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GOVERNMENT OF INDIA
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SELF-SHIELDED CROSS SECTIONS FOR THE MAIN FERTILE AND FISSILE NUCLEI

by

R. Shankar Singh and G. A. Desai
Reactor Engineering Division

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ABSTRACT

Self-shielded cross-sections for Th-232, U-235, U-238 and Pu-239 which exhibit resonance behaviour in their reaction cross-sections with neutrons are necessary to represent the proper effective values in a multigroup analysis of reactors and to predict accurately the reactivity coefficients due to Doppler effect etc. These have been evaluated here from resonance integral calculations under the NR approximation using the latest available resonance parameters at four temperatures (300, 750, 1500 and 2500° K) and at σ_p (potential scattering cross section per absorber atom) values of 40 and 60 barns for Th-232 and U-238 and 126, 200, 300 and 400 barns for U-235 and Pu-239. The status of resonance parameters for these elements has also been discussed in detail.

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I. INTRODUCTION

Several elements exhibit resonance behaviour in their reaction cross sections with neutrons. The presence of resonances causes fluctuations in the neutron spectrum of a reactor and it is necessary to evaluate effective cross sections in such resonance regions. This is done by calculating the effective resonance integrals which are a function of the total potential scattering cross section 'σ_p' per atom under consideration (governed by the composition) and the temperature. The effective cross sections over a certain energy range (group), so evaluated, are known as the self-shielded cross sections. Such cross sections are not only necessary to represent the correct values in a multigroup analysis of reactors, but are also essential in predicting the temperature coefficients of reactivity due to Doppler effect etc. The main fertile and fissile nuclei considered here are Th^{232}, U^{238}, U^{235} and Pu^{239}. Self-shielding for these elements is significant only below about 25 Kev, and the self-shielded cross sections have been evaluated from time to tome using the basic resonance parameters for these nuclei. The present work uses the latest resonance parameters which have been determined over larger energy ranges(1), made possible by the recent improvements in the energy resolution of neutron spectroscopy. Composition and temperature dependent cross-sections have been evaluated over a range of 'σ_p' values and temperatures to represent the composition of a number of reactor types. These have been evaluated under the narrow resonance (NR) approximation(2) without the resonance overlap effects and are presented in the lower groups of a 22-group(3) structure.

II. METHOD OF COMPUTATION

i) <u>The Code DOPINT</u>:

A computer program DOPINT (4) has been written for CDC-3600 to evaluate the resonance integrals and multigroup cross sections. The Narrow Resonance (NR) approximation which is valid for many resonances except a few at the lower energies, has been used to compute the resonance integrals in this code. Both the resolved and unresolved resonances can be treated and the effective group cross sections in the energy group structure of user's choice, can be evaluated.

ii) Heterogeneity Effects:

Whereas the self-shielding provided by the geometry (size) of the fuel elements plays an important role in thermal reactor calculations, such heterogeneity effects are negligible in fast reactor analyses wherein only the self-shielding due to the resonances is significant and resonance integrals are usually evaluated for a homogeneous mixture. Nevertheless, the code DOPINT contains the option for geometries like slab, cylinder and sphere and the heterogeneity is taken into account with the usual equivalence theory by defining a modified σ_p, the potential scattering cross section per absorber atom. It has been again shown by several people [5,6] that heterogeneity effects are negligible in fast reactors and hence the present calculations have been performed for homogeneous mixtures only.

iii) Resolved Resonances in Fissile Nuclei:

Since the data on the resonance parameters of fissile nuclei available hitherto has been meagre, resonance integral calculations have been based only on the average parameters in the unresolved region. As the situation in this respect is improving and more resonances are being resolved and parameters determined for fissile nuclei, resolved resonance integral calculations have been introduced in the code DOPINT for fissile nuclei also. This has been used for Pu^{239} resolved resonances below 300 ev.

iv) Unresolved Resonances:

In the unresolved resonance region, average resonance integrals at specified energies are evaluated using the average single level resonance parameters. Distribution functions for neutron and fission widths are taken into account by using ten discrete values for neutron width and five for fission width. The effect of overlapping of resonances has not been taken into account in the present work.

