDF/B-VII evaluation. This new analysis provides the basis for our evaluation of the (n,n'continuum) and (n,xn) reactions. Additionally, direct reaction cross sections and angular distributions, inferred from neutron spectrum measurements on <sup>238</sup>U, are included for groups of states with  $E_x=1-4$  MeV.

Major features of the  $n+^{235}U$  evaluation for ENDF/B-VII are the following:

- A new evaluation of the (n,f) cross section taken from ENDF/B-VII standard cross section analysis [6] is incorporated;
- 2. A new evaluation above thermal energy of prompt nubar that is consistent with experimental data within uncertainties and with fast critical benchmark measurements is included;
- 3. New unresolved resonance parameter data are incorporated;
- 4. A new analysis of the prompt fission neutron spectrum matrix based on the Los Alamos model [83] is used to calculate neutron spectra at all energies except thermal;
- 5. Improved delayed neutron data are incorporated;
- New reaction theory calculations are utilized for (n,xn) and other reactions. Direct reaction cross sections and angular distributions are extended to an excitation energy of 4 MeV;
- Improved fission energy release values are incorporated;

8. Post-fission  $\beta\text{-delayed}$  photon production data are included.

#### 2. <sup>235</sup> U resonance parameters

The resolved resonance region covers the incident neutron energy range from 0 to 2.25 keV. The resolved parameters are the same as those in the ENDF/B-VI Release 8 evaluation. These parameters are from an analysis of  $^{235}$ U data by Leal *et al.* [133] in 1997, using the multilevel R-matrix analysis code SAMMY [100]. In that analysis, integral data were fitted for the first time during the analysis process. Thermal cross sections (fission, capture, and elastic) and Westcott g-factors (fission and absorption) were obtained from the ENDF/B-VI standards [134]. The K1 value was obtained from Hardy [135].

The unresolved resonance parameter evaluation from ENDF/B-VI.8 was revised and updated at Oak Ridge [136] for the ENDF/B-VII evaluation. It covers the energy range 2.25-25 keV.

## 3. $^{235}U(n,f)$ cross section

The <sup>235</sup>U(n,f) cross section for the ENDF/B-VII evaluation was taken directly from the cross section standards analysis by Pronyaev et al. [6] with minimal smoothing. The energy grid of the original standards analysis was expanded somewhat for this evaluation using a spline fit to a logarithmic file of the standards data. The evaluated data up to 6 MeV are shown with the results of the ENDF/B-VII standards analysis in the upper half of Fig. 51, and with a sampling of experimental data in the lower half of Fig. 51. Similarly, the results from 4 to 20 MeV are shown in the upper and lower halves of Fig. 52. Again, only a portion of the extensive experimental database is shown here; see Ref. [6] for a complete discussion of the ENDF/B-VII standards analysis. In that analysis, all the  $^{235}U(n,f)$  cross section data were reviewed and corrections were made to measurements where necessary.

#### 4. $n+^{235}U$ prompt fission neutron multiplicity

The evaluation of the prompt fission neutron multiplicity (nubar) for ENDF/B-VII below 10 keV is very similar to the ENDF/B-VI.8 evaluation. We made minor changes at these energies to more closely approximate the energy dependence of the JENDL-3.3 evaluation and to accommodate changes we made in delayed nubar to enhance thermal reactor calculations.

Above 10 keV our nubar evaluations is based primarily on the results of a covariance analysis that we made for our ENDF/B-VI evaluation. Similar to the  $^{233}$ U analysis described in Sec. IV.B.1, the GLUCS code [97] was used to analyze the  $^{235}$ U prompt nubar experimental database, including standard deviations and correlations. The experimental data were renormalized to conform to ENDF/B-VII standards [6]. Our evaluation between 0 and 4 MeV is compared with the covariance analysis and



FIG. 51: The  $^{235}$ U(n,f) fission cross section from 0 to 6 MeV. The upper frame compares evaluated data to results of the standards analysis. The lower frame compares the evaluations directly to experimental data.

with other evaluations in Fig. 53, as well as with a selection of experimental data. Similarly, the same results from 4 to 24 MeV are shown in Fig. 54. Experimental data from Frehaut et al. [137], Howe [138], Gwin et al. [139], Savin et al. [140], [141], and Soleilhac et al. [142] are included in the figures. Generally we attempted to follow the covariance analysis results as well as possible, with the goal of staying within uncertainties in the covariance data while at the same time keeping good agreement with fast critical benchmarks. Our nubar results are generally similar to the ENDF/B-VI.8 evaluation, except we restored the structure that appears in the covariance analysis around  $E_n=0.1-0.4$  MeV, which was smoothed in the earlier evaluation. Also, the evaluation is modified slightly between 1.0 and 2.5 MeV to better represent the covariance analysis. Above 2.8 MeV, nubar in ENDF/B-VII differs from ENDF/B-VI.8 by a factor of 1.0004, due to renormalization to ENDF/B-VII standards.

#### 5. $^{235}U(n,xn)$ cross sections

The evaluated (n,xn) cross sections (and energy-angle distributions) were calculated with the GNASH nuclear



FIG. 52: The  $^{235}{\rm U(n,f)}$  fission cross section from 4 to 20 MeV. See caption to Fig. 51.

model code [46]. This version of GNASH corrects an error involving an inconsistent treatment of preequilibrium effects in the presence of fission, which is present in the previous analysis for the ENDF/B-VI.8 evaluation. The modifications to the cross sections are not large but are non-negligible. For example, changes in the (n,2n) cross section are +6% near 8 MeV, -5% at 12 MeV, +3.5% at 14 MeV, and +16% at 20 MeV. The revised (n,2n) cross section is in good agreement with the experimental data of Becker et al. [143], Frehaut et al. [60], and Mather et al. [67], [69]. The Becker data are based on new experimental data from a LANSCE-GEANIE experiment. The new results from that measurement are deduced from a combination of measured partial gamma-ray cross sections and enhanced Hauser-Feshbach reaction modeling. The evaluated (n,2n) cross section is compared to experimental data and to other evaluations in Fig. 55. The various evaluations are reasonably consistent and in good agreement with the experimental data below 16 MeV.

The new GNASH analysis also results in modified energy-angle distributions in the ENDF File 6.

#### 6. $n+^{235}U$ inelastic cross section

The total inelastic cross section for  $n+^{235}U$  reactions was determined by summing all the discrete and con-



FIG. 53:  $n+^{235}U$  Prompt fission neutron multiplicity from 0 to 4 MeV.

tinuum components. The results are compared to other evaluations and to the experimental data of Drake [144], Batchelor and Wykd [145], Knitter *et al.* [146], and Andreev [147] in Fig. 56.

# 7. $^{235}U(n,\gamma)$ cross section

The  $^{235}$ U(n, $\gamma$ ) radiative capture cross section below approximately 1 MeV is based mainly on measurements of alpha (ratio of capture to fission). At higher energies the cross section calculated with the GNASH code is utilized, after renormalization to agree with the experimental data below 1 MeV. Our evaluated results are compared to other evaluations and to a selection of experimental data in Fig. 57. The capture cross section up to 25 keV is determined by the unresolved resonance parameters. Generally the various evaluations are consistent and agree reasonably with the experimental data. The ~10% discrepancy near 100 keV with the JENDL-3.3 evaluation is now a topic of study in a new NEA WPEC Subgroup.



FIG. 54:  $n+^{235}U$  Prompt fission neutron multiplicity from 4 to 24 MeV.

# 8. $n+^{235}U$ total cross section

Our evaluated neutron total cross section of  $^{235}$ U below 25 keV, which is the top of the unresolved resonance region, was obtained from the ENDF/B-VI.8 evaluation. Our starting point for the evaluation of the total cross section above 25 keV was the ENDF/B-VI.8 evaluation. In the MeV region that evaluation resulted from a covariance analysis with the GLUCS code [97] of the experimental data available at that time. The experimental data used in that analysis includes the measurements of Foster and Glasgow [116], Vertebnyy et al. [148]. Boeckhoff et al. [149], Poenitz et al. [18], [118], Green and Mitchell [150], Schwartz et al. [151], Peterson et al. [152], Whalen et al. [153], Cabe and Cance [154], and Bratenahl et al. [155]. For our present revision we enlarged that analysis by incorporating the more recent experimental data of Lisowski [156] into the GLUCS analysis. The result of the enlarged analysis is a general lowering of the total cross section by a few tenths of a percent above 50 keV. In particular, the new result is lower than the previous one by 0.4% at 3 MeV, is unchanged at 8 MeV, and is lowered by 0.5% at 14 MeV and by 1.3% (maximum change) at 20 MeV.

Our evaluated total cross section is compared to other evaluations and experimental data between 3 keV and 2 MeV in Fig. 58. At these energies our evaluation is either the same as or very close to the ENDF/B-



 $^{235}$ U(n,2n) cross section from threshold to 20 MeV.



FIG. 56: Inelastic cross section of  $\rm n+^{235}U$  reactions between threshold and 20 MeV

VI.8, JEFF-3.1, and JENDL-3.3 evaluations. In Fig. 59, the ENDF/B-VII neutron total cross section between 2 and 20 MeV is compared to the other evaluations and to several of the most important measurements [18], [116], [151], [152], [156]. The experimental data in Figs. 58 and 59 are in good agreement, as are the various evaluations. The accuracy of the average total cross section over much of this energy range is estimated to be 2% or better, although at energies above 15 MeV there is a little more divergence in the data.

#### 9. Other $n+^{235}U$ reactions

As described in Secs. II and III above, the inelastic cross sections to discrete levels in  $^{235}$ U are largely based on compound nucleus and direct reaction calculations with the GNASH and ECIS96 codes. Additionally, cross sections to levels with  $E_x=1-4$  MeV are based on vibrational model calculations from our  $^{238}$ U analysis.

The elastic scattering cross section was determined by subtracting the sum of the nonelastic reaction cross sections from the evaluated neutron total cross section. The



FIG. 57:  $^{235}$ U(n, $\gamma$ ) cross section from 0.003 to 2 MeV.



FIG. 58: Total cross section of  $\rm n+^{235}U$  reactions between 0.003 and 2 MeV.

result is close to our optical model result although not identical.

## 10. $n+^{235}U$ angular distributions

As described in the <sup>235</sup>U Summary above (Sec. IV.D.1), the neutron elastic and inelastic scattering angular distributions for discrete levels were taken from the ENDF/B-VI.8 evaluation. These in turn are based on calculations with the ECIS70 [130], DWUCK [131], and COMNUC [52] model codes. The elastic neutron angular distributions that result are compared to the measurements of Haouat et al. [12] at 0.7 and 3.4 MeV in Fig. 60. Similarly, Haouat's  $^{235}$ U(n,n') angular distributions for the combined 46- and 52-keV levels at  $E_n 0.7$  and 3.4 MeV, and the 103-keV level at 3.4 MeV are compared with the evaluations in Fig. 61. Like ENDF/B-VII, the JEFF-3.0 evaluation is based on ENDF/B-VI.8, so the three evaluations are identical. Only JENDL-3.3 is independent of ENDF/B-VI.8; all four evaluations agree well with the experimental data.



FIG. 59: Total cross section of  $n+^{235}U$  reactions between 2 and 20 MeV.

#### 11. $n+^{235}U$ emission neutron distributions

The  $^{235}$ U(n,xn) emission spectra were obtained from the GNASH [46] calculations, with angular distributions from the Kalbach systematics [51], as described in Sec. III.B.

A prompt fission neutron spectrum matrix for the  $n+^{235}$ U system was calculated using the Los Alamos model (LAM, [83]) in its exact formulation with energy-dependent compound nucleus formation cross sections for the inverse processes. A summary of the model and methodology is given in Sec. II.B.4.a. The matrix includes first-, second-, and third-chance fission components and also includes the neutrons evaporated prior to fission in second- and third-chance fission. The ENDF/B tabulated distribution law (LF=1) is used to represent the data.

The matrix is calculated for 19 incident neutron energies between 0 and 15 MeV. The 20-MeV spectrum is simply a duplication of the 15-MeV spectrum. The thermal prompt fission neutron spectrum was replaced with the spectrum from the ENDF/B-VI.8 evaluation. This replacement was made because the two most recent differential measurements of the thermal spectrum and the most accepted set of integral cross section measurements in the thermal spectrum constitute three mutually incompatible experimental sets. This incompatibility has



FIG. 60: Measured and evaluated elastic scattering angular distributions of 0.7- and 3.4-MeV neutrons from  $^{235}\mathrm{U}.$ 

yet to be resolved, and the decision was made to continue with the ENDF/B-VI.8 spectrum because of favorable experience with thermal reactor calculations.

## 12. $n+^{235}U$ delayed neutron and photon data

Improved delayed neutron multiplicities and decay constants from fission were incorporated into our evaluation, as described in Section II.B.4.c.

 $\beta$ -delayed photon-production probabilities from fission reactions were incorporated for some 3262 discrete gamma rays taken from the work of Pruet *et al.* [157]. The data were generated by directly sampling prompt fission product yield distributions and then following the decay of each individual fission fragment in time and tabulating the resulting photon-production spectrum. It was necessary to develop new formats to represent these data in the ENDF/B-VII evaluations [158].

#### 13. Energy release from $^{235}U$ fission

A new evaluation of the energy released from fission was made, based largely on results from a new analysis by Madland [159]. The average total fission product kinetic energy and the average total prompt fission gamma-ray energy were taken from the Madland anal-



FIG. 61: Inelastic neutron scattering from  $^{235}$ U for the combined 46- and 52-keV levels at  $E_n=0.7$  (upper frame) and 3.4 MeV (middle frame), plus the 103-keV level at  $E_n=3.4$  MeV (lower frame).

ysis. The average total prompt fission neutron kinetic energy was obtained from our ENDF/B-VII evaluated fission neutron spectra and prompt neutron nubar, and the remaining smaller contributions from delayed neutrons, gammas, betas, and neutrinos were carried over from the ENDF/B-VI.8 evaluation.

