EVALUATION OF ²³⁸ Pu NEUTRON CROSS-SECTIONS IN THE ENERGY RANGE 10⁻⁵ Ev TO 14 Mev

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INTRODUCTION

This report describes the evaluation of the ²³⁸Pu neutron cross-sections in the energy range from 10⁻⁵ ev to 14 Mev. The experimental data base available for the evaluation has been reviewed. This data base is far from being complete, especially in the high energy region where only fission cross-sections have been measured. Therefore, optical model and statistical model calculations were performed in view of obtaining the unmeasured cross-sections. Some inconsistencies were found among the experimental data when compared to the calculated cross-sections, and made the evaluation somewhat difficult. In particular, the calculated capture cross-sections are about 30 % smaller than those measured. Finally, our evaluation was based on the experimental set of resonance parameters, on the optical model parameters available in the litterature and modified to reproduce the strength function at low energy and on the experimental fission cross-sections.

This evaluation has been performed under the CEA-IAEA Research Agreement n° 2663 CF. The results are available in ENDF/B-V format from IAEA Nuclear Data Section (INDL/A library).

THERMAL AND RESOLVED RESONANCES REGION

The experimental data

The experimental data available for the evaluation of the $^{238}_{\rm Pu}$ resonance parameters are the following :

1) The fission area of 5 resonances obtained by GERASIMOV et al. /1/ from a fission cross-section measurement in the energy range 0.02 ev to 400 ev.

2) The fission area of 16 resonances obtained by STUBBINS et al. /2/ from a fission cross-section measurement in the energy range 2 ev to 300 ev.

3) The neutron widths of 14 resonances and the capture widths of 3 resonances obtained by YOUNG et al. /3/ from a shape and area analysis of transmission data in the energy range 0.01 ev to 200 ev. The parameters of 2 negative resonances are also given from a fit of the total cross-section in the thermal region.

4) The neutron widths and the fission widths of 49 resonances obtained by SILBERT et al. /4,5/ from a combined area analysis of a simultaneous measurement of the fission and the capture cross-sections in the energy range 20 ev to 500 ev. In this analysis, the capture width was kept constant for all the resonances and equal to the value of 34 mev obtained by YOUNG et al.

The neutron widths

The values of Γ_n obtained by YOUNG et al. and by SILBERT et al. are compared in Table 1. The small resonances were not seen in the total cross-section of YOUNG et al. (the thicknesses of the samples were too small : only 0.0023 at/barn for the thickest one). For the large resonances, the agreement is rather good below 150 ev neutron energy. At higher energy, the resolution in YOUNG et al. experiment was not sufficient for an accurate determination of Γ_n . Nevertheless, the overall agreement which is found between YOUNG data and SILBERT data in the 20 ev to 150 ev energy range is a good test for the validity of the rather complicated method used by SILBERT et al. to evaluate the Γ_n and Γ_f values from their measured capture and fission cross-sections.

The fission widths

The fission areas are compared in Table 1. According to the authors, the measurement by STUBBINS et al. was not sensitive enough to observe the fission cross-section between the widely separated resonances ; the small resonances were not seen. Moreover, due to a lack of resolution above 100 ev neutron energy, it is obvious that the $\sigma_0 \Gamma_f$ of STUBBINS et al. should be compared to the summ of several SILBERT values ; then, there is a rather good agreement, as it is shown in Table 1. As for the values reported by GERASIMOV et al., they are much smaller than the other values.

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The discrepancy can be hardly attributed to the normalisation, for the ratio to the other data is not constant (Table 1).

The capture widths

The capture width can be assigned to 3 resonances only : 36.8 mev, 30.3 mev and 35.2 mev, respectively to the resonances at 2.885 ev, 9.976 ev and 18.562 ev. These values are obtained by combining the data of YOUNG et al. and STUBBINS et al. The average value is 34 mev which has been used by SILBERT et al. in their analysis.

The recommended set of resonance parameters

The list of the recommended resonance parameters is given in Table 2. This list has been established as follows :

1) Two negative energy resonances from the analysis of the thermal total cross-sections by YOUNG et al.

2) The parameters for the resonances at 2.885 ev, 9.976 ev and 18.562 ev from STUBBINS et al. and YOUNG et al.

3) Above 20 ev SILBERT data have been kept in their totality, apart the Γ_n° values of the resonance at 320 ev which has been taken equal to (7 ± 5) mev, instead of (10 ± 10) mev given by SILBERT et al.