To present a fairly wide range of compositions that are of interest in the current studies of fast reactors, values of σ_p =40 and 60 barns are chosen for Th^{232} and U^{238} and σ_p = 126, 200, 300 and 400 barns are used for U^{235} and Pu^{239}. Since the resonance integrals are weak functions of the potential scattering cross section per absorber atom σ_p, the errors involved in interpolation of cross sections for intermediate values of σ_p or using the cross sections corresponding to the σ_ps selected here when they are close to the actual ones in particular cases, are likely to be small. Four temperatures, T=300, 750, 1500 and 2500° K are chosen to represent the normal and extreme reactor operation conditions.

III. DISCUSSION OF RESONANCE PARAMETERS AND RESULTS :

The resonance parameters used in the present work for the four elements Th^{232}, U^{238}, U^{235} and Pu^{239} and the cross sections derived therefrom have been discussed below.

i) Thorium-232:

The recent improvements in the energy resolution of the neutron resonance experiments have resulted in the extension of the upper limit of the energy range in which the resonances are resolved. For Th^{232}, resonances have been resolved and analysed(1) upto 4000 eV. But, there remained considerable uncertainity in the radiation width Γ_γ, its values varying from 40 mv in the original Columbia measurements to 18 mv in some early Harwell measurements. In the earlier studies (7) pertaining to thorium self-shielded cross sections, values of Γ_γ between 20 mv and 30 mv for resonances below 800 ev, a value of 35 mv for resonances between 800 and 3000 ev and another value of 40 mv in the unresolved resonance region from 3 Kev to 25 Kev were used.

L.W. Nordheim proposed(8) a value of 34 mv for Γ_γ and showed that a very good agreement with this value is obtained between the calculated and experimental results of not only the infinite dilution resonance integral, but also for thorium metal and oxide rods.

To resolve this uncertainity in Γ_γ for Th^{232}, a group at General Atomic(9) developed a method based on the measurements of the absorption γ-rays as a function of energy which permits the determination of Γ_γ directly. They have obtained an average value of 24.5 mv for Γ_γ for the resonances measured below 222 ev. Nordheim [10] has shown that the new value of 24.5 mv when used to evaluate the resonance integrals gives a resonable agreement with the measured values when the experimental uncertainities are taken into account.

In the present work, resonance integrals for Th^{232} have been evaluated using the GA parameters [10] upto 222 ev and Columbia values[1] with a Γ_γ of 24.5 mv above this energy in the resolved resonance region.

In the unresolved resonance range the following parameters were employed.

s-waves : $\langle \frac{\Gamma_n^0}{D} \rangle = 0.69 \times 10^{-4}$; D = 17.5 ev : Γ_γ =0.0245 ev

p-waves : $\langle \frac{\Gamma_n^0}{D} \rangle = 2.2 \times 10^{-4}$; D1/2 = 17.5 ev; Γ_γ =0.0245 ev

$D_{3/2}$ = 8.75 ev;

The p-wave strength function of 2.2×10^{-4} (as compared to 1×10^{-4} in earlier work[7]) suggested by C.A. Uttley[11] and shown to give a good fitting between the computed and experimental values of the total cross section $\langle \sigma_t \rangle$, has been used here. This has resulted in a higher p-wave contribution to the capture cross sections in the unresolved resonance region (Table 1) than was obtained earlier[7]. But the s-wave contribution has become lower because of the lower value of Γ_γ used in the present work.

In the resolved resonance region (groups 15 to 22) the capture cross sections (see Table 2) have decreased in groups 15 to 19 because of lower Γ_γ, and have increased in groups 20 - 22, because the Γ_γ used here (0.0245 ev) is larger than that[1] used in earlier work[7], for the resonances in these groups.

The self-shielded capture cross sections for Th^{232} at σ_p =40 and 60 and four temperatures, in the unresolved resonance region are given in Table 1 and those in the resolved resonance region are given in Table 2.

The changes in capture cross sections of thorium brought about in the present work may affect the reactivity coefficients studied earlier[7] to some extent which can be examined more closely by re-evaluating some of those cases with the present data.

ii) Uranium - 238

The most reliable source of U^{238} resonance parameters presently available is the high resolution Columbia data[1]. More than 220 resonances were observed and analysed in this experiment. J.J. Schmidt[12] has compiled the resonance parameters for U^{238} from almost all the available sources of experimental data. These include the low energy p-wave resonances analysed recently by Thomas and Bollinger[13] in a high resolution fast chopper transmission experiment. This data has been used in the present work wherein 239 resolved resonances are present.