# E. n+<sup>236</sup>U evaluation

# 1. <sup>236</sup> U summary

ENDF/B-VII incorporates a complete revision of most of the data in the  $n+^{236}$ U evaluation above the resonance region. New evaluations were performed of all the major neutron cross sections, as well as their associated angular and energy distributions. Additionally, prompt fission nubar was revised using experimental data normalized to modern standards. The energy range of the evaluation was increased from 20 to 30 MeV.

# 2. <sup>236</sup> U resonance parameters

No changes were made to the resolved resonance parameters; we simply adopted the evaluation in ENDF/B-VI.8 by Mann and Schenter [160]. The resolved-resonance region covers the energy range from  $10^{-5}$  eV to 1.5 keV. It utilizes resonance parameters from the evaluation of Mughabghab [94] and experimental data from Macklin and Alexander [161].

The unresolved resonance region extends from 1.5 to 100 keV and is based on an earlier evaluation by Mann and Schenter [162]. We modified the fission widths slightly, so that the fission cross section from the resonance parameters now joins smoothly with the evaluated cross section above 100 keV, which is based on experimental data.

# 3. $n+^{236} U$ fission cross section

The only measurements considered in this evaluation are those in the form of ratios of the  $^{236}$ U(n,f) cross section to the  $^{235}$ U(n,f) cross section. This evaluation was completed prior to the release of the ENDF/B-VII standard cross sections. Therefore, the ratios were converted to absolute  $^{236}$ U(n,f) cross sections using a modification of the ENDF/B-VI.8  $^{235}$ U(n,f) standard cross section by Talou and Young [7], [8]. We did not consider any absolute  $^{236}$ U measurements in this analysis because of normalization questions.

The evaluated (n,f) cross section was obtained from an approximate average of the experimental data of Behrens and Carlson [124], Meadows [126], [104], Fursov *et al.* [163], Terayama *et al.* [164], and Goverdovskij [165], [166]. The data of Nordborg *et al.* [167] and Shpak *et al.* [168] were also considered but appeared inconsistent at some energies with most of the other data. Particular emphasis was placed in this analysis on the ratio data of Behrens and Carlson, and Meadows. The results of our ENDF/B-VII evaluation are compared to other evaluations and to the experimental data in Fig. 62.

#### 4. $n+^{236} U$ prompt fission neutron multiplicity

We found that the BROND-2.2 evaluation (Ma85) of prompt nubar by Malinovskij *et al.* [169] represented the experimental data well, so we adopted it below  $E_n=6$ 



FIG. 62: The  $^{236}$ U(n,f) cross section. The upper frame covers the energy range 0.1-1.0 MeV and the lower frame spans the energies 1-30 MeV.

MeV. Above 6 MeV, the evaluation is extended to 30 MeV using the shape of the ENDF/B-VII evaluation of nubar prompt for  $^{238}$ U, normalized to match the BROND-2.2 evaluation of  $^{236}$ U at 6 MeV. Our evaluated prompt nubar curve is compared to the other evaluations and to experimental data in Fig. 63 for neutron energies between 0 and 16 MeV. The prompt nubar experimental data of Conde and Holmberg [170], Malinovskij *et al.* [171], and Vorobjova *et al.* [172] are included in the figure. All these data were measured relative to  $^{252}$ Cf nubar and were normalized to the ENDF/B-VII standard value.

# 5. $^{236}U(n,xn)$ cross sections

Our evaluated  ${}^{236}$ U(n,2n),  ${}^{236}$ U(n,3n), and  ${}^{236}$ U(n,4n) cross sections were taken directly from our GNASH analysis, summarized in Section II.B.2. A comparison of the evaluated (n,2n) and (n,3n) cross sections with other evaluations is given in Fig. 63.



FIG. 63:  $n+^{236}U$  prompt fission neutron multiplicity.

# 6. $n+^{236}U$ inelastic cross section

Level structure information for the <sup>236</sup>U states was obtained from the RIPL-2 database [17]. Direct reaction and compound nucleus cross sections for the  $2^+$ ,  $4^+$ ,  $6^+$ and  $8^+$  states of the ground-state rotational band were calculated with the ECIS96 coupled-channels code using the optical potential [11] given in Section II.A. Compound nucleus cross sections for the higher ( $E_x > 600$ keV) states were calculated with the GNASH code, also including small preequilibrium contributions to approximate direct reaction effects. In addition, cross sections for grouped  $2^+$  and  $3^-$  vibrational levels over the excitation energy range  $E_x=1.17-3.40$  MeV were included, as described in Section II.B.4.b. These were obtained directly from our <sup>238</sup>U evaluation [4], with energy dependence determined from DWBA calculations with the ECIS96 code. The (n,n'continuum) cross section was also determined from the GNASH analysis. The total inelastic cross was obtained by summing over all discrete and the continuum states and is compared to other evaluations in Fig. 65.

# 7. $^{236}U(n,\gamma)$ cross section

The evaluated <sup>236</sup>U(n, $\gamma$ ) cross section above the unresolved resonance region is an approximate average of the experimental data of Buleeva *et al.* [173], Macklin and Alexander [161], and Kazakov *et al.* [174]. We also considered the experimental data of Trofimov [175] and Gudkov *et al.* [176]. Above  $E_n=1$  MeV, the evaluation follows the GNASH calculation, as described in Section II.B.3. Our evaluated <sup>236</sup>U(n $\gamma$ ) cross section is compared to the experimental data and to the other evaluations from  $E_n=0.1$ -16 MeV in Fig. 66.

#### 8. $n+^{236}U$ total cross section

The evaluated total cross section is based on coupledchannels optical model calculations with the ECIS96 code. We utilized the optical potential from reference [11]



FIG. 64:  $^{236}U(n,xn)$  cross sections. The  $^{236}U(n,2n)$  cross section is shown in the lower frame, and the  $^{236}U(n,3n)$  cross section is given in the upper frame.



FIG. 65: The  $n+^{236}U$  inelastic cross section from threshold to 30 MeV.

with the lowest 3 ground-state rotational band states coupled. See Section II.A for more details. The only experimental data available are at the low end of our energy range, namely, those of Purtov *et al.* [177], which cover the energy range 1.8-734 keV.

We compare our ENDF/B-VII evaluated total cross section with other evaluations and with the experimen-



FIG. 66: The  $^{236}$ U(n, $\gamma$ ) cross section for the neutron energy range 0.1 to 16 MeV.

tal data of Purtov *et al.* in Fig. 67. The calculated results agree reasonably with the measured data although not within the quoted experimental error at all energies. There is some scatter in the measured data.

# 9. Other $n+^{236}U$ reactions

GNASH calculations were utilized to obtain the reaction cross sections and to distribute the (n,f) cross section among the (n,nf), (n,2nf), (n,3nf) multichance fission channels. The <sup>236</sup>U elastic cross section was obtained by subtracting the sum of all nonelastic cross sections from the total cross section.

#### 10. $n+^{236}U$ angular and energy distributions

The neutron angular distributions and  $^{236}U(n,xn)$  emission spectra were obtained from the calculations, as described in Sec. III.B.

The fission neutron spectra were adopted directly from the ENDF/B-VI.8 evaluation with linear extrapolation of the data to 30 MeV.

# F. $n+^{237}U$ evaluation

## 1. <sup>237</sup> U summary

The cross section data file for neutron reactions with  $^{237}$ U was reevaluated over the incident neutron energy range from  $10^{-5}$  eV to 30 MeV. This work builds upon an earlier LANL evaluation by Young [178] that featured replacement of all cross section data above 10 keV with results from a new theoretical analysis, as described above in Section II. That is, our analysis updates the cross sections and continuum energy-angle distributions using results from a systematic analysis of neutron reactions with the A=232-238 uranium isotopes.



FIG. 67:  $n+^{236}U$  total cross section from 0.1 to 2 MeV (upper frame) and from 0 to 30 MeV (lower frame).

Details of the present analysis are given in the sections that follow. Some general features of the work are:

- 1. The systematic analysis of uranium isotopes described in Section II was utilized in obtaining all  $n+^{237}$ U cross sections. The isospin-dependent coupled-channel optical potential [3] was used to calculate the neutron total cross section, elastic and inelastic scattering cross sections, elastic scattering angular distributions, and reaction cross sections, as well as transmission coefficients for the reaction theory calculations.
- 2. We revised our earlier GNASH analysis [178] to better represent surrogate fission cross section data by modifying the fission barrier heights.
- 3. Prompt nubar and the fission neutron spectra were taken from the existing ENDF/B-VI.8 evaluation.
- 4. Angular distributions of (n,n') reactions were carried over from the 1994 evaluation [178]. Those distributions were obtained from a similar coupledchannels optical potential.

#### 2. <sup>237</sup> U resonance parameters

The ENDF/B-VI.8  $n+^{237}U$  resonance parameters were adopted at neutron energies below 10 keV with modification of the gamma and fission channels to better agree with data. The radiative capture width in the resolved and unresolved resonance regions was changed from 34.56 to 23 meV, which conforms to the value in the RIPL-2 data base [17]. The resonance analysis was suitably joined with the present analysis at 10 keV.

The resolved resonance region spans the energy range from 0 to 102.5 eV; the unresolved region covers the range from 102.5 eV to 10 keV. (In the course of this work, we discovered deficiencies in the unresolved resonance region, resulting in the (n,f) cross section being somewhat low in the unresolved region. This problem will be addressed in the next version of ENDF/B-VII.)

## 3. The $^{237}U(n,f)$ cross section

The fission cross section was reevaluated using model parameters consistent with neighboring U isotopes. Fission barrier parameters in the GNASH calculations were adjusted to approximate the surrogate fission cross section data of Younes and Britt [179] and Burke *et al.* [180]. The only direct differential measurement of the (n,f) cross section at higher energies is by McNally *et al.* [181], but those data are seriously inaccurate in the MeV region. Our evaluated fission cross section is taken directly from our GNASH calculations.

A comparison of the ENDF/B-VII evaluated (n,f) cross section to the ENDF/B-VI.8 evaluation and to the surrogate fission cross section data of Younes and Britt and Burke *et al.* is given in Fig. 68. We also include predictions from the systematics developed by Behrens [182]. The upper frame of the figure emphasizes the lower energy range with a log plot, whereas the lower frame details the data to 26 MeV. The shape and magnitude of the GNASH calculation differs somewhat from the measurement of Younes and Britt but is within about 2 standard deviations of the data. The calculation agrees best with the data of Plettner *et al.* over a broad energy range.

# 4. $n+^{237}U$ prompt fission neutron multiplicity

The evaluation of delayed and prompt nubar were carried over directly from the ENDF/B-VI.8 evaluation of  $^{237}$ U. Total nubar at thermal was taken from the semiempirical work of Gordeeva and Smirenkin [183], as revised using the systematics of Manero and Konshin [184]. The energy dependence of nubar above thermal is based on the systematics of Howerton [185]. The ENDF/B-VII evaluated curve for nubar prompt was shown earlier in Fig. 22 of Section III.A. It is shown there to be consistent with neighboring uranium isotopes.

# 5. $n+^{237}U$ inelastic and $(n,x\gamma)$ cross sections

Discrete (n,n') cross sections are included for the lowest 25 excited states of  $^{237}$ U. The first and second excited



FIG. 68: The  $^{237}$ U(n,f) fission cross section. The upper frame covers the energy range 0.01-10 MeV (logarithmically); the lower frame spans the range 0-26 MeV (linearly).

states are members of the K=1/2 ground-state rotational band and include coupled-channels as well as compound nucleus contributions.

The remaining discrete-state cross sections through the  $25^{th}$  excited state are based on compound nucleus calculations with preequilibrium corrections using the GNASH code. The inelastic data corresponding to excitation energies in  $^{237}$ U above 0.54 MeV are given as energy-angle correlated continuous spectra and were calculated with the GNASH code. Our evaluated  $^{237}$ U(n,2n), (n,3n), and (n,4n) cross sections result entirely from the theoretical analysis.

The total inelastic neutron cross section from the present analysis is seen in Fig. 69 to be significantly different from ENDF/B-VI.8 in the energy range below a few MeV. Additionally, it should be noted that the emission spectra of inelastic neutrons are very different from ENDF/B-VI, because they are dominated at lower energies by direct reaction effects, which were apparently not included in the ENDF/B-VI.8 evaluation. The  $^{237}U(n,x\gamma)$  photon-production data were taken from the ENDF/B-VI.8 evaluation, which is based on systemat-



FIG. 69: The <sup>237</sup>U+n inelastic scattering cross section.

ics [185].

#### 6. $^{237}U(n,\gamma)$ and $^{237}U(n,2n)$ cross sections

Below 10 keV, our evaluated ENDF/B-VII  $^{237}$ U(n, $\gamma$ ) capture cross section is based on the ENDF/B-VI.8 resonance parameters. At higher energies the capture cross section was taken from our GNASH calculations, using parameters consistent with neighboring uranium isotopes. It was calculated using the generalized Lorentzian model of Kopecky and Uhl [48]. The normalization of the gamma-ray strength function was adjusted to produce an  $(n,\gamma)$  cross section consistent with the <sup>235</sup>U $(n,\gamma)$ cross section. The <sup>237</sup>U capture cross section is compared to neighboring uranium isotopes in Fig. 21 of Section III.A. The  $^{237}U(n\gamma)$  and (n,2n) cross sections from our ENDF/B-VII evaluation are compared with the ENDF/B-VI.8, JEFF-3.1, JENDL-33, and Maslov [186] evaluations in Fig. 70. We also include approximate points from Bernstein et al. [187], which were inferred from  $^{238}U(\alpha, \alpha')$  measurements using a surrogate ratio method. Not surprisingly, there are significant differences among the evaluated and surrogate values of the  $(n,\gamma)$  and (n,2n) cross sections.

#### 7. $n+^{237}U$ total and elastic cross sections

The evaluated total cross section below 10 keV is obtained from the resonance parameter evaluation in ENDF/B-VI.8, with the fission channel modified as described above. From 10 keV to 30 MeV, the coupledchannel deformed optical model calculations are used directly.

