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A Reevaluation for ENDL of $\sigma(n,f)$
and $\bar{\nu}_p$ for ^{235}U and ^{239}Pu from
100 keV to 20 MeV

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ABSTRACT

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Reevaluations of the neutron-induced fission cross sections from 100 keV to 20 MeV and $\bar{\nu}_p(E)$ from 0 to 20 MeV for ^{235}U and ^{239}Pu have been completed and entered into the Livermore Evaluated Nuclear Data Library (ENDL). For $^{235}\text{U}(n,f)$ the recent evaluation of W. P. Poenitz¹ of Argonne National Laboratory has been adopted as the $^{235}\text{U}(n,f)$ ENDL standard. For $^{239}\text{Pu}(n,f)$ the $^{239}\text{Pu}/^{235}\text{U}$ fission cross section ratio measurement of Carlson and Behrens² of LLNL, which has served as the basis for the $^{239}\text{Pu}(n,f)$ ENDL evaluation to the present, is compared with several new ratio measurements^{3,4,5} for the new evaluation. For $\bar{\nu}_p(E)$ ratio values of Soleihac, *et al.*⁶ were renormalized to the currently accepted value for $^{252}\text{Cf } \bar{\nu}_{sf}$ and used as the basis for the present ENDL evaluation. Experimental $\bar{\nu}_p(E)$ values measured by Gwin, *et al.*⁷ in 1978 from 0.5 keV to 10 MeV are reasonably consistent with the values of Soleihac, *et al.* Results of criticality calculations using the new evaluated cross sections and $\bar{\nu}_p(E)$ are compared for various critical mass assemblies. Also, Monte Carlo calculations using these new evaluations are compared with experimental data from the LLNL 14-MeV pulsed sphere measurements.⁸

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I. INTRODUCTION

An evaluated data set can be based on one or more experimental measurements, model calculations, various systematics of related data, or any combination of these three. It is therefore important from time to time to look again at an evaluation in light of new experimental measurements or improved model calculations. Because of the importance of ^{235}U and ^{239}Pu to the Laboratory, we have completed a reevaluation of the fission cross sections and $\bar{\nu}_p(E)$ of these two isotopes. In the next section the importance of the ^{235}U "standard" cross section is discussed as well as why the evaluation of Poenitz has been adopted as the ENDF standard. In Section III new experimental data on the $^{239}\text{Pu}/^{235}\text{U}$ fission cross section ratio are presented and compared along with our new evaluation of the $^{239}\text{Pu}/^{235}\text{U}$ ratio. Similarly, in Section IV we discuss experimental and evaluated data for $\bar{\nu}_p(E)$ for ^{235}U and ^{239}Pu . In Section V we present results of calculations of criticality (k_{eff}) for critical mass assemblies and calculations of neutron time-of-flight spectra which are compared to data obtained experimentally from pulsed sphere measurements. These calculations, using the new evaluated fission cross sections and prompt neutron multiplicities, serve to test our evaluations against integral laboratory experiments. Section VI contains the conclusions of this work.

II. $^{235}\text{U}(n,f)$ CROSS SECTION STANDARD FROM 100 keV to 20 MeV

The fission cross section of ^{235}U typically serves as the cross section against which other fission cross sections (ratios) are measured. Experimentally, it is much easier to measure the ratio of two fission cross sections than to determine either cross section absolutely. We have adopted the recent evaluation (1979) of the $^{235}\text{U}(n,f)$ cross section of W. P. Poenitz¹ of Argonne National Laboratory as our standard cross section from 100 keV to 20 MeV. This evaluation includes experimental data through the 1978 Harwell Conference on Neutron Physics. More recent experimental data do not contradict this set of evaluated data. The methodology used by Poenitz is discussed in detail in Ref. 1. The shape and normalization are evaluated in separate steps and an extensive comparison of the evaluated results with experimental data is made.