Columbia data[1] gives the s-wave strength function as 0.9×10^{-4} and the mean level spacing as 17.7 ev for U^{238}. These values along with a p-wave strength function of 2.5×10^{-4} as proposed by Uttley[11] and the well established radiation width $\Gamma_\gamma = 0.0246$ ev were used to evaluate the capture cross sections in the unresolved resonance region at $\sigma_p = 40$ and temperature 300°K. The values so obtained seemed to be rather high. To select the final parameters in the unresolved resonance region, two more sources of data were chosen and the capture cross sections were evaluated at the same σ_p and temperature. These were the ANL[3] and Schmidt[12] data. The ANL data has a p-wave strength function of 1.5×10^{-4}. The Schmidt data recommends a p-wave strength function of 2.5×10^{-4}, but gives the level spacings as $D_{1/2} = 20.8$ and $D_{3/2} = 8.85$ ev. The capture cross sections evaluated in the three groups of the unresolved resonance region using these different data are given in Table 3. Columbia data gives higher capture cross sections where as ANL data gives lower values, with Schmidt data giving intermediate values. Parameters suggested by Schmidt have been finally chosen to evaluate the cross sections in the unresolved region, in order to give weight to his detailed analysis of resonance parameters.

The results obtained at two σ_p values and four temperatures are presented in Table 4 for the unresolved region and in Table 5 for the resolved resonance region.

iii) Uranium - 235

Resonance parameters for fissile nuclei have always been a troublesome feature because of the difficulties involved not only in the experiments, but also in their analysis due to multilevel effects etc. The fission and capture widths are obtained from the 'α' or 'η' measurements also.

Schmidt[12] has presented parameters for U^{235} resolved resonances (217 in number) upto an energy of 147 ev, selecting the values from different sources of measurements. Since there are many uncertainties in these values and they are resolved only to an energy of ~ 150 ev, resolved resonance integral calculations have not been done for U^{235} here.

The self-shielded capture and fission cross sections have been calculated only in the unresolved resonance region from 200 ev. to 12,000 ev. in the groups 13 to 21. The choice of resonance parameters has been made as follows:

The fission widths Γ_f estimated for the resolved resonance in the experiments are rather low (~65 mv) compared to those deduced from α values in the unresolved resonance region. The Γ_f values resulting from statistical theor[y] fits to α in the unresolved resonance range are more than twice as large as the resolved resonance Γ_f . Hence, if the low values of Γ_f (given for $E < 50$ ev by Schmidt) are employed for calculating the cross sections, the values so obtained do not agree with the experimental results in the higher energy regions.

The choice of Γ_f = 120 mv and Γ_γ = 33 mv, values used earlier by Hwang[14], has been made in the present work with the level spacing for the two spin states as D_3 = 1.72 and D_4 = 1.34 ev and the number of channels per fission as ν =2. The α values obtained from the capture and fission cross sections using the above parameters agree fairly well with measured values[15].

The fission and capture cross sections calculated with the above parameters at four σ_p values and four temperatures are given in Tables 6 and 7. The self-shielding effects are seen to be small at higher energies and become significant only at lower energies.

It should be noted as pointed out by Schmidt[12] that there are many inconsistencies, descrepancies and not understood facts in our present picture of U^{235} resonance fission and the cross sections evaluated here only represent the values as far as the resonance parameters hold. Future improvements in the knowledge of better resonance parameters should always be looked for and due corrections made.

iv) Plutonium - 239

The situation regarding the resonance parameters for Pu^{239} is slightly better than for U^{235}. Resonances are now resolved upto 300 ev and have been compiled by Schmidt (12). Earlier computations of self-shielded cross sections for Pu^{239} have normally been made using the average resonance parameters in the unresolved range due to lack of resolved resonance parameters at higher energies. Schmidt's parameters upto 300 ev have been used here to evaluate the resolved resonance capture and fission integrals and the cross sections in groups 21 and 22 covering these resonances.