The elastic cross section at all energies is obtained from the difference of the total and nonelastic cross sections. Below 10 keV it comes from the modified ENDF/B-VI.8 resonance parameters and at higher energies it is determined essentially by the coupled-channel optical model calculations. Angular distributions for elastic neutrons were obtained at all energies from our 1994 [178] coupledchannel calculations and are given as Legendre expan-



FIG. 70: The  $^{237}$ U(n, $\gamma$ ) and  $^{237}$ U(n,2n) cross sections. (The points from Bernstein *et al.* [187] were inferred using a surrogate ratio method and are regarded as approximate).

sions.

The evaluated  $n+^{237}U$  total and elastic cross sections are compared to the other evaluations in Fig. 71. There are considerable differences among the various evaluations, especially in the elastic cross section.

#### 8. $n+^{237}U$ angular and energy distributions

Angular distributions for the discrete inelastic neutrons are taken from the 1994 [178] analysis. As described in Section III.B, the energy-angle correlated continuum data for  $^{237}$ U(n,n'), (n,2n), (n,3n), and (n,4n) reactions are given in ENDF File 6 of the evaluation and utilize systematics by Kalbach [51] for angular distribution data, parameterized in terms of preequilibrium ratios calculated in GNASH.

The neutron energy spectra from prompt fission reactions are taken directly from the ENDF/B-VII  $^{237}$ U evaluation. Simple Maxwellian forms with energy-dependent temperatures are used to represent the spectra.



FIG. 71:  $n+^{237}U$  total and elastic scattering cross sections.

#### G. $n+^{238}U$ evaluation

#### 1. <sup>238</sup> U summary

The energy range of the <sup>238</sup>U evaluation was increased from 20 MeV in Version VI to 30 MeV in ENDF/B-VII. Because of the abundance of experimental data for  $n+^{238}$ U reactions, we relied heavily on measurements for our evaluation, both directly and in normalizing calculations. The evaluations of the total, (n,f), (n, $\gamma$ ), (n,2n), and (n,3n) cross sections for <sup>238</sup>U, as well as nubar, are based largely on the experimental data base. However, theoretical calculations from both the ECIS96 and GNASH analyses were used to supplement the cross section measurements for these reactions in energy regions where the data are sparse.

The theoretical analysis of  $n+^{238}U$  reactions is highlighted in Section II. The model calculations are instrumental in improving the overall neutron emission spectra from  $n+^{238}U$  reactions. The parts of the  $^{238}U$  evaluation where theory is most used are the (n,n') excitation cross sections, shapes of the  $(n\gamma)$  and (n,xn) reactions, angular distributions of elastic and inelastic neutrons, and energy-angle correlated neutron emission from continuum reactions.

Significant improvements were also made in the ENDF/B-VII resonance parameters, the fission cross section, the matrix of neutron spectra from prompt fission, delayed neutron data, and energy release data from fission reactions.

## 2. <sup>238</sup> U resonance parameters

A new analysis of the resolved resonance region was performed within WPEC, Subgroup 22 in 2004 [188]. This evaluation was performed with the computer code SAMMY [189] using the Reich-Moore formalism. Resolved resonance parameters are obtained over the incident neutron energy range 0 to 20 keV.

The ENDF/B-VI.8 unresolved resonance parameter evaluation by Fröhner [190] and Poenitz [77], which is based on a fit to experimental data with the FITACS code, was adopted for ENDF/B-VII. It covers the neutron energy range from 20 to 149 keV.

#### 3. $n+^{238}U$ total cross section

We adopted the ENDF/B-VI.8 evaluation of the neutron total cross section between 20 keV and 6 MeV. At energies above the resonance region, that evaluation is based on a covariance analysis using the GLUCS code [97] to analyze the experimental data of Foster and Glasgow [116], Schwartz et al. [151], Poenitz et al. [77], [118], Hayes et al. [191], Bratenahl et al. [192], Cabe and Cance [154], Peterson et al. [152], Whalen et al. [193], Batchelor et al. [26], Uttley et al. [194], Shamu [21], and Lisowski [195]. The coupled-channels optical potential was used to calculate the "prior" cross section for the analysis.

We adjusted the results of the ENDF/B-VI.8 covariance analysis above 6 MeV to include the newer measurements of Abfalterer *et al.* [19]. The changes were generally a lowering of the cross section between 6 and 17 MeV, and an increase above 17 MeV. The maximum change was about 1.7% but generally the changes were of the order of a few tenths of a percent. Additionally, the Abfalterer data were used to extend the evaluation from 20 to 30 MeV.

In Figs. 1 and 2 of Section II.A.1, we compare a selection of the  $n+^{238}U$  experimental total cross section database to coupled-channels optical model calculations. We include here in Figs. 72 and 73 similar comparisons to our evaluated total cross section and to other evaluations.

#### 4. $^{238}U(n,f)$ fission cross section

At all energies the ENDF/B-VII <sup>238</sup>U fission cross section is based on the experimental database. The cross section in the neutron energy range 20 keV to 1.0 MeV range is the same as the ENDF/B-VI.8 evaluation. That is, it is based on the unresolved resonance parameter analysis of Fröhner and Poenitz [190], [77] and on the ENDF/B-VI standards analysis, which is very similar to the ENDF/B-VII standards analysis at these energies.

Above 1.0 MeV, the fission cross section is based directly on the Version VII standards analysis of Pronvaev et al. [6]. As described earlier, much of the fission cross section experimental data for  $^{238}$ U is relative to  $^{235}$ U. However, there also are absolute measurements of the  $^{238}$ U(n,f) cross section, so the  $^{238}$ U fission cross sections and ratios were part of the database used in the standards analysis. The original standards energy grid used in the standards analysis is included as a subset of a larger energy grid for the ENDF/B-VII cross section. The expansion to the denser grid was accomplished using a spline fit to a log-log file of the  $^{238}$ U(n,f) data from the standards analysis. The decomposition of the evaluated fission cross section into first-, second-, third-, and fourth-chance fission channels was accomplished using calculated ratios from the GNASH analysis.

Earlier in Fig. 9 of Section II.B.1 we compared the  $^{238}{\rm U(n,f)}$  cross section from our GNASH analysis with



FIG. 72: The <sup>238</sup>U(n,f) cross section. The upper frame shows the cross section from 0.06 to 8 MeV; the lower frame spans the range  $E_n=0$  to 30 MeV.

experimental data. We now compare our evaluated (n,f) cross section in Fig. 73 with the ENDF/B-VI.8, JEFF-3.1, and JENDL-3.3 evaluations, as well as with the measurements of Behrens [54] and Lisowski [53] between  $E_n=0$  and 30 MeV. Of course, this is only a very small sampling of the available experimental data. However, the ENDF/B-VII standards analysis includes essentially the entire fission cross section database. The evaluations shown in Fig. 73 are in close agreement at most energies; however, significant differences among the evaluations occur above  $E_n=14$  MeV. The JENDL-3.3 evaluation is close to our evaluation at most energies.

# 5. $n+^{238}U$ radiative capture cross section

Similar to fission, the evaluated  $^{238}$ U(n, $\gamma$ ) radiative capture cross section is based on experimental data at most energies. The evaluated (n, $\gamma$ ) cross section is determined from the resonance analyses [188], [190], [77] below E<sub>n</sub>=149 keV. From 149 keV to 2.2 MeV, the evaluation closely follows results from the standards analysis by Pronyaev *et al.* [6]. Above 2.2 MeV, the evaluation is based on the JENDL-3.0 evaluation, with a smooth extrapolation from 20 to 30 MeV.

The evaluated  $^{238}U(n,\gamma)$  cross section that results is



FIG. 73: Comparison of measured and evaluated fission cross section from  $E_n=0$  to 30 MeV.

compared to the various evaluations and to different selections of experimental data in Figs. 74 and 75. The energy range of 0.01 to 2 MeV is covered in Fig. 74, and includes the measurements of Adamchuk et al. [196], DeSaussure et al. [197], Chelnokov et al. [198], Fricke et al. [199], Kazakov et al. [72], Poenitz et al. [200], Yamamuro et al. [201], Panitkin et al. [202], Spencer et al. [203], Buleeva et al. [173] and Voignier et al. [204]. Figure 75 spans the neutron energy range of 0.02-30 MeV and includes the experimental data of Drake et al. [71], Panitkin and Tolstikov [73], [74], Rimawi and Chrien [75], Block et al. [76], Poenitz et al. [77], Lindner et al. [78], Ryves et al. [79], Davletshin et al. [80], [81], and McDaniels et al. [82] There is a suggestion in Fig. 107 of Ref. [1] that the  $(n,\gamma)$  cross section should be raised a few percent below 1 MeV, and this is reinforced in Fig. 75.

The ENDF/B-VII <sup>238</sup>U(n, $\gamma$ ) radiative capture cross section agrees generally with the measurements, although it is biased toward the lower edge of the measurements below 1 MeV. This effect occurs because the standards evaluators believed the lower magnitude data to be correct. This conclusion was also reached by NEA WPEC Subgroup-4 [205] and is consistent with comparisons of calculations of critical assemblies Ref. [1], pg. 2957.

The largest discrepancies occur in the energy region 8-14 MeV, where the Panitkin measurements appear to be inconsistent with the data of Drake *et al.* and McDaniels *et al.*. Our evaluation follows the latter measurements.

#### 6. $^{238}U(n,xn)$ cross sections and angular distributions

Our evaluation of the <sup>238</sup>U(n,2n) cross section is based on a combination of our GNASH analysis, a covariance analysis of the experimental data base that we performed for ENDF/B-VI, and new experimental data. The GNASH calculation is used for the evaluation from threshold to  $E_n=7.5$  MeV, which is consistent with the (higher) measurements of Knight *et al.* [70]. In addition, the behavior of the cross section near threshold was validated in simulations of critical assembly reaction rate



FIG. 74: Measured and evaluated cross sections for the  $^{238}{\rm U}(n,\gamma)$  reaction from 0.02 to 2 MeV.



FIG. 75: Measured and evaluated cross sections for the  $^{238}{\rm U}({\rm n},\gamma)$  reaction from 0.02 to 30 MeV.

experiments having different degrees of hardness in their neutron spectra, discussed in Sec. V (see also Ref. [1], pg. 3018). Above 7.5 MeV, the evaluation is based on the experimental data, closely following our covariance analysis. In the 14-MeV region, the evaluation is consistent with the data of Barr *et al.* [58].

We compare the (n,2n) cross section evaluation in Fig. 76 with the experimental data base and with other evaluations from threshold to 20 MeV. Experimental data from Pepenik *et al.* [56], Kornilov *et al.* [57], Barr *et al.* [58], Frehaut *et al.* [59], [60], Veeser and Arthur [61], Karius *et al.* [62], Raics *et al.* [63], Konno *et al.* [64], Golovnya *et al.* [65], Filatenkov*et al.* [66], and Knight *et al.* [70] are shown in Fig. 76.

The evaluated  $^{238}$ U(n,3n) cross section from threshold to  $E_n=17$  MeV is based on the GNASH analysis. From 17 to 20 MeV, the GNASH analysis was modified to agree with experiment and renormalized above 20 MeV. The (n,3n) results are compared to the other evaluations and to the measurements of Allen *et al.* [68], White [44], Frehaut *et al.* [59], Veeser and Arthur [61], Mather*et al.* [67], and Mather and Pain [69] in Fig. 77.



FIG. 76: Evaluated and experimental cross sections for the  $^{238}$ U(n,2n) reaction from threshold to 20 MeV.



FIG. 77: Evaluated and experimental cross sections for the  $^{238}$ U(n,3n) reaction from threshold to 30 MeV.

The evaluated  $^{238}$ U(n,4n) cross section was taken directly from the GNASH analysis. It is in reasonable agreement with the measurement of Veeser and Arthur [61]. The energy-angle neutron emission distributions from the GNASH analysis were used directly for the (n,2n), (n,3n), and (n,4n) reactions, utilizing Kalbach [51] angular distribution systematics.

# 7. $n+^{238}U$ elastic scattering cross section and angular distributions

The evaluated elastic scattering cross section is determined by subtracting the sum of all nonelastic reactions from the total cross section. Because both the total and fission cross sections were determined from experimental data and several of the nonelastic channels were adjusted to improve agreement with measurements, the evaluated elastic cross section is not identical to the result of the coupled-channels optical model calculations. However, the difference is not large, as can be seen by comparing the evaluated elastic cross section here with the optical model result shown earlier in Figs. 3 and 4.

We compare our evaluated elastic cross section with the ENDF/B-VI.8, JEFF-3.1, and JENDL-3.3 evaluations and with experimental data in Figs. 78-79. The comparison in Fig. 78 covers the energy range  $E_n=0-4$  MeV. The experimental data of Murzin *et al.* [22]. Barnard *et al.* [23], Tsang and Brugger [24], Smith [25], Haouat *et al.* [12], Litvinskiy *et al.* [31], and Grigorev *et al.* [32] are included in Fig. 78. The resolution of these measurements was sufficient that only elastic scattering was measured.

In Fig. 79 we compare the sum of cross sections for the elastic plus the first 2 excited states from the various evaluations with experimental data for incident energies over the range  $E_n$  0-16 MeV. This sum approximately matches the resolution of the experimental data from the measurements of Smith and Guenther [27], Voignier [28], Shen *et al.* [29], Li Jingde *et al.* [30], Allen *et al.* [34], and Cranberg *et al.* [35], shown in Fig. 79. Also included are the experimental data of Batchelor *et al.* [26] and Knitter *et al.* [33], which have slightly poorer resolution. There are obvious inconsistencies among some of the measurements, but the four evaluations are reasonably consistent with most of the experimental data.

Initially, we utilized angular distributions from the 1992 Young optical potential [11] for our evaluation (see Secs. II.A.2 and III.B). However, we discovered empirically that using elastic angular distributions from the Maslov evaluation [10] below 10 MeV resulted in systematic improvement in calculations of several reactor benchmark experiments. In particular, use of the Maslov elastic angular distributions leads to improved calculation of neutron leakage from natural uranium reflectors in FLATTOP assemblies, as manifested by improved calculations of neutron multiplication,  $k_{eff}$ , and various ratio measurements. When we substituted the entire evaluation, however, we obtained poorer results in the benchmark calculations. Therefore, we utilized Legendre coefficients from Maslov *et al.* for  $E_n = 10^{-11}$  to 10 MeV and probability tabulations from the 1992 Young potential from  $E_n = 10-30$  MeV in the final evaluation. Thus, we based our decision to utilize Maslov's elastic distributions below 10 MeV entirely on pragmatic considerations. We hope that future work will combine the best possible theoretical calculations with experimental data and insights from critical assembly data.