In Fig. 1 a comparison is made between the evaluation of Poenitz and what has served as the ^{235}U fission cross section evaluation in ENDL since 1976. It is clear from the figure that no major discrepancies exist between the 1976 ENDL and 1979 Poenitz $^{235}\text{U}(n,f)$ evaluations. On the other hand, we believe that the 1979 Poenitz evaluation of $^{235}\text{U}(n,f)$ is the best evaluation of the cross section to date because it includes more recent experimental data, uses the best data fitting techniques and, is thoroughly documented. We also believe that, in the absence of future measurements accurate to at least 1%, no further reevaluation of this cross section will be necessary. The reader is referred to Ref. 1 for a discussion of what uncertainty in shape and normalization remains in the $^{235}\text{U}(n,f)$ cross section. The recommended values for the $^{235}\text{U}(n,f)$ cross section are reproduced from Ref. 1 in Table I.

FIG. 1. Comparison of ^{235}U fission cross section evaluation of Poenitz (Ref. 1) with what has served as the ^{235}U fission cross section evaluation in the LLNL Evaluated Nuclear Data Library (ENDL) since 1976. The newer evaluation of Poenitz has been adopted as the ENDL standard cross section from 190 keV to 20 MeV.

Table 1. Recommended values for $^{235}\text{U}(n,f)$ from Ref. 1.
These are also the new ENDL values.

E_n , MeV	σ , barn	E_n , MeV	σ , barn
0.100	1.556	3.200	1.186
0.120	1.503	3.600	1.148
0.140	1.457	4.000	1.117
0.150	1.439	4.200	1.107
0.160	1.423	4.500	1.100
0.180	1.392	4.700	1.079
0.200	1.361	5.000	1.052
0.220	1.327	5.200	1.043
0.240	1.298	5.300	1.038
0.250	1.286	5.400	1.035
0.260	1.276	5.500	1.034
0.280	1.258	5.600	1.034
0.300	1.248	5.700	1.039
0.325	1.235	5.800	1.046
0.350	1.219	5.900	1.065
0.375	1.205	6.000	1.105
0.400	1.194	6.200	1.196
0.425	1.181	6.400	1.290
0.450	1.169	6.500	1.348
0.475	1.160	6.700	1.447
0.500	1.154	7.000	1.534
0.540	1.144	7.250	1.639
0.570	1.137	7.500	1.710
0.600	1.129	7.750	1.756
0.650	1.123	8.000	1.775
0.700	1.120	8.150	1.780
0.750	1.119	8.250	1.782
0.780	1.119	8.500	1.780
0.800	1.122	9.000	1.770
0.830	1.123	9.500	1.757
0.850	1.127	10.000	1.742
0.900	1.147	10.500	1.730
0.940	1.177	11.000	1.722
0.960	1.192	11.500	1.729
0.980	1.199	12.000	1.745
1.000	1.204	12.200	1.760
1.050	1.197	12.500	1.811
1.150	1.195	13.000	1.901
1.250	1.204	13.500	1.982
1.400	1.218	14.000	2.052
1.600	1.249	14.500	2.077
1.700	1.263	15.000	2.077
1.800	1.274	15.500	2.065
1.900	1.280	16.000	2.044
2.000	1.286	16.650	2.072
2.100	1.285	17.000	1.962
2.400	1.263	17.500	1.936
2.600	1.245	18.000	1.916
2.800	1.226	19.000	1.944
3.000	1.204	20.000	2.000

III. THE $^{239}\text{Pu}/^{235}\text{U}$ EVALUATED FISSION CROSS SECTION RATIO

In Fig. 2 we compare two $^{239}\text{Pu}(n,f)$ evaluations and a recent absolute ^{239}Pu fission cross section measurement.³ The ENDF/B-V evaluation is widely used in the nuclear engineering community. The disagreement in the case of ^{239}Pu between ENDF/B-V, ENDL and this recent measurement is significant above approximately 13 MeV.