The calculated data

The cross-sections are calculated in the energy range from 10^{-5} ev to 400 ev from the resonance parameters. The single level Breit-Wigner formalism is sufficient for the fission cross-section calculation, the extra-accuracy which could be obtained by a multilevel formalism being negligible compared to the inaccuracy of the experimental data.

There are two anomalies in the experimental data when compared to the calculated cross-sections :

- 3 $s_{g^{(1)}}(g)$

1) YOUNG et al. used a potential scattering cross-section of 17 barns to fit the experimental total cross-section in the energy range 0.008 ev to 200 ev. This value is not realistic since one should expect $\sigma_p = (11 \pm 1)$ barns in the A = 238 mass region from systematics or model calculations. YOUNG et al. failed to explain this anomalous σ_p value by a water contamination of the PuO2 sample, and they retained the value of 17 barns as the proper value of the non resonant part of the cross-section. But nothing has been said concerning a possible systematic error in the normalisation of the measured transmission : 1 % systematic error in the normalisation coefficient is equivalent to 5 barns absolute error in the total cross-section obtained from the thickest sample used in YOUNG et al. experiment ;

2) the resonance parameters cannot reproduce the high values of the cross-section observed between the resonances in the experimental capture cross-sections of SILBERT et al., as it is shown in Table 3 and Figure 1. One should be strongly tempted to interpret this non resonant part in the capture cross-section as equivalent to the one observed in YOUNG et al. data. But this effect, which seems to vanish only around 100 kev in the capture cross-section, cannot be explained by the contribution of negative levels. It is also too large to be explained by any direct capture contribution.

We have assumed that this anomalous background in the measured total and capture cross-sections is due to unknown or unreported experimental effects for which the data must be corrected.

The cross-sections calculated at 0.0253 ev from the set of recommended resonance parameters are the following :

 $\sigma_{\rm T} = (583.75 \pm 19.00) \text{ b}$ $\sigma_{\rm n,\gamma} = (546.74 \pm 23.00) \text{ b}$ $\sigma_{\rm n,f} = (17.15 \pm 1.70) \text{ b}$ $\sigma_{\rm n,n} = (19.86 \pm 1.20) \text{ b}$

They are compared to KEDAK and ENDF/B-V in Table 4.

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The calculated cross-sections in the thermal region are compared to the experimental data of YOUNG et al. and of GERASIMOV et al. in Figure 2. The calculated total cross-section is 6 barns lower than YOUNG data, since the potential scattering cross-section has been taken equal to 11 barns.

THE AVERAGE RESONANCE PARAMETERS FOR THE UNRESOLVED REGION

Level spacing and strength function

All the resonances seen in the experimental cross-sections have been considered as s-wave resonances. The smallest measured Γ_n° value is about 6 times as large as the average value obtained for the p-wave resonances by assuming $S_1 = 2.0 \times 10^{-4}$ and \Box $D_{1=1} = 3$ ev. Therefore, the statistically overabundance of small neutron widths in the Γ_n° distribution (Figure 3), which was already pointed out by SILBERT et al., is not due to the presence of p-wave levels. It is possible that the small values have been systematically underestimated. On the other hand, due to the bad experimental resolutions, it is highly probable that some of the large I values correspond to multiplets of unresolved resonances. For these reasons, it is not surprising to observe a reduced neutron width distribution somewhat distorted (Figure 3). Therefore, any statistical method applied to this distribution for the determination of the number of missed levels should not work. As a matter of fact, all attempt in using the maximum likelihood method or the missing level estimator method gave inconsistent results.

Figure 4 shows the number of levels seen in the interval of energy 0 to E as a function of E. Up to 250 ev the staircase is roughly represented by a straight line. Above, the effect of the missed levels becomes important. In the first part of the staircase, the observed mean level spacing is equal to 8.30 ev. We recommend the following value for the s-wave resonances :

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 $\langle D \rangle_{1=0} = (7.7 \pm 0.6) ev,$

assuming that about 10 % of levels could still be missed in the low energy part of the data.

The s-wave strengh frunction is calculated as follows :

$$S_0 = \left(\sum_{0}^{E} \Gamma_n^{\circ}\right)/E = (1.17 \pm 0.10) \times 10^{-1}$$

in the entire energy range of the measurements.