Extensive comparisons are given in App. C of Ref. [4] of elastic scattering angular distributions from various evaluations with experimental data. Examples of three angular distributions are shown here in Fig. 80. In the upper frame we include evaluated elastic angular distributions at  $E_n=2.5$  MeV, compared to the experimental data of Haouat *et al.* [12] and Beghian *et al.* [206]. In the middle frame we compare the angular distributions at 8.03 MeV with the experimental data of Smith and Chiba [207], and in the lower frame we show the evaluations at 14.1 MeV compared with experimental data from Hansen *et al.* [208], Voignier [28], and Kammerdiener [209]. Again, contributions from inelastic scattering are included in the calculated curves, appropriate for the resolution of each angular distribution measurement.



FIG. 78: Measured and evaluated cross section for elastic scattering from 0 to 4 MeV.

# 8. $n+^{238}U$ inelastic scattering cross section and angular distributions

Results from both the ECIS96 and GNASH calculations were utilized in evaluating the (n,n') reactions. The (n,n') cross sections and angular distributions calculated with ECIS96 (direct and compound nucleus) were used directly for states in the ground state rotational band up to  $E_x=776$  keV. Note that the Young, 1992 potential [11], which was used in these calculations, only couples the lowest 3 rotational states, so a special calculation was performed for the discrete level data with additional states coupled. The cross sections for the remaining real discrete levels up through  $E_x=1.106$  MeV were calculated with the GNASH code, assuming them to be essentially compound nucleus reactions but with a small direct component from a preequilibrium calculation. The angular distributions for these states were calculated with the COMNUC code [52], again combining a small direct (preequilibrium) component.

The calculated cross sections for the inelastic states were used as the starting point for all the (n,n') evaluated cross sections. Small adjustments were then made to some of the calculations to improve agreement with measurements, where available.

We present our evaluated (n,n') cross sections to the  $1^{st}$ ,  $2^{nd}$ , and  $5^{th}$  excited states for  $E_n0-4$  MeV in Fig. 81. These are compared with other evaluations and experimental level excitation cross sections from Haouat et al. [12], Guenther et al. [210], Litvinskiy et al. [31], Kornilov and Kagalenko [211], Moxon et al. [212], Murzin et al. [22], Smith [25], Vorotnikov et al. [213], Beghian [206], Winters et al. [214], Kegel [215], and et al. The  $1^{st}$  and  $2^{nd}$  excited states Shao *et al.* [216].  $(E_r=0.045 \text{ and } 0.148 \text{ MeV})$  are members of the ground state rotational band and still have appreciable (direct) cross sections at  $E_n=4$  MeV. The (n,n') cross section to the  $5^{th}$  excited state (E=0.680 MeV) is dominated by compound nucleus reactions and is nearly zero at 4 MeV. In most cases the various evaluations are in reasonable agreement with measurements, although in some cases improvements could be achieved with better nor-



FIG. 79: Measured and evaluated cross section for elastic scattering from 0 to 16 MeV. The inelastic cross section for states up to  $E_x=0.5$  MeV are included.

malizations. More extensive comparisons of our evaluated  $^{238}$ U(n,n') discrete-level cross sections to other evaluations and to experimental data are given in Ref. [4].

The <sup>238</sup>U(n,n'continuum) cross section thresholds at  $E_n=1.12$  MeV. Therefore, the discrete cross sections from groups of collective states between  $E_x=1-4$  MeV described in Sec. II.B.4.b are underlain by compound-nucleus-plus-preequilibrium continua out to  $E_x=4$  MeV. The combination of these two comprises the neutron emission spectra at these excitation energies. The GNASH cross sections and energy-angle distributions were used directly for the (n,n'continuum) reactions, incorporating Kalbach [51] angular distribution systematics, which are based on extensive experimental data.

Our evaluated inelastic scattering angular distributions at  $E_n=2.5$  and 3.4 MeV for the 148-keV  $2^{nd}$  excited state are compared in Fig. 82 to the other evaluations and to the experimental data of Haouat *et al.* [12] and Beghian *et al.* [206]. The agreement of all the evaluations with the measurements is seen to be reasonable. Again, more extensive comparisons of our evaluated (n,n') distributions with other data are given in Ref. [4].

The integrated  $^{238}U(n,n')$  inelastic cross sections from ENDF/B-VII and the other evaluations are compared with experimental data in Fig. 83. The experimental data of Andreev et al. [147], Allen [217], Allen et al. [68], Batchelor et al. [218], Clarke et al. [219], Cranberg et al. [220], Glazkov [221], Rosen and Stewart [222], Tsang et al. [24], and White et al. [44] are included for comparison. Although most of the measurements are over 40 years old, there is surprising agreement with the data of Allen et al., Tsang et al., and Glazkov at lower neutron energies. All the measurements appear to be low near 14 MeV. This is probably due to the low-energy cutoff of detectors used to measure the neutron spectra. Below  $E_n=1.5$  MeV, there is reasonable agreement among the various evaluations. At higher energies, however, significant differences occur. Note that inclusion of more vibrational levels in the (n,n') calculations will increase the inelastic cross section somewhat, as noted in Sec.II.B.4.



FIG. 80: Comparison of measured and evaluated elastic scattering angular distributions at  $E_n=2.5$ , 8.08, and 14.1 MeV. Contributions from unresolved excited states are included, as described in the text.

# 9. $n+^{238}U$ nonelastic cross section

The evaluated nonelastic cross section was obtained by summing all the individual nonelastic reaction channels, that is, by summing the  $(n,\gamma)$ , (n,f), (n,n'), (n,2n), (n,3n), and (n,4n) cross sections.

Comparisons of a sampling of experimental nonelastic cross sections with the evaluated nonelastic cross sections are given in Fig. 84. The figure includes the experimental data of Bethe *et al.* [36], Lebedev *et al.* [223], Ennis [39], Cohen [40] Degtyarev and Nadtochu [41], Voignier [28],



FIG. 81: Evaluated and measured cross sections for the  $^{238}$ U(n,n') reaction to the  $1^{st}$ -,  $2^{nd}$ -, and  $5^{th}$ -excited states of  $^{238}$ U at 45, 148, and 680 keV for incident energies between 0 and 4 MeV.

MacGregor *et al.* [42], and Didier and Dilleman [43]. It should be noted that the measurements of Lebedev and Didier are for natural uranium, whereas the others are for isotopic  $^{238}$ U.

As was the case with the optical model calculations, the evaluated nonelastic cross sections are higher than most of the measurements below about  $E_n=3$  MeV. We suspect that there might have been problems in some of these older measurements. There is considerable scatter in the experimental data and, because of this, most of the



FIG. 82: Measured and evaluated angular distributions at  $E_n=2.5$  and 3.4 MeV for the  $^{238}U(n,n')$  reaction to the first excited state of  $^{238}U$  at  $E_x=148$  keV.

evaluations are reasonably consistent with some of the data. Certainly the present evaluation appears consistent with the bulk of the experimental data.

#### 10. $n+^{238}U$ neutron emission spectra

In this section we discuss the evaluated prompt fission neutron spectra, which is directly represented in the evaluation, and the neutron emission spectra that result from a combination of (n,n'), (n,2n), (n,3n) and (n,f)reactions.

#### 11. prompt fission neutron spectra

As described in Sec. II.B.4, prompt fission neutron spectra were calculated using the Los Alamos model [83] in its exact formulation with energy-dependent compound nucleus formation cross sections for the inverse processes. The matrix includes first-, second-, third-, and fourth-chance fission components and also includes the neutrons emitted prior to fission in second-, third-, and fourth-chance fission. More details of the Los Alamos model are included in Ref. [1]. The lowest incident neutron energy for a measured fission cross section for n +  $^{238}$ U is just under 2 eV with a value of about 5 microbarns. The multiple-chance fission average prompt



FIG. 83: Evaluated and measured cross sections for the  $^{238}$ U(n,n') reaction for E<sub>n</sub>=0-16 MeV.



FIG. 84: Evaluated and measured  $^{238}\mathrm{U+n}$  nonelastic cross sections for  $\mathrm{E}_n{=}0{-}20$  MeV.

neutron multiplicity was calculated simultaneously and, in reproducing experiment, was important in determining the matrix. Until more experimental data become available, spectra for incident neutron energies above 20 MeV are roughly approximated by using the 20-MeV spectrum. An average over the spectra from 13 MeV to 18 MeV would be a better approximation.

The existing thermal ENDF/B-VI.8 spectrum, which was obtained from an earlier Los Alamos model calculation, was retained in our evaluation. This was done because the earlier spectrum has been used in many analyses of thermal reactor systems and its good performance is generally accepted within the Cross Section Evaluation Working Group (CSEWG) community.

#### 12. Neutron emission spectra from (n,n') and (n,xn)reactions

As described in Sec. II.B.4.b, contributions to neutron emission from (n,n') and (n,xn) reactions were obtained from our Hauser-Feshbach, preequilibrium, and

DWBA calculations. Comparisons are given in that section to angle-integrated total neutron emission spectra at 14 MeV (Fig. 13) and to double-differential neutron emission spectra for different angles at  $E_n=4.25$ , 14.05, and 18.0 MeV (Figs. 14-16). We include here additional comparisons of angle-integrated neutron emission spectra at  $E_n=4.2$ , 6.1, and 18.0 MeV in Fig. 85, again including fission neutrons. More extensive comparisons of our evaluation with experimental data are given in Ref. [4].

In viewing Fig. 85, it should be noted that the angleintegrated spectra are not accurate in the region of the elastic scattering peaks. This problem occurs because the double-differential spectra are only measured at a few angles, and the integration is not accurate for parts of the spectra that change rapidly with angle, that is, for the elastic scattering region of the spectra. This problem is much less important for the (n,n') part of the spectra, and is probably negligible for the (n,xn), and (n,f,n) regions of the spectra.

As would be expected, the evaluated results generally agree better with the angle-integrated results than with the double-differential measurements from which they are derived. The ENDF/B-VII data, in particular, agree well with the experimental results of Baba *et al.* [45] and Matsuyama *et al.* [88] in Fig. 85. Less satisfactory agreement occurs with the other evaluations. Again, a slight improvement could be achieved in the 4.2-MeV ENDF/B-VII spectrum by including contributions from vibrational states with  $E_x=0.5-1.1$  MeV.

The spectrum at  $E_n=18$  MeV in Fig. 85 (and  $E_n=14.05$  in Fig. 13) are especially interesting in that they clearly exhibit the importance of including collective effects in the region of  $E_x \sim 1-4$  MeV. Apparently, these effects are included only approximately in the JEFF-3.0 evaluation. The importance of the underlying fission neutron spectrum is seen most clearly in the 4.25 MeV measurement and evaluations.

# 13. $n+^{238} U$ prompt fission neutron multiplicities

Our evaluation of the neutron multiplicities from prompt fission is taken from the ENDF/B-VI.8 evaluation, except nubar was extended to 30 MeV. Nubar values above 4 MeV were renormalized to reflect the ENDF/B-VII  $^{252}$ Cf nubar standard. The extension to 30 MeV is based mainly on the measurements of Frehaut *et al.* [224]. The ENDF/B-VI.8 evaluation is retained below 4 MeV because of good agreement with fast criticals.

The original ENDF/B-VI.8 evaluation is based on an evaluation by Frehaut [225] in 1986, with an approximate correction for ENDF/B-VI.8 standards. Frehaut's evaluation is based on the extensive experimental database available at that time.

We compare our evaluation with the other evaluations and with experimental data in Fig. 86. The nubar measurements of Bao [226], Savin *et al.* [227], Malynovskyj *et al.* [228], Frehaut [224], Mather *et al.* [129], Asplund-Nilsson *et al.* [229], Leroy [230], and Fieldhouse *et al.* [231] are included in our comparisons. All results were normalized to ENDF/B-VII standards. Most of the measurements are relative to spontaneous fission of  $^{252}$ Cf, which has a standard total nubar value of  $3.7692\pm0.13\%$ . The various evaluations are reasonably consistent over most of the 0-30 MeV energy interval, except for the lower and higher energies.

## 14. <sup>238</sup> U delayed neutron multiplicity and spectra

New delayed neutron multiplicities and decay constants are included in the ENDF/B-VII evaluation. The methodology followed for the evaluations is described in Sec. II.B.5. The spectra for the delayed neutrons were adopted from ENDF/B-VI.8.

#### 15. Energy release from fission of $^{238}U$

Similar to our  $n+^{235}U$  evaluation, the energy release data from fission was modified on the basis of the new Madland analysis [159]. That is, the average total fission product kinetic energy and the average total prompt fission gamma-ray energy were taken from the Madland analysis. The average total prompt fission neutron kinetic energy was obtained from our ENDF/B-VII evaluated fission neutron spectra and prompt neutron nubar, and the remaining smaller contributions from delayed neutrons, gammas, betas, and neutrinos were carried over from the ENDF/B-VI.8 evaluation. The Q-value for the  $^{238}U(n,f)$  reaction was changed from 198.06 MeV to 198.032 MeV to maintain consistency with these new energy release values.

## H. n+<sup>239</sup>U evaluation

# 1. $^{239}U$ summary

No previous evaluation of  $n+^{239}$ U reactions existed in the ENDF/B, JEFF, or JENDL databases prior to the issuing of our ENDF/B-VII evaluation. This evaluation covers the energy range from  $10^{-5}$  eV to 30 MeV. Some key features of the evaluation are:

- a The systematic analysis of uranium isotopes described in Section II was utilized in obtaining all  $n+^{239}U$  cross sections.
- b The isospin-dependent coupled-channel optical model potential given in Table II [3] was used to calculate the neutron total cross section, elastic and inelastic scattering cross sections, elastic scattering angular distributions, and reaction cross sections, as well as transmission coefficients for the reaction theory calculations.
- c The surrogate data of Younes and Britt~[232] were utilized in our evaluation of the  $^{239}\rm{U}(n,f)$  cross section.