As discussed in the last section the ratio of two cross sections is much easier to measure than either cross section independently and most recent measurements of $^{239}\text{Pu}(n,f)$ are in the form of ratios to the $^{235}\text{U}(n,f)$ cross section. In this evaluation we consider four recent ratio measurements, three of which are, to our knowledge, the only systematic measurements from low energies to 20 MeV. The data considered in this evaluation are hereafter referred to as Carlson,² Kari,³ Weston,⁴ and Meadows.⁵

The ratio measurement of Carlson has served as the basis of the $^{239}\text{Pu}(n,f)$ ENDL evaluation to the present. Figure 3 shows a comparison of the data of Kari versus those of Carlson and it appears from the figure that there exists an energy calibration error in at least one of the two data sets. Both sets of data were taken with a 'white' source of neutrons and the energy of the neutrons was determined by time-of-flight (TOF) techniques. The Kari data were taken with a neutron flight path of 12 meters and the Carlson data with a flight path of 34 meters. All other things being equal, the longer flight path would require less precision in electronic timing than the shorter flight path for a specified energy uncertainty. However, in an attempt to determine which energy scale is more correct, the data of Meadows, which only extend to 10 MeV but cover the steep descent in the cross section ratio at

FIG. 2. Comparison of the ENDF/B-V and ENDL evaluations for $^{239}\text{Pu}(\text{n},\text{f})$ along with a recent absolute measurement of the ^{239}Pu fission cross section of Kari, Ref. 3. The disagreement between the evaluations and new measurement is significant above 14 MeV.

FIG. 3. Comparison of the $^{239}\text{Pu}/^{235}\text{U}$ fission cross section ratios of Kari and Carlson. The data of Carlson have served as the basis of the ENDL $^{239}\text{Pu}(n,f)$ evaluation since 1976. Both sets of data were taken with a 'white' source of neutrons and there clearly exists a difference in energy calibration between these measurements.

6 MeV, are plotted against the data of both Kari and Carlson in Fig. 4a. The data of Meadows are systematically higher than the other sets in this region and to make a careful check of the energy calibration we multiplied the cross section of Meadows by a factor of 0.96. The results are plotted in Fig. 4b and it is clear from this figure that, in energy, the data of Meadows agree well with those of Carlson in the region of the sharp descent at 6 MeV. Therefore, we converted the energy scale of Kari to time-of-flight, subtracted 8.0 nanoseconds from each time channel, and reconverted the time-of-flight to energy. The results are plotted against the data of Carlson in Fig. 5. With this recalculation of the energy scale, the data of Kari and those of Carlson are now in good agreement to at least 15 MeV. While 8 nanoseconds is a large timing error, both the data of Meadows and Carlson as well as those of Weston, discussed below, are in good agreement in energy at the 6 MeV slope in the fission cross section ratio. Therefore, we have adjusted the data of Kari in time-of-flight by 9 nanoseconds.

Above 15 MeV there exists a shape difference in the ratio measurement of Kari compared to that of Carlson. Weston and Todd of Oak Ridge National Laboratory have recently published a new ratio measurement⁴ spanning an energy range from 6 keV to 21 MeV. These new data are compared with the other three data sets in Figs. 6, 7, and 8. In these figures the data of Meadows have been plotted as they are listed in Ref. 5 and are not multiplied by the factor of 0.96 discussed above. Also plotted is the new ratio evaluation for ENOL with a $\pm 3\%$ band indicated. Figures 6, 7, and 8 cover the energy ranges 0.1 to 1.0 MeV, 1.0 to 10 MeV and 10 to 20 MeV respectively. In the following paragraphs each energy range is discussed separately.

In the energy range 0.1 to 1.0 MeV (Fig. 6) the greatest weight was given to the data sets of Carlson and Weston. The agreement between these two ratio

FIG. 4a. Comparison of the ratio data of Meadows along with the same data sets as plotted in Fig. 3. The data of Meadows are systematically higher above approximately 1 MeV.