The fission channels

The most striking feature of the fission widths is shown in Figure 5, due to SILBERT et al. /5/. The intermediate structure due to a double humped fission barrier is evident. It appears that there is one structure covering the energy range 0 ev to 500 ev, corresponding to a class II state in the vicinity of 285 ev neutron energy. All the fission widths in this energy range come under the influence of the class II state, modifying completely their statistical behaviour. Then, the interpretation of the fission width distribution, which is shown in Figure 6, is difficult. Furthermore, this distribution shows two families corresponding to different average values, when one spin state is involved in the 238 Pu fission in the resonance region. SILBERT et al. have fitted

the family of small values to a chi-square distribution of 7 degrees of freedom. Such large value of the degree of freedom has been interpreted as the proof of the $(n,\gamma f)$ process in the low energy induced fission of ²³⁸Pu (see also BOWMAN et al. /21/). LYNN /22/ has objected that the number of fission channels for the $(n,\gamma f)$ process should be much larger than 7 and that the average width proposed by SILBERT or BOWMAN is too large compared to the value of 0.1 mev expected from the theory for the $(n,\gamma f)$ process in ²³⁸Pu.

It is not the purpose of this evaluation to give an interpretation of the apparent anomaly in the distribution of the ²³⁸Pu fission widths. We think that this distribution is too much affected by the class II state and all attempt of explanation without taking into account this effect is questionable. It is not possible from the existing sample of fission widths to obtain accurate average fission parameters which could be used in a statistical

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model calculation at higher energy.

In summary, the average parameters available for the calculation in the unresolved region are the following :

$$\langle D \rangle_{1=0} = (7.7 \pm 0.6) \text{ ev}$$

 $S_0 = (1.17 \pm 0.10) 10^{-4}$
 $\langle \Gamma_{\Upsilon} \rangle = (34 \pm 6) \text{ mev}$
 $R' = (9.36 \pm 0.50) \text{ fm}.$

The S₁ strength function should be obtained from the optical model calculations.

THE OPTICAL MODEL PARAMETERS

There is no experimental total cross-section or elastic cross-section available above several kev neutron energy. The evaluation must rely on optical model calculations. A set of optical model parameters has been proposed by C. LAGRANGE /6/ for the calculation of the even Pu isotope cross-sections. He used the deformation parameters of MOLLER /7/ and the optical potential obtained by fitting the 232 Th and 238 U data /8/. These parameters are equivalent at low energy to the strength functions $S_0 = 0.944 \times 10^{-4}$, $S_1 = 1.90 \times 10^{-4}$ and to the scattering radius R' = 9.26 fm. This S_0 strength function is 20 % smaller than the one obtained in the previous section from the resonance parameters. We have obtained a better agreement by modifying slightly the LAGRANGE parameters. These modified optical model parameters are shown on Table 5. They correspond to $S_0 = 1.12 \times 10^{-4}$ and R' = 0.931.

Selected values of the total and the compound nucleus formation cross-sections obtained from the coupled channel code ECIS /9/ by using the LAGRANGE parameters and our modified parameters are compared on Table 6. Significant differences appear only on the compound nucleus formation cross-sections below several hundred kev neutron energy. Some values obtained from the statistical model code FISINGA /10/ by using the average resonance parameters are also shown. An excellent agreement is found between FISINGA and ECIS calculations below 40 kev. One should note that the value of $S_1 = 2.00 \times 10^{-4}$ has been used in FISINGA calculations.

THE CROSS-SECTIONS IN THE UNRESOLVED RESONANCE REGION

Two sets of experimental data are available in the unresolved region : the capture and the fission cross-sections from SILBERT et al. /4,5/. The intermediate structure seen in the resonance region in the fission data, is still apparent up to about 10 kev. The average spacing of the class II states is equal to about 1 kev /4/. The other problem is the non resonant component which is seen in the capture data in the low energy range. This component exists also at the beginning of the unresolved region and at higher energy. In the purpose of evaluating its importance in this region, the partial cross-sections have been calculated with the statistical code FISINGA, by enforcing the calculated fission crosssections to be equal to the average experimental values in 5 energy intervals, as it is shown in Table 3 and Figure 7. In each interval, the calculated capture cross-section is much smaller than the average experimental value. The difference is approximatively equal to 40 % of the measured cross-section. As in the resonance region, we have considered this difference as an experimental effect for which the experimental data should be corrected.

Therefore, the evaluation has been concluded in the following way :

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1) Between 400 ev and 4 kev, YOUNG total cross-sections and SILBERT fission and capture cross-sections have been averaged on 50 ev energy intervals (from 400 ev to 1000 ev) and on 200 ev energy intervals (from 1 kev to 4 kev). The total cross-sections of YOUNG have been normalized to obtain an agreement with the statistical model FISINGA calculations. The capture cross-sections of SILBERT have been corrected for 2.10 b at 400 ev and 1.15 b at 4 kev and between these energies for a value obtained by log-log interpolation. The elastic scattering cross-sections were obtained by difference.