# $2. \quad ^{239} U \ resonance \ parameters$

The ENDF/B-VII  $n+^{237}U$  resonance parameters were adopted for  $n + ^{239}U$  at neutron energies below 10



FIG. 85: Comparison of angle-integrated neutron emission spectra calculated from evaluations with measurements of Baba *et al.* and Matsuyama *et al.* at  $E_n$ =4.25, 6.10, 18.0 MeV.

keV. The resolved resonance parameters cover the energy range 10-5 to 102.5 eV; the unresolved resonance parameters span the range 102.5 eV to 10 keV. The resonance analysis was suitably joined with the present smooth cross section analysis at 10 keV. As noted in Sec. IV.F.2, deficiencies in the unresolved resonance region need to be corrected in the next issue of ENDF/B-VII.



FIG. 86: Measured and evaluated prompt nubar for  $^{238}$ U for  $E_n=0$  to 8 MeV (upper) and  $E_n=8$  to 30 MeV (lower).

#### 3. $^{239}U(n,f)$ cross section

The  $^{239}$ U (n,f) cross section is based on our calculations with the GNASH code, as indicated above. The parameters for the initial analysis are based on systematics from fitting (n,f) and other data from the more stable uranium isotopes for which experimental data exists. We then revised our GNASH analysis to better represent the surrogate (n,f) fission cross section data of Younes and Britt [232], by adjusting the fission barrier heights for first chance fission. The shape of first-chance fission and all the cross sections for multi-chance fission are based on the calculations.

We compare our evaluated  $^{239}$ U(n,f) cross section to the surrogate cross section measurements of Younes and Britt [232] and to the systematics of Behrens [182] in Fig. 87.

### 4. $n+^{239}U$ prompt fission neutron multiplicity

The evaluation of delayed nubar were carried over directly from the ENDF/B-VI.8 evaluation of  $^{237}$ U. The prompt nubar evaluation is based on the systematics of Manero and Konshin [184], updated using experimental values for targets of  $^{235}$ U and  $^{238}$ U. We show the results



FIG. 87: Evaluated  $^{239}$ U(n,f) cross section compared to surrogate fission measurements and systematics.

of our evaluation for prompt nubar in Fig. 88.

#### 5. $n+^{239}U$ inelastic, (n,xn), and $(n,x\gamma)$ cross sections

Discrete (n,n') cross sections are included for the lowest 11 excited states of  $^{239}$ U. The first and second excited states are members of the K=5/2 ground-state rotational band and include coupled-channel as well as compound nucleus contributions from COMNUC calculations. The remaining discrete-state cross sections through the 11th excited state are combinations of compound nucleus and preequilibrium contributions and were calculated with the GNASH code. The inelastic data for compound nucleus reactions corresponding to excitation energies in  $^{239}$ U above 0.373 MeV are given as energy-angle correlated continuous spectra and were calculated with the GNASH code.

The  $^{239}$ U(n,2n), (n,3n), and (n,4n) cross sections result entirely from the theoretical analysis and GNASH calculations. The  $^{237}$ U(n,n'), (n,2n), and (n,3n) cross sections from our ENDF/B-VII evaluation are presented in Fig. 89.

The  $^{239}$ U(n,x $\gamma$ ) photon-production data were taken from the  $^{237}$ U evaluation, which is based on systematics [185].

#### 6. $n+^{239}U$ total, elastic, and $(n,\gamma)$ cross sections

The evaluated total cross section below 10 keV is obtained from the resonance parameter evaluation. From 10 keV to 30 MeV, the coupled-channel deformed optical model calculations are used directly.

The elastic cross section at all energies is obtained from the difference of the total and nonelastic cross sections. Below 10 keV it comes from the resonance parameters and at higher energies it is determined essentially by the coupled-channel optical model calculations.

The capture cross section below 10 keV is based on the resonance parameters. At higher energies the cross



FIG. 88: n+<sup>239</sup>U prompt fission neutron multiplicity

section is calculated using the generalized Lorentzian model of Kopecky and Uhl [48]. The normalization of the strength function was set by requiring the calculated  $(n,\gamma)$  cross section be consistent with measured values for  $^{235}$ U, as was done in our  $n+^{237}$ U evaluation.

The evaluated  $n+^{239}U$  total, elastic, and  $(n,\gamma)$  cross sections are compared to the ENDF/B-VI.8 evaluation in Fig. 90.

#### 7. $n+^{239}U$ angular and energy distributions

Angular distributions for elastic neutrons were obtained at all energies from the ECIS coupled-channel calculations combined with the COMNUC compoundelastic calculations (see above) and are given as Legendre expansions.

Angular distributions for discrete inelastic neutrons are appropriate combinations of the compound nucleus, direct reaction, and preequilibrium contributions and are represented by Legendre expansions. For higher (n,n') states ( $E_r = 0.43-3.91$  MeV), we assume that the neutron spectrum is similar to that measured for  $^{238}\mathrm{U},$  which was calculated from assumed grouped collective states. We further assume that similar fragmented states exist for <sup>239</sup>U and simply adopt the data from the <sup>238</sup>U evaluation. The angular distributions of all excited levels are represented by Legendre expansions. As described in Section III.B, the energy-angle correlated continuum data for  $^{239}U(n,n')$ , (n,2n), (n,3n), and (n,4n) reactions are given in File 6 of the evaluation and utilize systematics by Kalbach [51] for angular distribution information, parameterized in terms of preequilibrium ratios calculated in GNASH.

The neutron energy spectra from prompt fission reactions are taken directly from the ENDF/B-VII  $^{237}$ U evaluation, which in turn was taken from ENDF/B-VI.8. Simple maxwellian forms with energy-dependent temperatures are used to represent the spectra.



FIG. 89:  $n+^{239}U$  inelastic and (n,xn) cross sections.



FIG. 90:  $n+^{239}U$  total, elastic, and  $(n,\gamma)$  cross sections.

# I. $n+^{240}U$ evaluation

# 1. $^{240}U$ summary

The  $n+^{240}$ U evaluation above the resonance region is based entirely on the model calculations described in Sec. II and the evaluation methodology in Sec. III. We used the optical potential in Table I [11] for the coupledchannels optical model calculations, coupling in either 3 (for the transmission coefficients) or 5 (for discrete level cross sections) of the lowest members of the ground state rotational band. Parameters for the GNASH calculations were taken from the systematics of our analysis of all the uranium isotopes.

#### $2. \quad ^{240}U\ resonance\ parameters$

The resolved resonance parameters  $(10^{-5}-986 \text{ eV})$  were adopted from the ENDF/V-VI.8 evaluation of  $n+^{242}$ Pu reactions. This was done because  $^{241}$ U and  $^{243}$ Pu have the same spin and parity. This is, of course, a gross approximation and cannot be accurate in any detail. Our made for greater consistency with the unresolved resonance parameters. The unresolved resonance parameters (0.986-10 keV) of the  $^{243}$ Pu ENDF/V-VI.8 evaluation also were adopted for  $^{241}$ U, for the same reason given above. Adjustments

were made to all the widths to obtain consistency with the smooth cross sections at 10 keV.

# 3. $n+^{240}U$ cross sections above the resonance region

The  $^{240}$ U(n,f) cross section that results from our reaction theory model calculations is shown in Fig. 91, together with the prompt fission neutron multiplicity. The latter quantity, as well as the delayed neutron multiplicity from fission and the energy release quantities from fission, were adopted from the ENDF/B-VI.8 evaluation of  $^{238}$ U.

The n+<sup>240</sup>U inelastic and <sup>240</sup>U(n,xn) cross sections from the model calculations are shown in Fig. 92. Coupled-channels calculations were used for the lowest 4 excited states of <sup>240</sup>U, and compound nucleus calculations for the levels in the range  $E_x=0.6-1.11$  MeV. For excitation energies between 1.12 and 3.91 MeV, cross sections were calculated with ECIS96 for grouped 2+ and 3vibrational levels, taken from our <sup>238</sup>U evaluation as described earlier. The continuum cross section thresholds at  $E_x=1.12$  MeV. The <sup>240</sup>U(n,xn) cross sections shown in Fig. 92 were calculated with the GNASH code.

Similarly, the total, elastic, and  $(n,\gamma)$  cross sections from  $n+^{240}$ U reactions are shown in Fig. 93. Note that there are no experimental or evaluated data to compare with our calculated data in Figs. 91-93. The photonproduction data from the ENDF/B-VII  $n+^{238}$ U evaluation were adopted for  $n+^{240}$ U except for radiative capture, which was taken from our GNASH analysis.

## 4. $n+^{240}U$ angular and energy distributions

The neutron angular distributions for elastic scattering and the lowest 4 excited states were obtained from the ECIS96 coupled-channels calculations. Similarly, the angular distribution for the vibrational states between  $E_x=1.12$  and 3.91 MeV were obtained in ECIS96 calculations, as described in Sec. III.B. Neutron energyangle correlations for the (n,n'continuum) and (n,xn) reactions were obtained from the GNASH calculations and the Kalbach systematics [51].

The prompt fission neutron spectra are taken from the ENDF/B-VI.8 evaluation for  $^{236}$ U.

# J. $n+^{241}U$ evaluation

# 1. $^{241}U$ summary

Like  $^{240}$ U, the n+ $^{241}$ U evaluation above the resonance region is based entirely on the model calculations described in Sec. II and the evaluation methodology in Sec. III. In this case, we used the isospin-dependent optical



FIG. 91: Evaluated  $n+^{240}$ U prompt fission neutron multiplicity and fission cross section.



FIG. 92: n+<sup>240</sup>U inelastic and (n,xn) cross sections.

potential in Table II [3] for the coupled-channels optical model calculations, coupling in the lowest 3 members of the ground state rotational band. As with  $^{240}$ U, parameters for the GNASH calculations were taken from the systematics of our analysis of all the uranium isotopes.

#### 2. $^{241}U$ resonance parameters

No suitable nearby nucleus with the same spin and parity as  $^{241}\mathrm{U}$  and with known resonance parameters was identified. Therefore, we simply adopted the ENDF/B-VI.8  $\mathrm{n}+^{237}\mathrm{U}$  resonance parameters for our ENDF/B-VII



FIG. 93:  $n+^{240}U$  total, elastic, and  $(n,\gamma)$  cross sections.

evaluation of  $n+^{241}$ U reactions at neutron energies below 10 keV. The resonance analysis was suitably joined with our smooth cross section calculations above 10 keV, the maximum energy of the unresolved resonance region.

#### 3. $n+^{241}U$ cross sections above the resonance region

The <sup>241</sup>U(n,f) cross section that results from our reaction theory model calculations is shown in Fig. 94, together with the prompt fission neutron multiplicity. The prompt nubar evaluation is based on the systematics of Manero and Konshin [184], updated using experimental values for targets of  $^{235}$ U and  $^{238}$ U. The delayed neutron multiplicity from fission and the energy release quantities from fission were adopted from the ENDF/B-VI.8 evaluation of  $^{237}$ U. The n+ $^{241}$ U inelastic and  $^{241}$ U(n,xn) cross sections from the model calculations are shown in Fig. 95. Coupled-channels calculations were used for the lowest 2 excited states of <sup>241</sup>U. Discrete (n,n') cross sections are included for the lowest 2 rotational levels of <sup>241</sup>U, calculated with ECIS96, and for 25 (representative) collective levels at higher excitation energies. Because the structure of  $^{241}U$  is unknown, the rotational states were estimated from a rotational model. The two excited states are members of the K=7/2 ground-state rotational band; the cross sections and angular distributions include direct components from the ECIS calculations as well as compound nucleus contributions from the COMNUC calculations. The other collective levels are based on calculations for <sup>235</sup>U and <sup>238</sup>U, also including both direct and compound nucleus contributions, under the assumption that similar states exist for  $^{241}$ U. The angular distributions of all excited levels are represented by Legendre expansions.

The (n,n'continuum) inelastic cross sections, resulting from compound nucleus and preequilibrium reactions at excitation energies in  $^{241}$ U above 0.123 MeV, were calculated with the GNASH code.

The total, elastic, and  $(n,\gamma)$  cross sections from  $n+^{241}$ U reactions are shown in Fig. 96. The total cross section results from the coupled-channels optical model calculations. The  $(n,\gamma)$  cross section was calculated with the

Lorentzian model of Kopecky and Uhl [48]. The normalization of the strength function was set by requiring the calculated  $(n,\gamma)$  cross section be consistent with measured values for <sup>235</sup>U, similar to our n + <sup>237</sup>U evaluation. As was the case with the n+<sup>240</sup>U evaluation, there are no experimental or evaluated data to compare with our calculated <sup>241</sup>U data in Figs. 94-96.

The gamma-ray production data from our  $n+^{237}U$  evaluation was adopted for  $n+^{241}U$ .

#### 4. $n+^{241}U$ angular and energy distributions

The neutron angular distributions for elastic scattering and the lowest 2 excited states were obtained from the ECIS96 coupled-channels calculations. Similarly, the angular distributions of (n,n') reactions to states at higher excitation energies include direct and compound nucleus contributions from ECIS and COMNUC calculations.

The (n,n'continuum) inelastic distributions are included as energy-angle correlated continuous spectra and were calculated with the GNASH code. The results are given in File 6 of the ENDF-6 format and utilize systematics by Kalbach [51] for angular distribution information, parameterized in terms of preequilibrium ratios calculated with the GNASH code.

The fission neutron spectra in the revised evaluation is carried over directly from the  $^{237}$ U evaluation in ENDF/B-VI.8. A maxwellian representation is used for the spectrum shape, with energy-dependent temperature parameters based on systematics.

#### K. $n+^{239}$ Pu evaluation

#### 1. <sup>239</sup>Pu summary

Major features of the ENDF/B-VII evaluation are:

- 1. A new evaluation of the <sup>239</sup>Pu(n,f) cross section based on ENDF/B-VII standard cross section analysis is incorporated.
- 2. A new evaluation of nubar consistent with experimental data and with fast critical benchmark measurements is included.
- 3. Improved delayed neutron data and fission energy release values are incorporated.
- 4. A new analysis of the prompt fission neutron spectrum matrix based on the Los Alamos model is used to calculate neutron spectra at all incident neutron energies.
- 5. New (n,2n) experimental data from a LANSCE GEANIE experiment are combined with older data and GNASH theoretical calculations to produce a new evaluation of the <sup>239</sup>Pu(n,2n) cross section.
- 6. Direct reaction cross sections and angular distributions are extended to an excitation energy of 4 MeV using a DWBA analysis of  $^{238}$ U emission neutron data.