FIG. 4b. Multiplying the data of Meadows by a factor of 0.96 and comparing them to the same sets as in Fig. 4a, it is clear that these data agree very well, in energy, with the data of Carlson at the steep slope in the fission ratio at 6 MeV.

FIG. 5. Comparison of the fission ratio data of Kari with those of Carlson after converting the Kari data to time-of-flight, subtracting 8.0 nanoseconds, and re-converting the data to energy. Both data sets are now in good shape agreement to 15 MeV and also agree in shape with the data of Meadows.

FIG. 6. Comparison of all $^{239}\text{Pu}/^{235}\text{U}$ fission ratio data sets and the evaluated curve with a $\pm 3\%$ band indicated between 100 keV and 1.0 MeV. The energy scale of the Kari data has been modified as described in the text.

measurements is excellent throughout this region. The data of Meadows serve to confirm the shape and lay within the $\pm 3\%$ band for the most part. Little weight was given to the data of Kari in this energy range because these data extend down in energy to only 500 keV and, in this region, have a larger statistical scatter.

In the energy range 1.0 to 10 MeV (Fig. 7) the evaluation follows the data of Carlson closely. The Weston data agree well with those of Carlson throughout this region. The data of Meadows are systematically higher as previously discussed and the data of Kari a little lower below 5 MeV. In the region above 5 MeV the data of Meadows are systematically higher than the other three sets and have more scatter.

In the energy range 10 to 20 MeV (Fig. 8) there exist only three sets of ratio measurements; those of Carlson, Kari, and Weston. While for the most part all data sets fall within the $\pm 3\%$ band of the new evaluation up to 15 MeV none of the ratio measurements have the same shape above 15 MeV. The data of Weston are widely binned and shown in Fig. 8 as a histogram with the bin centers indicated by triangles. The errors quoted on these data are at the 2 to 3% level from 10 to 20 MeV. The data sets of Kari and Carlson have similar quoted errors. We have chosen the evaluated cross section above 15 MeV to be an approximate average of the data sets with some weight given to keep most of the points inside the $\pm 3\%$ band around the evaluated cross section. In Table II we list the recommended $^{239}\text{Pu}/^{235}\text{U}$ fission cross section ratio values from the present evaluation.

FIG. 7. Comparison of all fission ratio data sets and the evaluation between 1.0 and 10 MeV. A $\pm 3\%$ band around the evaluation is indicated. The energy scale of the Kari data has been adjusted as described in the text.

FIG. 8. Comparison of fission ratio data sets of Carlson, Kari, and Weston with the evaluation from 10 to 20 MeV. A $\pm 3\%$ band around the evaluation is indicated. The energy scale of the Kari data has been adjusted as described in the text. All three sets of data have different shapes above 15 MeV but generally lie within 3% of the evaluation.

Table II. Recommended $^{239}\text{Pu}/^{235}\text{U}$ fission cross
section ratio values from the present evaluation.

En, MeV	Ratio	En, MeV	Ratio
0.100	0.955	1.590	1.530
0.104	0.961	2.160	1.521
0.107	0.992	2.770	1.485
0.110	1.007	3.000	1.520
0.118	0.987	3.640	1.512
0.128	1.000	4.030	1.520
0.138	1.028	4.500	1.546
0.150	1.050	5.030	1.555
0.175	1.055	5.380	1.561
0.192	1.063	5.535	1.566
0.200	1.080	5.720	1.584
0.210	1.135	5.900	1.597
0.231	1.156	6.070	1.568
0.257	1.177	6.270	1.518
0.271	1.210	6.420	1.479
0.285	1.246	6.740	1.364
0.316	1.237	7.050	1.305
0.338	1.247	7.340	1.263
0.358	1.255	7.720	1.247
0.385	1.279	8.020	1.228
0.407	1.294	8.310	1.225
0.437	1.332	8.670	1.224
0.466	1.357	8.970	1.222
0.510	1.370	9.480	1.225
0.537	1.391	9.710	1.233
0.585	1.411	10.21	1.239
0.600	1.426	10.55	1.249
0.632	1.434	11.48	1.260
0.700	1.445	11.97	1.256
0.730	1.484	12.45	1.240
0.765	1.512	12.91	1.208
0.800	1.520	13.22	1.167
0.837	1.509	13.56	1.144
0.878	1.474	14.20	1.117
0.922	1.436	14.60	1.111
0.958	1.420	15.30	1.087
1.070	1.455	16.08	1.079
1.150	1.492	17.00	1.067
1.200	1.510	18.00	1.097
1.270	1.535	19.00	1.116
1.340	1.555	20.00	1.103