2) Between 4 kev and 40 kev, SILBERT capture and fission data have been averaged on 1 kev energy intervals (from 4 kev to 10 kev) and on 2 kev energy intervals (from 10 kev to 40 kev). The correction to the SILBERT capture was still 1.15 b at 4 kev and 0.45 b at 40 kev and log-log interpolation between these energies. The total and compound nucleus formation cross-sections were obtained from ECIS and the scattering cross-sections by difference between the calculated total and the sum of the fission and the capture cross-sections.

The evaluated data in the unresolved region are shown in Figure 8.

THE CROSS-SECTIONS IN THE ENERGY RANGE 40 KEV TO 4 MEV

Evaluation of the experimental data

Apart from the capture cross-sections by SILBERT et al. which are available up to 200 kev, only fission cross-sections have been measured in the high energy range /4,5/, /11-17/, /26/. The data are shown on Figures 9 and 10. The measurements by VOROTNIKOV et al. /12/ have been normalised to one absolute measurement at 720 kev with an accuracy not better than 20 %. BUTLER et al. /11/ have also normalised their results to several absolute measurements in the energy range 0.14 to 1.8 Mev, in excellent agreement with VOROTNIKOV results. The other measurements

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were performed relatively to 235 U fission cross-sections and normalised to the standard of DAVEY /23/ or ENDF/B-V. Unfortunately, above 0.5 Mev, the results of the absolute measurements are about 30 % higher than those from the measurements relative to 235 U fission cross-sections, as it is shown on Figure 9. On the other hand, the calculations based on the systematic by BEHRENS et al. /18/ or by LYNN /19/ confirm the data obtained from the relative measurements. For these reasons, we have excluded the VOROTNIKOV and BUTLER data.

The results of our experimental evaluation are shown on Figure 9 and 10. They have been obtained by an averaging procedure from the selected experimental data. Some selected values are also given in Table 7.

The calculated cross-sections

The procedure of the evaluation in this energy range is similar to the one used in ref. /25/ for 237 Np. The neutron transmission coefficients, the potential scattering and the direct inclastic cross-sections were obtained from the coupled channel optical model code ECIS with the parameters of Table 5. They were then used as input in the statistical model code FISINGA in order to obtain the capture, the fission, the compound elastic and inelastic cross-sections. The other parameters needed in FISINGA calculations - double humped fission barrier parameters, density of the fission channels, density of the inelastic channels, formalism and method of calculation... - were taken from LYNN systematic /20/. The discrete low-lying levels of 238 Pu were those from nuclear data sheets /24/ up to 1 Mev. Only the calculated fission cross-sections could be compared to experimental data. This comparaison is shown on fig. 10. The agreement is reasonably good and no attempt was made to improve the fit by modifying some input parameters. Nevertheless, as the evaluated experimental fission cross-sections were those to be kept as final values, the other calculated partial cross-sections were adjusted in order to conserve the calculated total values.

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THE CROSS-SECTIONS ABOVE THE SECOND CHANCE FISSION TRESHOLD

1. 5. 3.

Between 4 Mev and 10 Mev, the only data available are the fission cross-sections from KNITTER et al. and BUDTZ-JORGENSEN et al. /26/. There is one fission measurement at 14.9 Mev from BARTON et al. /13/ normalized on DAVEY standard and 7 points between 13 Mev and 17 Mev from ERMAGAMBETOV et al. /16/ normalized on PARKER /27/ standard. The calculations were performed in the energy range 4 Mev to 14 Mev with the FISINGA and SI2N /28/ codes. The first and second chance fission cross-sections and the (n,2n) cross-sections were obtained (figure 11). In the SI2N calculations the fission probabilities of 238 Pu compound nucleus, measured by WILHEMY /29/, were reproduced (Figure 12). The calculated total fission cross-sections are in agreement with the experimental values (fig. 11) and have been kept as final evaluation in this energy range.

The estimated uncertainties on the evaluated cross-sections are given in Table 8 in the energy range thermal to 14 Mev.

COMPARISON WITH OTHER EVALUATIONS AND INTEGRAL DATA

The results of the present evaluation are compared to ENOF/B-V and KEDAK on the Figure 13-17 in the energy range 1 kev to 14 Mev. The most striking points arising from this comparison are the following :

1) Capture cross-sections - Except in the hundred kev region, ENDF/B-V and KEDAK are very similar. In the unresolved region Cadarache data are about 30 % lower ; that is due to different way of interpreting the SILBERT et al. experimental data. The difference reaches a maximum of 200 % in the Mev region.