FIG. 94: Evaluated  $n+^{241}U$  prompt fission neutron multiplicity and fission cross section.



FIG. 95: n+<sup>241</sup>U inelastic and (n,xn) cross sections.

The evaluation of other reactions above 10 keV is based on ENDF/B-VI.8, which, in turn, is based on a detailed theoretical analysis [11] utilizing the available experimental data.

#### 2. <sup>239</sup>Pu resonance parameters

The resolved resonance parameters are the same as those in ENDF/B-VI.8. They were first installed in MOD 2 of ENDF/B-VI in January, 1993, by H. Derrien (ORNL) and T. Nakagawa (JAERI). This revision extended the resolved resonance region to 2.5 keV. The



FIG. 96:  $n+^{241}U$  total, elastic, and  $(n,\gamma)$  cross sections.

resonance parameters are based on a SAMMY analysis of high resolution experimental data, obtained at Oak Ridge National Laboratory. Details of the analysis are given in the descriptive section of File 1 of the ENDF/B-VII evaluation.

The unresolved resonance parameters are given in the energy range 2.5 keV to 30 keV for 70 energy points. They were obtained by using the Cadarache statistical code FISINGA to fit the gross structure of experimental total cross sections below 4 keV and of selected experimental fission cross sections normalized to ENDF/B-VI standard evaluation. Above 4 keV no high resolution total cross section data are available; average total cross sections were calculated to be consistent with the statistical parameters obtained in the resolved resonance region and with optical model parameters obtained by fitting experimental data at higher energies.

## 3. $^{239}Pu$ (n,f) cross section

The  $^{239}$ Pu(n,f) cross section that resulted from the simultaneous standards analysis for ENDF/B-VII [6] was used with minimal smoothing at all incident neutron energies above the resonance region. The original standard energy grid is included as a subset of a denser grid. The expansion to the denser grid was accomplished using a spline fit to a log-log file of the standard data.

The Q-value was changed from 199.92 MeV to 198.8438 MeV to maintain consistency with the revised fission energy release data for ENDF/B-VII, described below.

We compare our ENDF/B-VII evaluated fission cross section from  $E_n 0$  to 6 MeV with other recent evaluations and with the results of the ENDF/B-VII simultaneous standards analysis and a sampling of experimental data in Fig. 97. The same comparisons are given over the neutron energy range 5-20 MeV in Fig. 98. The <sup>239</sup>Pu(n,f) measurements of Lisowski [53], Meadows [104], [233], and Shcherbakov *et al.* [234] are included in the figures.



FIG. 97:  $^{239}$ Pu(n,f) cross section from 0 to 6 MeV. The upper frame compares the results of the ENDF/B-VII standards analysis with evaluations; the lower frame compares experimental data with current evaluations.

#### 4. $n+^{239}Pu$ prompt fission neutron multiplicity

In the incident neutron energy range  $10^{-5}$  eV-1.0 keV, the evaluation is taken directly from ENDF/B-VI.8 without change. The ENDF/B-VI.8 evaluation in this energy range is based on an evaluation by Fort *et al.* [235], after a small renormalization for consistency with the CSEWG thermal nubar value from the ENDF/B-VI standards analysis.

In the energy region 1 keV-20 MeV, minor modifications were made to the ENDF/B-VI.8 evaluation to improve agreement with the results of the covariance analysis of experimental data that was used for that evaluation and with integral experimental results. Also, the ENDF/B-VI.8 data were adjusted above 6-8 MeV for consistency with the ENDF/B-VII standard <sup>252</sup>Cf nubar value.

The results of our evaluation are compared to experimental data and to other evaluation between  $E_n 0.001$ -2.0 MeV in Fig. 99. A similar comparison is given for neutron energies between 2 and 18 MeV in Fig. 100. The experimental data in Figs. 99 and 100 are from the measurements of Frehaut *et al.* [224], Gwin *et al.* [113], Zhang *et al.* [236], Hopkins and Diven [237], Conde *et al.* [238], and Savin *et al.* [239].



FIG. 98:  $^{239}$ Pu(n,f) cross section from 5 to 20 MeV. See caption to Fig. 97 for details.

We attempted to follow the covariance data as well as possible but mainly to stay within uncertainties in the data and at the same time to keep good agreement with fast critical benchmarks. In order to get good agreement with the JEZEBEL fast critical assembly, however, the evaluated curve is slightly higher than the uncertainty limit in the covariance analysis around 1 MeV, although it remains well within the scatter in the experimental data (see Fig. 99). At all other energies the evaluated nubar curve is within uncertainties in the covariance analysis and agrees well with that analysis (Figs. 99 and 100).

# 5. $n+^{239}Pu$ total cross section

The n+<sup>239</sup>Pu total cross section above the resonance region (0.03-20 MeV) was taken from ENDF/B-VI.8, which is based on coupled-channel optical calculations combined with a covariance analysis of the experimental database available circa 1990. The covariance analysis was performed using the GLUCS code system [97], as described earlier (Sec. IV.B.1). The experimental data of Poenitz *et al.* [18], [118], Shamu [21], Schwartz *et al.* [151], Foster and Glasgow [116], Smith *et al.* [240], Nadolny *et al.* [241], Peterson *et al.* [152], Cabe and Cance [154], and Lisowski [31] were included in the co-



FIG. 99:  $n+^{239}$ Pu prompt nubar between 1 keV and 2 MeV. Evaluated data are compared to the results of our covariance analysis in the upper frame and to experimental data in the lower frame.

variance analysis. The results of the analysis, which agree well with Derrien's (De89) unresolved resonance analysis at 30 keV, were smoothly joined to Derrien's results between 30 and 50 keV.

We compare our evaluation between 0.03 and 2.0 MeV with other evaluations and with the measurements of Poenitz *et al.*, Schwartz *et al.*, Shamu, and Peterson *et al.* in Fig. 101. We include similar comparisons for  $E_n$  2-20 MeV in Fig. 102, also including experimental data from Foster and Glasgow and a more recent measurement by Lisowski [53].

#### 6. $^{239}Pu(n,xn)$ cross sections

The  $^{239}$ Pu(n,2n) cross section is based to a large extent on new experimental data from the LANSCE-GEANIE facility by Bernstein *et al.* [242] and newly reported data from Lawrence Livermore National Laboratory (LLNL) by Lougheed *et al.* [243]. These results were combined with GNASH theoretical calculations to obtain the ENDF/B-VII evaluation.

The new GEANIE results are deduced from a combination of measured partial gamma-ray cross sections and enhanced Hauser-Feshbach reaction modeling. Older



FIG. 100:  $n+^{239}$ Pu prompt nubar from 2 to 18 MeV. See caption of Fig. 99 for details.



FIG. 101:  $n+^{239}$ Pu total cross section from 0.03 to 2 MeV.

measurements by Mather *et al.* [244] and Frehaut *et al.* [245] are not included in the analysis due to large uncertainties and scatter in those data. The results of our evaluation are compared with experimental data and with other current evaluations in Fig. 103. The analysis of the GEANIE data and the evaluation is discussed in detail in Ref. [242].



FIG. 102:  $n+^{239}$ Pu total cross section from 2 to 20 MeV.

# 7. $^{239}Pu(n,\gamma)$ cross section

The radiative capture cross section above the resonance region is taken directly from the ENDF/B-VI.8 evaluation. The results are compared to other evaluations and to the experimental data of Kononov *et al.* [246], Gwin *et al.* [247], and Hopkins [98] in Fig. 104.

# 8. $n+^{239}Pu$ elastic cross section and angular distributions

Our evaluated elastic scattering cross section was determined by subtracting the sum of all nonelastic cross sections from the evaluated total cross section.

The elastic scattering angular distributions from ENDF/B-VI.8 were adopted for ENDF/B-VII. These distributions are based on coupled-channels calculations with the ECIS70 code [130], [248]. A compound elastic component from COMNUC [52] calculations was included in the angular distributions below  $E_n=6$  MeV.

We compare our evaluation of elastic scattering angular distributions with other evaluations and experimental data in Fig. 105. In Fig. 105 we include measurements of the sum of scattering to the ground and first excited states of <sup>239</sup>Pu by Egan *et al.* [249] at  $E_n=0.57$  MeV, and Haouat *et al.* [12] at  $E_n=0.7$  and 3.4 MeV. Similarly,



FIG. 103:  $^{239}\mathrm{Pu}(\mathrm{n,2n})$  cross section from threshold to 20 MeV. The 11 MeV point labeled as Navratil represents an infrared estimate by LLNL obtained by from subtracting estimated fission and inelastic cross sections from the reaction cross sections.



FIG. 104: The  ${}^{239}$ Pu(n, $\gamma$ ) cross section from 0.03 to 20 MeV.

in Fig. 106 we compare the evaluations with the measurement of Hansen *et al.* at  $E_n$ =14.1 MeV of elastic scattering plus (n,n') scattering to states up to  $E_x$ =250 keV.

#### 9. <sup>239</sup>Pu (n,n') cross sections and angular distributions

The (n,n') cross sections to <sup>239</sup>Pu states with excitation energy lower than 1.17 MeV were taken from the ENDF/B-VI.8 evaluation. The low-lying level cross sections from that evaluation are based on coupled-channels optical model calculations [11] including the 3/2+ to 13/2+ members of the K=1/2 ground state rotational band of <sup>239</sup>Pu, using the ECIS70 deformed optical model code [130]. Direct reaction contributions to several states at higher excitation energies were calculated with the DWUCK code [131]. The (n,n') cross sections from higher (collective) states between  $E_x=1.17$  and 4 MeV were calculated as described in Sec. II.B.4.b and combined with the ENDF/B-VI.8 data at lower excitation energies. Compound nucleus contributions were included in all the discrete state (n,n') data, obtained from calculations with the COMNUC code [52].

The <sup>239</sup>Pu(n,n') cross section to continuum states was calculated with the GNASH code, as described in Sec. II.B. The continuum cross section thresholds at 0.63 MeV. Therefore, discrete states that lie above  $E_x=0.63$  MeV overlap with the continuum region.

The total  $^{239}$ Pu(n,n') cross section is the sum of the discrete state and continuum region cross sections. It is compared to the measurements of Andreev [147] and Batchelor *et al.* [145] in Fig. 107, together with other current evaluations.

Angular distributions of the <sup>239</sup>Pu(n,n') reactions were obtained in the model calculations summarized above. We compare our evaluated results in Fig. 108 with the measurements of Haouat *et al.* [12] at  $E_n=0.7$  MeV for the first three excited states of <sup>239</sup>Pu. We also include evaluated results from ENDF/B-VI.8, JEFF-3.1, and JENDL-3.3 in Fig. 108. Similarly, in Fig. 109 we compare the evaluations for the sum of the 2<sup>nd</sup> and 3<sup>rd</sup> excited states with the measurement of Egan *et al.* [249] at  $E_n=0.57$  MeV and with the measurement of Haouat *et al.* at  $E_n=3.4$  MeV. Also included in Fig. 109 (lower frame) is a comparison with the Haouat *et al.* data for the sum of the 4<sup>th</sup> and 5<sup>th</sup> excited states at  $E_n=3.4$  MeV.

#### 10. $n+^{239}Pu$ emission neutron distributions

The  $^{239}$ Pu(n,xn) emission spectra were adopted from ENDF/B-VI.8. They were obtained originally from GNASH [46] calculations, with angular distributions from the Kalbach systematics [51], as described in Sec. III.B.

As with  $^{235}$ U, a prompt fission neutron spectrum matrix for the  $n+^{239}$ Pu system was calculated using the Los Alamos model [83] in its exact formulation with energy-dependent compound nucleus formation cross sections for the inverse processes. The model and methodology is summarized in Sec. II.B.4.a.

The matrix includes first-, second-, and third-chance fission components and also includes the neutrons emitted prior to fission in second- and third-chance fission. The multiple-chance fission average prompt neutron multiplicity (nubar prompt) was calculated simultaneously and, in reproducing experiment, was crucial in determining the fission spectrum matrix. The ENDF/B tabulated distribution law (LF=1) is used to represent the data. The matrix is calculated for 19 incident neutron energies between 0 and 15 MeV. The 20-MeV spectrum is simply a duplication of the 15-MeV spectrum.

# 11. $n+^{239}$ Pu delayed neutron and photon data

Improved delayed neutron multiplicities and decay constants from fission were incorporated into our evaluation, as described in Section II.B.5. Similar to our  $n+^{235}$ U evaluation,  $\beta$ -delayed photon-production probabilities from fission reactions were incorporated for some



FIG. 105: n+<sup>239</sup>Pu elastic scattering angular distributions.

3129 discrete gamma rays taken from the work of Pruet *et al.* [157]. As with  $^{235}$ U, the data were generated by directly sampling prompt fission product yield distributions and then following the decay of each individual fission fragment in time and tabulating the resulting photon-production spectrum.

# 12. Energy release from <sup>239</sup>Pu fission

As with  $^{235}$ U, a new evaluation of the energy released from fission was made for  $^{239}$ Pu, based largely on results from a new analysis by Madland [159]. The average total fission product kinetic energy and the average total



FIG. 106:  $n+^{239}$ Pu elastic scattering angular distributions.



FIG. 107:  $^{239}$ Pu(n,n') cross section from threshold to 20 MeV.

prompt fission gamma-ray energy were taken from the Madland analysis. The average total prompt fission neutron kinetic energy was obtained from our ENDF/B-VII evaluated fission neutron spectra and prompt neutron nubar, and the remaining smaller contributions from delayed neutrons, gammas, betas, and neutrinos were carried over from the ENDF/B-VI.8 evaluation.