Schmidt has observed that the average fission widths $\overline{\Gamma_f}$ apparently sub-divide into two groups-one with rather small and another with very large values. From the considerations of channel theory of fission, he expects the larger Γ_f to belong to J = 0 and the smaller Γ_f to J = 1 resonances. He has pointed out the rather anomalous behaviour of α of Pu^{239}, measured by Diven and Hopkins[16] showing an abrupt decrease in the energy range 15 to 60 Kev, as a second check to his above observation on Γ_f. The following parameters recommended by him in the unresolved resonance region have been used in our present calculations.

s - wave strength function: $\left\langle \frac{\Gamma_n^0}{D} \right\rangle = 1.07 \times 10^{-4}$; $\Gamma_\gamma = 0.0387$ ev.

For J = 0 , $D_0 = 8.78$ ev and $\Gamma_{f0} = 2.8$ ev

J = 1 , $D_1 = 3.12$ ev and $\Gamma_{f1} = 0.057$ ev

No. of channels per fission: $\nu = 2$

The fission and capture cross sections corresponding to the four σ_p values and four temperatures have been presented in Tables 8 and 9. Contribution from p-waves has not been evaluated in the absence of reliable parameters and the present values do not contain the p-wave contribution.

The fission and capture cross sections in the present results are slightly higher than the corresponding ones from ANL[17] in groups 14 to 20. The fission cross sections in groups 21 and 22 are considerably higher than the ANL ones, but compare well with the higher values used by other organizations in the inter-comparision studies[18, 6]. Since resolved resonance parameters have been used in the last two groups (21 and 22), one can perhaps put better confidence in the values presented here.

Table 1. Th^{232} Capture Cross Sections in Unresolved Region (barns)

σ_P = 40 barns

$\left\langle \frac{\Gamma_n^o}{D} \right\rangle = 0.69 \times 10^{-4}$ for S-wave ; $D_{\frac{1}{2}}$ = 17.5 ev ; Γ_γ = 0.0245

$= 2.2 \times 10^{-4}$ for p-wave ; $D_{3/2}$ = 8.75 ev

J	E_1 (kev)	T = 300° s-wave l=0, J=½	T = 300° p-wave l=1, J=½	T = 300° p-wave l=1, J=3/2	T = 300° Total σ_c	T = 750° s-wave l=0, j=½	T = 750° p-wave l=1, j=½	T = 750° p-wave l=1, j = 3/2	T = 750° Total σ_c
12	15.0	0.164	0.114	0.333	0.611	0.169	0.115	0.339	0.623
13	9.1	0.241	0.136	0.367	0.744	0.254	0.138	0.374	0.766
14	4.0	0.367	0.148	0.390	0.905	0.397	0.151	0.399	0.947
j	E_L (kev)	T = 1500°				T = 2500°			
12	15.0	0.173	0.116	0.342	0.631	0.175	0.116	0.342	0.633
13	9.1	0.262	0.139	0.378	0.779	0.267	0.140	0.379	0.786
14	4.0	0.417	0.153	0.404	0.974	0.430	0.154	0.406	0.990

σ_p = 60 barns

J	E_L	300°	750°	1500°	2500°
12	15.0	0.623	0.632	0.637	0.639
13	9.1	0.765	0.782	0.791	0.797
14	4.0	0.946	0.979	0.999	1.013

Table 2. Th^{232} - Capture Cross Sections in Resolved Region (barns)

j	E_L (kev)	σ_p = 40 barns				σ_p = 60 barns			
		300°	750°	1500°	2500°	300°	750°	1500°	2500°
15	2.8	0.601	0.664	0.707	0.736	0.662	0.717	0.754	0.778
16	2.0	0.695	0.798	0.874	0.928	0.795	0.892	0.961	1.008
17	1.4	0.734	0.869	0.978	1.059	0.869	1.008	1.113	1.189
18	1.0	0.899	1.050	1.166	1.250	1.046	1.194	1.303	1.379
19	0.55	0.982	1.197	1.384	1.531	1.205	1.441	1.637	1.786
20	0.30	1.054	1.314	1.571	1.795	1.339	1.664	1.971	2.230
21	0.10	1.482	1.817	2.177	2.512	1.903	2.351	2.816	3.234
22	0.03	0.815	0.924	1.053	1.182	1.035	1.191	1.369	1.542

Table 3. Parameter Variation in Unresolved Region for U^{238}

(s-wave + p-wave Capture cross sections in barns)

σ_p = 40 barns ; T = 300°K

j	E_L (kev)	Columbia data *	ANL data**	Schmidt data***
12	15.0	0.6555	0.5495	0.5678
13	9.1	0.8098	0.6650	0.7130
14	4.0	0.9646	0.7853	0.8639