The new $^{239}\text{Pu}(n,f)$ evaluation for ENDL is plotted in Fig. 9 along with the old ENDL evaluation. As this figure shows there are no major discrepancies in the two evaluations but the new evaluation, based on a new $^{235}\text{U}(n,f)$ standard cross section as well as several new cross section ratio measurements, should be considered a refinement of the former and a truer representation of the $^{239}\text{Pu}(n,f)$ cross section. In Table III we list the new ENDL values for the $^{239}\text{Pu}(n,f)$ cross section. The values are chosen such that linear interpolation is appropriate for obtaining the cross section at energies other than those listed. The values in Table III were obtained by appropriate linear interpolation of values in Table I multiplied by the ratio values listed in Table II. The values listed in Tables I and III are currently in the Livermore Evaluated Nuclear Data Library (ENDL).

Although the total cross section is not explicitly represented in the ENDL files, it may be calculated by summing the elastic, inelastic and reaction cross sections and compared to the measured total cross section. Any changes in, for example, the fission cross section will be reflected in the total cross section unless compensated for by changes in another partial cross section. We chose to make the compensation by adjustments to the elastic cross section for two reasons. First, the absolute uncertainty in the magnitude of the elastic cross section is the greatest of the uncertainties for the various partial cross sections and second, the elastic cross section itself is the largest of the partial cross sections and consequently any changes to it will result in the least fractional change. We have, therefore, adjusted the elastic cross section such that the sum of the partial cross sections will agree with recent total cross section measurements by Poenitz and Aalen⁹ that extend from 0.47 to 20.9 MeV.

FIG. 9. Comparison of the former $^{239}\text{Pu}(\text{n},\text{f})$ ENDL evaluation with the evaluation from the present work. There exist no major discrepancies between the two evaluations but the new evaluation, based on a new $^{235}\text{U}(\text{n},\text{f})$ standard cross section as well as several new cross section ratio measurements, should represent a refinement of the former and a truer representation of the $^{239}\text{Pu}(\text{n},\text{f})$ cross section.

Table III. New ENDL $^{239}\text{Pu}(n,f)$ evaluated cross
section derived from values given in Tables I and II.

En, MeV	σ , barn	En, MeV	σ , barn
0.100	1.486	1.590	1.909
0.104	1.485	2.160	1.948
0.107	1.525	2.770	1.825
0.110	1.540	3.000	1.830
0.118	1.489	3.640	1.731
0.128	1.485	4.030	1.696
0.138	1.503	4.500	1.701
0.150	1.511	5.030	1.634
0.175	1.477	5.380	1.617
0.192	1.460	5.535	1.619
0.200	1.470	5.720	1.648
0.210	1.525	5.900	1.701
0.231	1.516	6.070	1.783
0.257	1.505	6.270	1.865
0.271	1.532	6.420	1.925
0.285	1.564	6.740	1.990
0.316	1.533	7.050	2.029
0.338	1.530	7.340	2.102
0.358	1.524	7.720	2.183
0.385	1.536	8.020	2.181
0.407	1.540	8.310	2.182
0.437	1.565	8.670	2.175
0.466	1.579	8.970	2.164
0.510	1.578	9.480	2.153
0.537	1.592	9.710	2.159
0.585	1.599	10.21	2.152
0.600	1.610	10.55	2.160
0.632	1.613	11.48	2.178
0.700	1.618	11.97	2.191
0.730	1.661	12.45	2.235
0.765	1.692	12.91	2.277
0.800	1.705	13.29	2.273
0.837	1.697	13.56	2.277
0.878	1.678	14.20	2.303
0.922	1.671	14.60	2.308
0.968	1.697	15.30	2.250
1.070	1.741	16.08	2.201
1.150	1.783	17.00	2.095
1.200	1.811	18.00	2.102
1.270	1.851	19.00	2.170
1.340	1.885	20.00	2.206