#### V. INTEGRAL DATA COMPARISONS

We have completed new evaluations for ENDF/B-VII of neutron-induced reaction data for  $^{232-234,236-241}$ U over the incident neutron energy range from  $10^{-5}$  eV to 30 and for  $^{235}$ U and  $^{239}$ Pu from  $10^{-5}$  eV to 20 MeV. In the above sections we have shown comparisons of the new results with much of the available experimental data above  $E_n=10$  keV and with the existing ENDF/B-VI.8, JEFF-3.1, and JENDL-3.3 evaluations. All the evaluations described in this paper are on file at the NNDC at BNL as part of the ENDF/B-VII library [1].



FIG. 108: <sup>239</sup>Pu(n,n') angular distributions at  $E_n 0.7$  MeV to the first three excited states of <sup>239</sup>Pu.

#### A. Critical assembly data testing

Considerable effort has been expended in testing the evaluations in the new database, and these are detailed in Ref. [1]. Of particular relevance to the present work are testing results for fast U and Pu critical assembly benchmarks, included in Sec. X.B.2 of Ref. [1]. We include here in Table VII the results presented graphically in Fig. 86 of Ref. [1] for calculations of  $k_{eff}$  for the LANL HEU (highly enriched uranium), Pu, and <sup>233</sup>U unmoderated critical assembly benchmarks, which compare calculated/experimental results obtained with the MCNP5 code using ENDF/B-VI.8 and ENDF/B-VII cross section



FIG. 109: <sup>239</sup>Pu(n,n') angular distributions to the second and third excited states at  $E_n = 0.57$  and 3.4 MeV, and to the sum of the fourth and fifth excited states at  $E_n = 3.4$  MeV.

data.

The LANL benchmark experiments are described in the ICSBEP handbook [250]. The unmoderated, enriched <sup>235</sup>U benchmarks given in Table VII include Godiva (ICSBEP abbreviated designation HMF1), Flattop-25 (HMF28), and Big-10 (IMF7). Unmoderated plutonium benchmarks include Jezebel (PMF1), Jezebel-240 (PMF2), Flattop-Pu (PMF6), and Thor (PMF8). Unmoderated enriched <sup>233</sup>U benchmarks include Jezebel-23 (UMF1) and Flattop-23 (UMF6).

The Godiva assembly is a bare sphere of HEU; Jezebel is a bare sphere of plutonium; and Jezebel-23 is a bare sphere of  $^{233}$ U. The Flattop assemblies involve spherical cores of HEU or plutonium surrounded by  $^{238}$ U reflector material to make the composite systems critical. The various assemblies all result in neutron spectra that are fast, with neutrons mainly in the 100 keV to few MeV regions. The exact spectra vary from assembly to assembly and at different locations within each assembly. The Big-10 assembly, for example, has a neutron spectrum that is softer than both the Godiva and Flattop-25 assemblies.

The improved accuracy in calculated  $k_{eff}$  in the LANL unmoderated benchmarks is evident in Table VII. All calculated/experimental ratios for  $k_{eff}$  move closer to unity except for Flattop-25 and Flattop-23, and these are both within the estimated  $1\sigma$  experimental errors. Additionally, eight of the nine C/E values for  $k_{eff}$  are now within experimental uncertainty. Furthermore, even though the Flattop-25 and Flattop-23 C/E values are worse for ENDF/B-VII than for ENDF/B-VI.8, the reflector bias due to <sup>238</sup>U reflection has now been reduced significantly. That is, the differences between Flattop-25 and Godiva, Flattop-23 and Jezebel-23, and Flattop-Pu and Jezebel have all been reduced.

In several cases significant improvement was achieved in the critical assembly simulations, e.g., Big-10, Godiva, Jezebel, and Jezebel-23. The improved C/E ratio for Big-10, as well as the improved reflection bias for the <sup>238</sup>U-reflected Flattop assemblies, strongly suggest that improvements have been made to the  $n+^{238}U$  elastic and inelastic scattering angular distributions. Overall improvement in the evaluated data files is strongly indicated by these results.

A recent paper by Wilkerson *et al.* [251] summarizes many of the key benchmark experiments made at Los Alamos and presents reaction rate comparisons with calculations using the ENDF/B-VII database. Numerical tables are given for many of the benchmark measurements. Because several of Wilkerson's results are highly relevant to evaluations described in this paper, we repeat some of those results here.

As one moves out from the centers of the various critical assemblies, the neutron spectrum becomes softer. Holes were drilled in the various assemblies to allow placement of foils of different materials, which were then exposed to different neutron spectra depending upon their location. The foils can be used to measure the reaction rates for different reactions under exposure to the different neutron spectra. By then performing calculations that simulate the exposure of the foils, additional information can be obtained about the quality of the nuclear data.

An example of such data for the  $^{238}$ U(n,f) and (n,2n) reactions, as obtained in the Flattop-25, Big-10, Flattop-Pu, Jezebel, and Topsy<sup>1</sup> assemblies, is shown in Refs. [1] and [251], and is reproduced here in Fig. 110. The abscissa in Fig. 110,  $^{238}$ U(n,f)/ $^{235}$ U(n,f), is a measure of the hardness of the spectrum (spectral index), and the ordinate is the ratio of the  $^{238}$ U(n,2n)/ $^{235}$ U(n,f) reaction rates. In the figure the measured ratios from sev-

<sup>[1]</sup> Topsy was an early mock up of a  $^{235}\mathrm{U}$  core reflected by natural uranium.

TABLE VII: LANL HEU, Pu, and <sup>233</sup>U unmoderated benchmark C/E values for  $k_{eff}$  calculated with ENDF/B-VI.8 and ENDF/B-VII cross section data.

		Calculated/	Experiment
Assembly	Experiment	ENDF/B-VI.8	ENDF/B-VII
Godiva	1.0000(10)	0.9966(2)	1.0000(1)
Flattop-25	1.0000(30)	1.0018(1)	1.0028(1)
Big-10	1.0045(7)	1.0116(2)	1.0002(1)
Jezebel	1.0000(20)	0.9975(2)	0.9999(1)
Jezebel-240	1.0000(20)	0.9980(1)	1.0001(1)
Flattop-Pu	1.0000(30)	1.0027(2)	1.0002(1)
Thor	1.0000(6)	1.0058(1)	0.9980(2)
Jezebel-23	1.0000(10)	0.9926(1)	0.9996(1)
Flattop-23	1.0000(14)	1.0006(2)	0.9991(1)

eral assemblies are compared to calculated values for the Flattop-25 and Topsy assemblies. This type of graph permits data from different assemblies to be compared on a common basis. Comparisons such as are given in Fig. 110 provide increased confidence in the accuracy of the evaluated data, primarily the  $^{238}U(n,2n)$  cross section, but also the data involved in neutron transport, especially the prompt fission neutron spectrum. The overprediction of the Flattop-25 measurements at lower spectral index values might indicate that the  $^{238}$ U(n,2n) cross section is too high close to threshold. (The overprediction seems to be less when the calculations are compared to the Topsy measurements.) Our preference to follow the LANL radiochemistry measurements near threshold by Knight et al. [70] and 14.1 MeV by Barr et al. [58], together with our GNASH calculations, led us to the evaluated (n,2n) cross section, shown earlier in Fig. 76.

A similar comparison for the <sup>238</sup>U neutron capture rate was also presented in Refs. [1], [251], and we reproduce it here in Fig. 111. In Fig. 111 the integral <sup>238</sup>U capture rate divided by the <sup>235</sup>U fission rate is shown as a function of spectral index for different critical assembly locations, again for the Flattop-25, Big-10, Flattop-Pu, Jezebel, and Topsy assemblies. The measured results in uranium assemblies for both the <sup>238</sup>U(n,2n) and <sup>238</sup>U(n, $\gamma$ ) reactions are tabulated in Table VIII; the measurements for plutonium assemblies are given in Table IX.

There is fair agreement between the Flattop-25 and Flattop-Pu calculations with the different critical assembly measurements in Fig. 111. However, there is indication of an underprediction of the capture data by 5-10%for the harder spectrum systems (larger values of <sup>238</sup>U fission/ <sup>235</sup>U fission). Although the <sup>238</sup>U(n, $\gamma$ ) cross section is thought to be known to better than 3% over the low keV to 2 MeV range from the ENDF/B-VII standards analysis [6], the results in Fig 111 suggest that a new, accurate measurement of the  $^{238}$ U(n, $\gamma$ ) cross section in this energy region might be warranted. Benchmark measurements are also available for (n,f) and  $(n,\gamma)$  reactions on <sup>236</sup>U with the Flattop-25 assembly and were presented at the Nice conference by Wilkerson et al. [251]. These measurements are compared to calculations using the ENDF/B-VII database in Figs. 112 and 113 for (n,f) and  $(\mathbf{n},\gamma)$  reactions, respectively. See Table X for a tabulation of the measured data. The results in Fig. 112 indicate that the evaluated <sup>236</sup>U fission cross section at lower energies might be too low. Similarly, the compar-



FIG. 110: Comparison of experimental and calculated radiochemical values for radial traverses in the Flattop-25 and Topsy assemblies. The ratio of the  $^{238}$ U(n,2n) reaction rate to the  $^{235}$ U fission rate is plotted as a function of the ratio of the  $^{238}$ U fission rate to the  $^{235}$ U fission rate (spectral index) at different positions in the assemblies. The Big-10 result is computed at the center of the assembly.



FIG. 111: The integral  $^{238}$ U neutron capture rate divided by the  $^{235}$ U fission rate as a function of spectral index for different critical assembly locations. See caption of Fig. 110.

isons in Fig. 113 suggest that the  $^{236}$ U(n, $\gamma$ ) cross section might be generally low in the keV to low MeV region. Of course, the available experimental data for the  $^{236}$ U evaluation is more limited than for  $^{238}$ U. We include in Fig. 114 a comparison of Flattop-25 measurements of the  $^{237}$ U(n,f)/ $^{235}$ U(n,f) reaction rate ratio as a function of spectral index with calculations of the ratio using the ENDF/B-VII evaluations. Again, these results are taken from the Nice paper by Wilkerson *et al.* [251]. In this case there is good agreement of the calculated values in the softer region of the spectrum with the measurement, but

TABLE VIII: <sup>238</sup>U data for uranium critical assemblies.

		Ratio to <sup>235</sup>	<sup>5</sup> U(n,f)	
$^{238}U(n,f)$	$^{238}U(n,2n)$	$^{238}U(n,\gamma)$	Assembly	Loc. (cm)
1.14710E-2	3.79700E-4		Topsy	25.68
1.36170E-2	5.85530E-4	1.06110E-1	Topsy	20.24
2.04187E-2	8.96963E-4	1.17752E-1	Flattop-25	14.75
2.06020E-2	$9.06480\mathrm{E}\text{-}4$	1.12200E-1	Topsy	15.67
2.72910E-2	1.26360E-3	1.12500E-1	Topsy	12.66
2.75553E-2	1.28007E-3	1.13307E-1	Flattop-25	12.78
3.75000E-2	1.73250E-3	1.06119E-1	Bigten	
$4.23241\mathrm{E}\text{-}2$	1.69191E-3	1.09518E-1	Flattop-25	9.62
$5.03110\mathrm{E}\text{-}2$	$2.36960\mathrm{E}\text{-}3$	1.27160E-1	Topsy	9.66
$7.00776\mathrm{E}\text{-}2$	$3.15537\mathrm{E}\text{-}3$	1.00505E-1	Flattop-25	7.7
$9.91197\mathrm{E}\text{-}2$	$4.68075\mathrm{E}\text{-}3$	1.00904E-1	Flattop-25	6.31
9.93180E-2	4.70102E-3	$9.49281\mathrm{E}\text{-}2$	Flattop-25	6.32
1.13420E-1	5.72780E-3	8.82760E-2	Topsy	5.49
1.24990E-1	5.84752E-3	9.07552E-2	Flattop-25	5.6
1.27369E-1	6.15464E-3	$9.44058\mathrm{E}\text{-}2$	Flattop-25	5.16
1.40354E-1	$6.65877\mathrm{E}\text{-}3$	$9.05140\mathrm{E}\text{-}2$	Flattop-25	3.7
1.41642E-1	$6.56435\mathrm{E}\text{-}3$	$8.38096\mathrm{E}\text{-}2$	Flattop-25	3.69
1.44730E-1	7.48270E-3	$7.66360\mathrm{E}\text{-}2$	Topsy	0.24
1.48382E-1	7.03968E-3	$8.86881\mathrm{E}\text{-}2$	Flattop-25	0.01
1.49274E-1	$6.96724\mathrm{E}\text{-}3$	8.81763E-2	Flattop-25	1.02
1.52446E-1	7.21574E-3	$8.28697\mathrm{E}\text{-}2$	Flattop-25	0.4

TABLE IX:  $^{238}\mathrm{U}$  data for plutonium critical assemblies.

	Ratio to <sup>235</sup>	<sup>5</sup> U(n,f)		
$^{238}U(n,f)$	$^{238}U(n,2n)$	$^{238}$ U(n, $\gamma$ )	Assembly	Loc. (cm ) $$
6.93000E-2	3.5620E-3	9.45252E-2	Flattop-Pu	6.07
1.19100E-1	6.0741E-3	8.93488E-2	Flattop-Pu	4.53
1.58800E-1	8.4482E-3	8.20202E-2	Flattop-Pu	2.97
1.69100E-1	9.2667E-3	7.80227E-2	Flattop-Pu	1.44
2.17000E-2		1.25576E-1	Flattop-Pu	
2.62000E-2		1.15356E-1	Flattop-Pu	
2.12116E-1	1.40934E-2	6.69863E-2	Jezebel	
2.13603E-1	1.45441E-2	6.88015E-2	Jezebel	
2.09638E-1	1.42511E-2	6.79647E-2	Jezebel	
2.14693E-1	1.44533E-2	6.74996E-2	Jezebel	
2.08845E-1	1.42889E-2	6.73944E-2	Jezebel	

the calculations appear to fall about 15% below the measurement at higher values of the spectrum index. Whilst this might indicate that the average  $^{237}$ U(n,f) cross section should be higher by this amount at faster neutron energies (say, 100 keV-1 MeV), our evaluation of this cross section appears to be reasonably consistent with surrogate (n,f) data, as shown in Fig. 68. However, the uncertainties on the surrogate data are fairly large and a higher (n,f) cross section would not be inconsistent with those

TABLE X: <sup>236</sup>U data for Flattop-25 critical assembly.