* Columbia data

s- waves : $\left\langle \frac{\Gamma_n^o}{D} \right\rangle = 0.9 \times 10^{-4}$; $D_{\frac{1}{2}} = 17.7$ ev ; $\Gamma_\gamma = 0.0246$ ev

p-waves : $\left\langle \frac{\Gamma_n^o}{D} \right\rangle = 2.5 \times 10^{-4}$; $D_{3/2} = 8.85$ ev

**ANL data

s- waves : $\left\langle \frac{\Gamma_n^o}{D} \right\rangle = 0.9 \times 10^{-4}$; $D_{\frac{1}{2}} = 17.7$ ev ; $\Gamma_\gamma = 0.0246$ ev

p-waves : $\left\langle \frac{\Gamma_n^o}{D} \right\rangle = 1.5 \times 10^{-4}$; $D_{3/2} = 8.85$ ev

*** Schmidt data

s- waves : $\left\langle \frac{\Gamma_n^o}{D} \right\rangle = 0.9 \times 10^{-4}$; $D_{\frac{1}{2}} = 20.8$ ev ; $\Gamma_\gamma = 0.0246$ ev

p-waves : $\left\langle \frac{\Gamma_n^o}{D} \right\rangle = 2.5 \times 10^{-4}$; $D_{3/2} = 11.4$ ev

TABLE 4

U^{238} - Capture Cross Sections in Unresolved Region (Barns)

$\left\langle \frac{\Gamma_n^o}{D} \right\rangle = 0.9 \times 10^{-4}$ s wave $D_{\frac{1}{2}} = 20.8$ ev

$= 2.5 \times 10^{-4}$ p wave $D_{3/2} = 11.4$ ev $\Gamma_\gamma = 0.0246$

$\sigma_p = 40$ barns

j	E_L (kev)	T = 300°K				T = 750°K			
		s-wave 1=0, J=½	p-wave 1=1, J=3/2	p-wave 1=1, J=3/2	Total	s-wave 1=0, J=½	p-wave 1=1, J=½	p-wave 1=1, J=3/2	Total
12	15.0	0.145	0.109	0.314	0.568	0.151	0.111	0.321	0.583
13	9.1	0.212	0.136	0.365	0.713	0.226	0.139	0.375	0.740
14	4.0	0.320	0.157	0.387	0.864	0.350	0.161	0.399	0.910
j	E_L	T = 1500°K				T = 2500°K			
12	15.0	0.155	0.112	0.325	0.592	0.158	0.113	0.326	0.597
13	9.1	0.235	0.140	0.380	0.755	0.240	0.141	0.383	0.764
14	4.0	0.371	0.163	0.406	0.940	0.385	0.164	0.409	0.958

$\sigma_p = 60$ barns

j	E_L (kev)	300°	750°	1500°	2500°
12	15.0	0.582	0.594	0.601	0.604
13	9.1	0.739	0.759	0.771	0.778
14	4.0	0.909	0.947	0.971	0.986

TABLE 5

U^{238} - Capture Cross Sections in Resolved Region (barns)

j	E_L (kev)	σ_p = 40 barns 300°	750°	1500°	2500°	σ_p = 60 barns 300°	750°	1500°	2500°
15	2.8	0.492	0.550	0.592	0.662	0.549	0.603	0.640	0.666
16	2.0	0.586	0.669	0.735	0.783	0.671	0.754	0.816	0.861
17	1.4	0.619	0.720	0.803	0.866	0.726	0.829	0.912	0.973
18	1.0	0.744	0.871	0.976	1.058	0.874	1.008	1.116	1.196
19	0.55	0.882	1.055	1.213	1.342	1.067	1.266	1.440	1.578
20	0.30	0.766	0.925	1.067	1.180	0.930	1.109	1.263	1.384
21	0.10	1.252	1.439	1.643	1.838	1.570	1.819	2.087	2.338
22	0.03	2.250	2.382	2.551	2.732	2.792	2.986	2.233	3.495

TABLE 6

U^{235} - Fission Cross Sections (barns)

s-wave: $\left\langle \frac{\Gamma_n^0}{D} \right\rangle = 1 \times 10^{-4}$ $D_3 = 1.72$ ev $\Gamma_\gamma = 0.033$ ev