IV. PROMPT FISSION NEUTRON MULTIPLICITY

Experimental values of $\bar{\nu}_p(E)$ for ^{235}U and ^{239}Pu have been measured by Soleihac, et al.⁶ in 1966 and revised in 1976. These remain the only sets of data which span most of the energy range of concern. Their measurements extend from 0.27 to 22.7 MeV incident neutron energy. More recently, Gwin, et al.⁷ measured $\bar{\nu}_p(E)$ for incident neutrons from .00075 to 9.5 MeV. All of the data sets discussed here were measured relative to the $\bar{\nu}_{sf}$ value of ^{252}Cf . We renormalized all the data to the current ENDL standard value of 3.758 for $\bar{\nu}_{sf}$ of ^{252}Cf . These data then formed the basis for the new ENDL $\bar{\nu}_p(E)$ for ^{235}U and ^{239}Pu . Figures 10a and 10b show the new ENDL $\bar{\nu}_p(E)$ values for ^{235}U and the experimental data on which they are based. Figures 11a and 11b show the same for ^{239}Pu . In Table IV and V we list the new ENDL values for $\bar{\nu}_p(E)$ of ^{235}U and ^{239}Pu respectively. The values are chosen such that linear interpolation is appropriate for obtaining $\bar{\nu}_p$ at energies other than those listed.

FIG. 10a. Comparison of the evaluated prompt fission neutron multiplicity of ^{235}U as a function of incident neutron energy with the data sets of Soleihac and Gwin between 0.0 and 5.0 MeV. The ENDL evaluation follows primarily the data of Soleihac.

FIG. 11a. Comparison of the evaluated prompt fission neutron multiplicity of ^{239}Pu as a function of incident neutron energy with the data sets of Soleihac and Gwin between 0.0 and 3.5 MeV. The data of Gwin were taken at two different neutron flight paths and agree well with the data of Soleihac.

FIG. 11b. Comparison of the evaluated prompt fission neutron multiplicity of ^{239}Pu as a function of incident neutron energy with the data sets of Soleihac and Gwin between 0.0 and 20 MeV. The data of Gwin were taken at two different neutron flight paths and agree well with the data of Soleihac.

Table IV. New ENDL evaluated prompt fission
neutron multiplicity, $\bar{\nu}_p(E)$, for ^{235}U .

E_n , MeV	$\bar{\nu}_p$
1.00×10^{-10}	2.405
3.50	2.800
5.00	3.013
7.00	3.400
10.0	3.860
15.0	4.520
20.0	5.150

Table V. New ENDL evaluated prompt fission
neutron multiplicity, $\bar{\nu}_p(E)$, for ^{239}Pu .

E_n , MeV	$\bar{\nu}_p$
1.00×10^{-10}	2.864
3.50	3.347
5.00	3.608
6.00	3.760
11.0	4.530
13.0	4.800
14.3	4.950
15.0	5.050
20.0	5.650

V. DATA TESTING

To test the updated ENDL fission cross sections and $\bar{v}_p(E)$ values against bulk experiments we calculated criticality (k_{eff}) values for 21 Oralloy (Oy) fueled and 14 ^{239}Pu fueled spherical just-critical assemblies reflected by various materials. For pulsed 14 MeV incident neutrons we also calculated the neutron time-of-flight spectra from a 1.25 mean-free-path ^{239}Pu sphere and a 1.50 mean-free-path Oy sphere.