	Ratio to 2	$^{235}U(n,f)$		
$^{238}U(n,f)$	$^{236}U(n,f)$	$^{236}U(n,\gamma)$	Assembly	Loc. (cm )
$2.050\mathrm{E}\text{-}2$	8.24E-2	1.780E-1	Flattop-25	15.3
$3.490\mathrm{E}\text{-}2$	1.07E-1	1.720E-1	Flattop-25	11
$6.240\mathrm{E}\text{-}2$	1.54E-1	1.530E-1	Flattop-25	8.1
1.254E-1	2.92E-1	1.280E-1	Flattop-25	5
1.270E-1	2.85E-1	1.300E-1	Flattop-25	4.9
1.414E-1	3.04E-1	1.240E-1	Flattop-25	3.9
1.468E-1	3.17E-1		Flattop-25	0.2
1.527E-1	3.33E-1	1.220E-1	Flattop-25	0.8
$1.540\mathrm{E}\text{-}1$	3.15E-1	1.195E-1	Flattop-25	1.0



FIG. 112: Comparison of measured and experimental values of the ratio of the  $^{236}$ U fission rate to the  $^{235}$ U fission rate as a function of spectral index at different locations in the Flattop-25 critical assembly. Calculated results are also shown for the Big-10 and Jezebel assemblies. See caption for Fig. 110.



FIG. 113: The integral  $^{238}$ U neutron capture rate divided by the  $^{235}$ U fission rate as a function of spectral index for different critical assembly locations. Calculated results are also shown for the Big-10 and Jezebel assemblies. See caption of Fig. 110 for more details.

data. The measured  $^{237}U(n,f)/^{235}U(n,f)$  reaction rate ratios are given in Table XI. Although the ENDF/B-VII evaluation of  $n+^{241}$ Am reactions is not described in this paper, for completeness we show comparisons of calculations with that evaluation of the  $^{241}$ Am $(n,\gamma)/^{235}U(n,f)$ reaction rate ratio and critical assembly measurements in Fig. 115. As before, the results are presented as functions of spectral index for the Flattop-25, Big-10, Flattop-Pu,

TABLE XI:  $^{237}\mathrm{U}$  data for Flattop-25 critical assembly.

	Ratio to <sup>2</sup>	$^{235}U(n,f)$	
$^{238}U(n,f)$	$^{237}U(n,f)$	Assembly	Location (cm)
0.02487	0.391	Flattop-25	13.97
0.1397	0.537	Flattop-25	1.11



FIG. 114: Comparison of measured and experimental values of the ratio of the  $^{237}$ U fission rate to the  $^{235}$ U fission rate as a function of spectral index at different locations in the Flattop-25 critical assembly. See caption for Fig. 110.

TABLE XII:  $^{242}\mathrm{Am}$  capture data for uranium critical assemblies.

	Ratio Data	
$^{238}$ U(n,f)/ $^{235}$ U(n,f)	$^{241}$ Am(n, $\gamma$ )/ $^{239}$ Pu(n,f)	$Assembly^a$
2.000E-2	5.5680E-1	Flattop-25
3.300E-2	4.8610E-1	Flattop-25
5.400E-2	4.2290E-1	Flattop-25
1.260E-1	2.9710E-1	Flattop-25
1.380E-1	2.7740E-1	Flattop-25
1.460E-1	2.5360E-1	Flattop-25
1.467E-1	2.5520E-1	Flattop-25
1.500E-1	2.5010E-1	Flattop-25
3.710E-2	4.9500E-1	Bigten

 $^a{\rm The}$  measurements, which detect  $^{242}{\rm Cm},$  are divided by 0.84 to account for the fraction of  $^{242g}{\rm Am}$  that beta decays to  $^{242}{\rm Cm}.$ 

and Jezebel assemblies. In this case the calculated and measured ratios agree well over the whole range of spectral hardness that is covered by the measurements. The measured reaction rate ratios for uranium assemblies are tabulated in Table XII and for plutonium assemblies in Table XIII.

Finally, we include in Table XIV experimental results for the <sup>241</sup>Am(n,f)/<sup>239</sup>Pu(n,f) ratio measured at two different locations in the Flattop Oy 1971 critical assembly as a function of the ratio <sup>193m</sup>Ir/<sup>192</sup>Ir. The sample is natural Ir so <sup>193m</sup>Ir refers to the <sup>193</sup>Ir(n,n')<sup>193m</sup>Ir reaction and <sup>192</sup>Ir refers to the sum of <sup>191Ir</sup>(n,\gamma)<sup>192</sup>Ir and <sup>193Ir</sup>(n,2n)<sup>192Ir</sup> reactions. The measured results for the americium fission cross section (in ratio to plutonium fission) are compared in Fig. 116 to calculated values for the Big-10, Flattop-25, Flattop-Pu, and Jezebel critical assemblies using 30-group cross sections from the ENDF/B-VII data base. The iridium ratio shown in Fig. 116 represents an integral measure of how hard the neutron spectrum is at the two locations. The threshold for the <sup>193</sup>Ir(n,n')<sup>193m</sup>Ir reaction is about 80 keV, so these data sample a different energy region than is covered in Figs. 111-115. Good agreement is seen with the trends of the calculated values, building confidence in

TABLE XIII:  $^{242}\mathrm{Am}$  capture data for plutonium critical assemblies.

	Ratio Data	
$^{238}U(n,f)/^{235}U(n,f)$	$^{241}Am(n,\gamma)/^{239}Pu(n,f)$	$Assembly^a$
1.53515E-2	6.17458E-1	Flattop-Pu
1.93834E-2	5.71464E-1	Flattop-Pu
2.85215E-2	5.23705E-1	Flattop-Pu
5.01347E-2	4.42311E-1	Flattop-Pu
1.34348E-1	2.69738E-1	Flattop-Pu
1.59120E-1	2.32849E-1	Flattop-Pu
1.70192E-1	2.16007E-1	Flattop-Pu
1.75940E-1	2.07189E-1	Flattop-Pu
1.78760E-1	2.02827E-1	Flattop-Pu
1.79638E-1	2.01488E-1	Flattop-Pu
2.09100E-1	1.74200E-1	Jezebel

 $<sup>^</sup>a{\rm The}$  measurements, which detect  $^{242}{\rm Cm},$  are divided by 0.84 to account for the fraction of  $^{242}g{\rm Am}$  that beta decays to  $^{242}{\rm Cm}.$ 



FIG. 115: Comparison of measured and experimental values of the ratio of the  $^{241}$ Am neutron capture rate to the  $^{239}$ Pu fission rate as a function of spectral index at different locations in the Flattop-25, Big-10, Flattop-Pu, and Jezebel critical assemblies. The measurements, which detect  $^{242}$ Cm, are divided by 0.84 to account for the fraction of  $^{242g}$ Am that beta decays to  $^{242}$ Cm.

the  $^{241}$ Am(n,f) cross section below a few MeV. Because  $^{241}$ Am is a threshold fissioner, good agreement between the trend of the calculation and the measured value at 13.97 cm, where many of the neutrons are sub-threshold, is particularly gratifying since the uncertainties in the evaluated data for the lower sub-threshold fission cross sections are likely larger.

TABLE XIV:  $^{241}\mathrm{Am}(\mathrm{n,f})$  data for Flattop Oy 1971 critical assembly.

	Ratio Data	
$^{193m}$ Ir $/^{192}$ Ir	$^{241}Am(n,f)/^{239}Pu(n,f)$	Location (cm)
0.176	0.184	13.97
1.314	0.577	1.11



FIG. 116: Comparison of measured and experimental values of the ratio of the  $^{241}$ Am fission rate to the  $^{239}$ Pu fission rate as a function of  $^{193m}$ Ir/ $^{192}$ Ir reaction rate (see text) at different locations in the Big-10, Flattop-25, Flattop-Pu, and Jezebel critical assemblies.

#### B. LLNL pulsed sphere experiments

A number of experiments have been performed [252], [253] in which spheres of various materials were pulsed with 14-MeV neutrons, and neutron emission spectra were measured by time-of-flight in collimated detectors located 7-10 meters from the pulsed spheres. The measurements were made at Lawrence Livermore National Laboratory's ICT (Insulated Core Transformer) accelerator facility. The measurements described here were all made at 9.455 m along the  $26^{\circ}$  flight path.

Over the years many improvements [254], [255], [256], [257] have been made to the early simulations of these benchmark measurements. New simulations were made [258] for the smallest spheres of <sup>235</sup>U, <sup>238</sup>U, and <sup>239</sup>Pu, comparing results with the ENDF/B-VI.8 and ENDF/B-VII evaluations. The results are presented in Figs. 117, 118, and 119 for  $^{235}$ U. <sup>238</sup>U, and <sup>239</sup>Pu, respectively. Previous evaluations, including ENDF/B-VI.8, have not described the emission neutrons very well near 20 shakes<sup>2</sup> ( $E_{n'} \sim 8-12$  MeV), where preequilibrium and direct inelastic reactions are important, and this problem is seen in Figs. 116-118 for the three actinides. For ENDF/B-VII, however, we incorporated improved direct reaction effects in inelastic neutron scattering, as described in Sec. II.B.4.b. These improvements result in the better agreement seen between the ENDF/B-VII simulations and the measurements in Figs. 116-118.

Many other comparisons of calculation versus measurement for integral experiments involving actinides are presented in the paper by Chadwick *et al.* [1]. While some problems are known to exist in a few of the evaluations,



FIG. 117: Measured and calculated time-of-flight neutron spectrum from a 0.7 mfp sphere of  $^{235}$ U pulsed with 14-MeV neutrons. The simulated results were obtained using the ENDF/B-VI.8 and ENDF/B-VII evaluations. Note the improved simulation results with ENDF/B-VII near 20 shakes, corresponding to  $E_{n'} \sim 8-12$  MeV where preequilibrium and direct inelastic reactions are important.



FIG. 118: Measured and calculated time-of-flight neutron spectrum from a 0.7 mfp sphere of  $^{238}$ U pulsed with 14-MeV neutrons. See caption of Fig. 117 for details.

there is no question from the integral data comparisons that the ENDF/B-VII database for the major actinides is substantially improved relative to ENDF/B-VI.8.

#### VI. CONCLUDING REMARKS

We have completed new evaluations for ENDF/B-VII of neutron-induced reaction data for  $^{232-234,236-241}$ U over the incident neutron energy range from  $10^{-5}$  eV to 30 and for  $^{235}$ U and  $^{239}$ Pu from  $10^{-5}$  eV to 20 MeV.

<sup>[2]</sup> One shake is  $10^{-8}$  seconds.



FIG. 119: Measured and calculated time-of-flight neutron spectrum from a 0.7 mfp sphere of  $^{239}$ Pu pulsed with 14-MeV neutrons. See caption of Fig. 117 for details.

In the above sections we have shown comparisons of the new results with much of the available experimental data above  $E_n=10$  keV and with the existing ENDF/B-VI.8, JEFF-3.1, and JENDL-3.3 evaluations. All the evaluations described in this paper are on file at the NNDC at BNL as part of the ENDF/B-VII library [1].

The integral data comparisons of the previous section are extremely useful in validating the ENDF/B-VII evaluations and in suggesting where improvements might be made. However, it is not always straightforward to draw unequivocal conclusions from such comparisons. For example, in the reaction rate measurements we cannot be certain whether problems are caused by the cross sections of the sample materials or by the neutron spectra that impinge on the samples. Nonetheless, the integral comparisons can point the way toward needed improvements, and we discussed several possibilities in the previous section.

A file of known problems in all ENDF/B-VII evaluations is being kept at the NNDC at BNL and will be addressed in future updates of the ENDF/B-VII database. Throughout this paper we have noted several deficiencies in the evaluations that are described here. A summary of some of the deficiencies is as follows:

- 1. Where sufficient structure information on vibrational states is available, more extensive direct reaction calculations should be performed for <sup>232–241</sup>U and <sup>239</sup>Pu isotopes, particularly at excitation energies in the range 0.5-1.0 MeV. Such calculations primarily would improve the spectral data for neutron energies in the range of a few MeV.
- 2. Consideration should be given to utilizing MSC/MSD calculations to represent direct reaction contributions at excitation energies above 1 MeV, particularly for the isotopes for which good experimental data does not exist, *i.e.*, other than  $^{238}$ U.

- 3. Improved fission and level density models should be explored for improving reaction data at lower incident neutron energies.
- 4. Semi-direct or preequilibrium processes should be included in the calculation of prompt neutron fission.
- 5. The use of Hauser-Feshbach theory in calculations of neutron and gamma-ray spectra from fission reactions should be pursued.
- 6. The formats and procedures for representing energy release from fission should be modified and extended for full representation of the data.
- 7. We have seen some evidence (Fig. 111) that an increase of the order of 5% or so in the  $^{238}\text{U}(n,\gamma)$  cross section below ~1 MeV is needed to improve agreement with integral measurements. Such an increase would be within the scatter of the current differential database (Fig. 75). Therefore, as this change would exceed the present <3% uncertainty provided by the standards evaluators, we would encourage the standards community to study this issue further. If feasible, a new, very accurate measurement would be useful in settling this question.
- 8. Similarly, the integral comparisons from Figs. 112 and 113 suggest that some increase in both the  $^{236}U(n,\gamma)$  and  $^{236}U(n,f)$  cross sections below ~1 MeV might be in order. Again, measurements would be most useful.
- 9. At the softer end of the spectrum, the  $^{237}$ U(n,f) evaluation is supported by the integral comparison in Fig. 114, whereas there is a ~15% discrepancy for a harder spectrum. In this case the experimental data are predominantly surrogate fission measurements, and the ENDF/B-VII evaluation seems reasonably consistent with those data, considering the scatter in the data and the relatively large uncertainties. Perhaps an improved theoretical analysis might be useful for this problem.

Several additional suggestions for actinide data improvement are included in the paper of Chadwick *et al.* [1]. We have not repeated all those recommendations but are in full agreement with them.

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