$D_4 = 1.34$ ev $\Gamma_f = 0.120$ ev

$\nu = 2$

j	E_L (kev)	σp = 126 barns 300	750	1500	2500	σp = 200 barns 300	750	1500	2500
13	9.1	1.883	1.889	1.892	1.894	1.889	1.893	1.895	1.896
14	4.0	2.682	2.697	2.706	2.710	2.697	2.708	2.713	2.716
15	2.8	3.834	3.872	3.894	3.906	3.874	3.900	3.914	3.922
16	2.0	4.608	4.671	4.706	4.726	4.675	4.717	4.740	4.754
17	1.4	5.495	5.593	5.650	5.683	5.603	5.669	5.650	5.730
18	1.0	6.518	6.669	6.761	6.815	6.690	6.795	6.761	6.892
19	0.55	8.010	8.264	8.424	8.522	8.311	8.490	8.424	8.666
20	0.30	10.276	10.735	10.047	11.248	10.857	11.200	11.047	11.565
21	0.10	13.704	14.547	15.189	15.639	14.909	15.602	15.189	16.444

j	E_L	σp = 300 barns				σp = 400 barns			
13	9.1	1.893	1.895	1.897	1.897	1.894	1.897	1.898	1.898
14	4.0	2.707	2.714	2.717	2.719	2.711	2.717	2.720	2.721
15	2.8	3.898	3.916	3.926	3.931	3.910	3.924	3.932	3.936
16	2.0	4.715	4.744	4.760	4.770	4.735	4.758	4.771	4.778
17	1.4	5.668	5.715	5.741	5.757	5.702	5.738	5.758	5.770
18	1.0	6.795	6.869	6.912	6.937	6.850	6.907	6.940	6.960
19	0.55	8.499	8.628	8.706	8.752	8.599	8.699	8.760	8.796
20	0.30	11.240	11.495	11.658	11.758	11.449	11.652	11.780	11.859
21	0.10	15.771	16.324	16.709	16.964	16.269	16.728	17.041	17.245

TABLE 7

U^{235}- Capture Cross Sections (barns)

(Resonance Parameters same as given in Table 6)

j	E_L (kev)	σ_p = 126 barns				σ_p = 200 barns			
		300	750	1500	2500	300	750	1500	2500
13	9.1	0.843	0.845	0.847	0.847	0.845	0.847	0.848	0.848
14	4.0	1.232	1.239	1.243	1.245	1.239	1.244	1.246	1.247
15	2.8	1.805	1.823	1.833	1.839	1.824	1.836	1.843	1.846
16	2.0	2.194	2.224	2.242	2.251	2.227	2.247	2.258	2.264
17	1.4	2.641	2.692	2.720	2.737	2.696	2.729	2.748	2.759
18	1.0	3.159	3.240	3.287	3.314	3.247	3.302	3.334	3.351
19	0.55	3.910	4.053	4.138	4.188	4.067	4.168	4.227	4.261
20	0.30	5.032	5.305	5.480	5.589	5.344	5.549	5.675	5.751
21	0.10	6.648	7.185	7.570	7.828	7.307	7.754	8.057	8.253

j	E_L	σ_p = 300 barns				σ_p = 400 barns			
13	9.1	0.847	0.848	0.849	0.849	0.848	0.849	0.849	0.849
14	4.0	1.243	1.246	1.248	1.249	1.246	1.248	1.249	1.250
15	2.8	1.835	1.844	1.848	1.850	1.841	1.848	1.851	1.853
16	2.0	2.246	2.260	2.268	2.272	2.256	2.267	2.272	2.276
17	1.4	2.728	2.752	2.765	2.772	2.745	2.763	2.773	2.778
18	1.0	3.301	3.339	3.361	3.373	3.329	3.359	3.375	3.385
19	0.55	4.167	4.239	4.280	4.304	4.219	4.276	4.307	4.326
20	0.30	5.552	5.706	5.797	5.851	5.666	5.789	5.861	5.903
21	0.10	7.788	8.147	8.381	8.528	8.069	8.369	8.560	8.678

TABLE 8

Pu^{239} Fission Cross Sections (Barns)

s-wave : $\left\langle \frac{\Gamma_n^o}{D} \right\rangle = 1.07 \times 10^{-4}$; Γ_γ = 0.0387 ev ; ν = 2