The models of the critical assemblies used to determine the calculated values for k_{eff} have uncertainties associated both with the geometry of the experimental configurations and the method used to determine the just-critical thicknesses for reflectors. Holes in the core or reflector, support mechanisms, and room-return of neutrons all have to be compensated for in describing the idealized assembly. The method used to determine the just-critical configuration is usually an extrapolation of the inverse multiplication of the assembly with safety considerations determining the maximum allowable multiplication. Taken together, these uncertainties result in an estimated uncertainty of 0.7% in k_{eff} for any of the assemblies. The Monte Carlo method used for calculating k_{eff} has an intrinsic statistical uncertainty that is set in advance of doing the calculation. We used 0.3% as the Monte Carlo criterion for completing the calculation for all but the bare ^{235}U and ^{239}Pu assemblies. For those we used 0.1% because we believe that k_{eff} for the just-critical configuration is known to about 0.3%.

The results for the Oy-fueled assemblies are given in Table VI and those for the ^{239}Pu fueled assemblies in Table VII. Note that the average k_{eff} for all the Oy spheres and all the ^{239}Pu spheres are 0.9998 and 0.9990 respectively.

Table VI. Calculated k_{eff} for O_y Spherical Critical Assemblies.

Reflector	Thickness (cm)	k_{eff}
None	0.	$1.001 \pm .001$
Be	2.22	$.993 \pm .003$
Be	3.26	$1.002 \pm .003$
Be	4.71	$1.001 \pm .003$
Be	5.44	$1.000 \pm .003$
Be	9.27	$.999 \pm .003$
Be	11.79	$1.004 \pm .003$
Be	20.27	$1.001 \pm .003$
C	10.16	$.995 \pm .003$
C	15.24	$.994 \pm .003$
Ni	4.94	$1.000 \pm .003$
Cu	5.03	$1.001 \pm .003$
Cu	10.56	$1.011 \pm .003$
W	5.08	$1.001 \pm .003$
W	10.16	$.995 \pm .003$
Pb	8.99	$.998 \pm .003$
Pb	17.22	$.988 \pm .003$
NAT _U	1.76	$1.005 \pm .003$
NAT _U	4.47	$1.008 \pm .003$
NAT _U	9.96	$1.003 \pm .003$
NAT _U	18.01	$.997 \pm .003$
Average =		0.9998

Table VII. Calculated k_{eff} for ^{239}Pu Spherical Critical Assemblies.

Reflector	Phase	Thickness (cm)	k_{eff}
None	δ	0.	$.999 \pm .001$
Be	δ	3.69	$1.001 \pm .003$
Be	α	5.22	$1.001 \pm .003$
Be	δ	5.25	$1.002 \pm .003$
Be	α	8.17	$1.001 \pm .003$
Be	α	13.00	$.998 \pm .003$
C	δ	3.83	$.994 \pm .003$
Ti	δ	8.00	$.989 \pm .003$
W	δ	4.70	$.997 \pm .003$
^{235}U	δ	.66	$1.004 \pm .003$
NAT_{U}	δ	1.93	$.991 \pm .003$
NAT_{U}	δ	4.13	$1.002 \pm .003$
NAT_{U}	δ	6.74	$1.001 \pm .003$
NAT_{U}	δ	19.16	$1.006 \pm .003$
Average =			0.9990

Time spectra for emergent neutrons from 14-MeV incident neutrons in ^{235}U and ^{239}Pu spheres are shown in Figs. 12 and 13 respectively. The time integrals of the emergent neutrons are given Table VIII. These show quite acceptable agreement between calculation and experiment although the plots indicate that there are apparently compensating errors, probably associated with the spectra of neutrons from the fission process. Whether measurements of microscopic fission spectra using a coincidence method would resolve these discrepancies is uncertain.

FIG. 12. Comparison of experimental measurement with Monte Carlo calculations of time spectrum for emergent neutrons from 14-MeV incident neutrons in a 1.5 mean-free-path ^{235}U sphere (see Ref. 8 for details of LLNL pulsed sphere experiments).

FIG. 13. Comparison of experimental measurement with Monte Carlo calculations of time spectrum for emergent neutrons from 14-MeV incident neutrons in a 1.25 mean-free-path ^{239}Pu sphere (see Ref. 8 for details of LLNL pulsed sphere experiments).

Table VIII. Time Integrals of Emergent Neutrons from the Pulsed Spheres

Material	Transmitted Neutrons and Elastic Peak			Nonelastic Neutrons			Total Neutrons (14.6 to 1.0 MeV)		
	Calc.	Exp.	% Dev.	Calc.	Exp.	% Dev.	Calc.	Exp.	% Dev.
^{235}U	.483	.483	0.0	3.249	3.277	-0.9	3.732	3.710	+0.6
^{239}Pu	.524	.544	-3.7	5.656	5.711	-1.0	6.180	6.255	-1.2

VI. CONCLUSIONS

We have completed a reevaluation of the neutron-induced fission cross section, $\sigma(n,f)$, and prompt fission neutron multiplicity, $\bar{\nu}_p(E)$, of both ^{235}U and ^{239}Pu . For $^{235}\text{U}(n,f)$ we have adopted the recent evaluation of Poenitz for use in ENDL. Poenitz's evaluation is well-documented and considers a large body of experimental data. While large uncertainties still exist above 14 MeV in $^{235}\text{U}(n,f)$, for energies less than 14 MeV Poenitz concludes:

The normalization of the ^{235}U cross section appears to be well established by a large number of experiments. The latest reported data seem to increase the dispersion. However, the uncertainties of these data are such that they cannot suggest values differing from the present evaluation result one way or another. It is recommended that future measurements be made with an uncertainty of 1% in order to be significant.

For ^{239}Pu we have evaluated the shape and normalization of the $^{239}\text{Pu}/^{235}\text{U}$ fission cross section ratio using recent independent measurements from four different laboratories. The new ENDL values for $^{239}\text{Pu}(n,f)$ have been obtained from this ratio evaluation and the $^{235}\text{U}(n,f)$ evaluation of Poenitz. For both $^{235}\text{U}(n,f)$ and $^{239}\text{Pu}(n,f)$ the changes from the previous evaluations in ENDL are not large and suggest that, below 14 MeV, the fission cross sections for both isotopes are reasonably well established. Above 14 MeV there remain large uncertainties for both isotopes, particularly in the case of ^{239}Pu .

We have included plots of the $^{239}\text{Pu}/^{235}\text{U}$ fission ratio measurements used in this work along with our evaluated curve with $\pm 3\%$ bands included so that the reader can judge the uncertainty which exists in the $^{239}\text{Pu}(n,f)$ cross section. We have also included plots of measured $\bar{\nu}_p(E)$ data considered in this work as well as our evaluation of $\bar{\nu}_p(E)$ for both ^{235}U and ^{239}Pu . We have made comparisons of Monte Carlo calculations, using these evaluations,

with integral laboratory experiments involving both fission and fusion neutron spectra. While the uncertainty in $^{239}\text{Pu}(n,f)$ is greater than that for $^{235}\text{U}(n,f)$, it is clear from the comparison of the calculations with integral experiments that the product $\sigma_f \cdot \bar{\nu}_p$ over all energies is certainly better established than either σ_f or $\bar{\nu}_p$ at a particular energy. Furthermore, the overall normalization of the cross section for ^{239}Pu must be reasonably well established or the average k_{eff} of all the Pu critical assemblies would be significantly different from unity. The recommended (evaluated) values for σ_f and $\bar{\nu}_p$ for ^{235}U and ^{239}Pu as given in Tables I, III, IV, and V are currently in the LLNL Evaluated Nuclear Data Library.

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