For J = 0, D_o = 8.78 ev and Γ_{fo} = 2.8 ev

J = 1, D_1 = 3.12 ev and Γ_{f1} = 0.057 ev

Note: Resolved resonance parametere are used in groups 21 and 22

j	E_L (kev)	σ_p = 126 barns 300°	750°	1500°	2500°	σ_p = 200 barns 300°	750°	1500°	2500°
14	4.0	2.298	2.322	2.337	2.345	2.327	2.343	2.353	2.359
15	2.8	3.295	3.355	3.392	3.414	3.369	3.410	3.435	3.450
16	2.0	3.955	4.048	4.107	4.143	4.071	4.138	4.178	4.203
17	1.4	4.696	4.837	4.928	4.986	4.876	4.979	5.043	5.083
18	1.0	6.007	6.251	6.420	6.531	6.333	6.523	6.649	6.728
19	0.55	6.725	7.033	7.254	7.403	7.150	7.398	7.568	7.678
20	0.30	8.563	9.044	9.420	9.691	9.288	9.711	10.024	10.242
21	0.10	10.375	11.068	11.698	12.206	11.723	12.420	13.019	13.481
22	0.03	16.024	16.707	17.486	18.230	18.573	19.413	20.317	21.147

j	E_L (kev)	σ_p = 300 barns 300°	750°	1500°	2500°	σ_p = 400 barns 300°	750°	1500°	2500°
14	4.0	2.344	2.356	2.363	2.367	2.353	2.362	2.367	2.370
15	2.8	3.413	3.443	3.460	3.471	3.437	3.460	3.473	3.481
16	2.0	4.144	4.192	4.221	4.238	4.183	4.221	4.243	4.256
17	1.4	4.991	5.067	5.113	5.141	5.053	5.113	5.149	5.171
18	1.0	6.554	6.670	6.793	6.851	6.677	6.795	6.870	6.915
19	0.55	7.445	7.641	7.770	7.852	7.614	7.775	7.879	7.944
20	0.30	9.829	10.188	10.440	10.611	10.155	10.463	10.675	10.815
21	0.10	12.832	13.491	14.029	14.430	13.552	14.163	14.646	14.996
22	0.03	20.862	21.810	22.793	23.663	22.470	23.482	24.496	25.367

TABLE 9.

Pu^{239} Capture Cross Sections (barns)

(Resonance parameters same as given in Table 8)

j	E_L (kev)	σ_p = 126 barns 300°	750°	1500°	2500°	σ_p = 200 barns 300°	750°	1500°	2500°
14	4.0	1.114	1.131	1.140	1.146	1.132	1.143	1.149	1.153
15	2.8	1.664	1.710	1.735	1.751	1.713	1.744	1.761	1.772
16	2.0	2.029	2.103	2.147	2.173	2.110	2.162	2.192	2.209
17	1.4	2.434	2.551	2.622	2.665	2.562	2.648	2.698	2.728
18	1.0	3.125	3.342	3.482	3.571	3.367	3.536	3.641	3.705
19	0.55	3.484	3.766	3.955	4.078	3.803	4.032	4.177	4.268
20.	0.30	4.316	4.784	5.128	5.365	4.870	5.285	5.573	5.763
21	0.10	5.068	5.771	6.375	6.838	6.036	6.751	7.331	7.759
22	0.03	7.550	8.538	9.599	10.563	9.453	10.708	11.990	13.111
		σ_p = 300 barns				σ_p = 400 barns			
14	4.0	1.143	1.151	1.155	1.157	1.148	1.154	1.157	1.159
15	2.8	1.743	1.765	1.777	1.784	1.759	1.776	1.785	1.790
16	2.0	2.160	2.198	2.219	2.231	2.188	2.217	2.233	2.242
17	1.4	2.646	2.709	2.744	2.765	2.691	2.741	2.769	2.784
18	1.0	3.535	3.665	3.742	3.788	3.629	3.735	3.796	3.832
19	0.55	4.032	4.212	4.323	4.389	4.164	4.313	4.402	4.455
20	0.30	5.299	5.652	5.885	6.034	5.563	5.868	6.064	6.186
21	0.10	6.879	7.563	8.092	8.468	7.449	8.090	8.571	8.903
22	0.03	11.386	12.863	14.305	15.517	12.889	14.500	16.016	17.256

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