2) Fission cross-sections - ENDF/B-V and Cadarache agree fairly well. There is a tendancy in KEDAK data to be lower, particularly around 30 kev where the difference reaches a value of 20 %.

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3) Total inelastic cross-sections - The spread of the evaluated data is rather large. Above 200 kev the Cadarache values are the largest, the difference being mainly due to the direct componant in the 2^+ and 4^+ channels which does not exist in ENDF/B-V and KEDAK.

4) (n,2n) cross-sections - As it is shown on Figure 11, the ENDF/B-V values are about 5 times larger than those from Cadarache. However both agree on the total fission cross-section values in the corresponding energy range ; therefore, the ENDF/B-V compound nucleus formation cross-section must be more than 1 barn larger than the Cadarache value obtained from a realistic coupled channel optical model calculation.

The results of a optical model statistical model calculation performed by P. THOMET /31/ are also shown on fig. 14-16.

Integral measurements of the fission and the capture rate were performed in ERMINE /32/ and PHENIX /33/ and were used to adjust the CARNAVAL IV /34/ data. The capture cross-section integrated on a typical fast spectrum is equal to 0.410 barns when calculated from the 25 groups cross-sections of CARNAVAL IV and to 0.424 barns from the present evaluation, which is a quite good agreement. But for the fission cross-section the situation is different. One obtain an integrated value of 0.885 barns from CARNAVAL IV and 1.189 barns from the evaluation, i.e. a difference of 26 % which is not consistent with the 2 or 3 % accuracy claimed for CARNAVAL IV and the 6 or 7 % accuracy obtained in the evaluation of the microscopic fission data in the significant part of the spectrum.

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CONCLUSION

The capture cross-section accuracies requested in reactivity calculations are 5 % for thermal reactors and 10 % for fast breeder reactors: /35/. It has been shown in the present evaluation that the experimental data of SILBERT et al, which are the only data available, are not accurate enough to meet these requirements. More experimental data are needed. However, the results of integral measurements in fast assemblies indicate that the capture crosssection integrated over a typical fast reactor spectrum could be calculated from the present evaluation with better accuracy than we should expect from the uncertainties quoted on Table 8. As for the fission cross-sections, 3.5 % accuracy are requested for fast reactor calculations /35/. Although the uncertainties on the evaluated fission data are rather small (6 to 12 % as it is shown on Table 8) the requested accuracy is not obviously obtained. However one must realize, that the 3 or 4 % accuracy archieved on the fission cross-section of important material like 235 U and 239 Pu have been obtained after years and years of experiments. One cannot expect that such effort should be put on ²³⁸Pu fission experiments. The best that can be done at present is the recent measurement by KNITTER et al. who obtained an accuracy not better than 5 %. On the other hand the severe discrepancy existing between the microscopic and integral fission data should be solved by new fission integral measurements.

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ļ	RESONANCE	I FI	SSION AREA			NEUTRON	IDTHS II
	ENERGY	SILBERT	STUBBINS	GERASIMOV		SILBERT	YOUNG
	2.885	1	2.14	0.76	, , 		0.044
1	9.976	1	9.85	7.80 1	1		0.066 11
1	18.562	23.60	18.48	14.00	11	0.96	0.310 11
İ	32.2 1	0.70		1	L I	0.012	
1	36.6 1	0.25		1	1	0.004	1
1	59.8 1	1.08				0.17	0.20 11
1	70.1	1 15.9	15.8	6.3	11	0.130	1 0.30 II
1	77.7	1 0.19		l I	11	0.003	1 1
$ \mathbf{L} $	83.0 1	1 39.5	38.6	20.0	11	2.26	2.10 11
1	96.2	1 0.19		1	11	0+006	1 - 11
	99.6	1 0.89		l	11	0.026]
1	110.1 1	1 12.7 -1	22.3 -		-	0.54	0.50 11
	111.2 1	1 0.251				0.012	• 11
1	113.6	1 29.9 1+	26.0 +		1	1.15	0.97 11
1	118.6	1 15.9 1	23.9 1	i I	11	2.83	2.93 11
1	122.4	1 76-4 -	70.7 -	i I	11	2.71	2. 41
1	129.	1 0.13	-	! I		0.019	· · · · · · · · · · · · · · · · · · ·
1	132.4	2.22			11	0.074	
	139.7 1	1 7.90			H	0.24	
11	151.1 1	1 65.0	63.5	1	1	2.39	1.2 11
	165.0 1	1 0.83			11	0.017	
11	171.0	6.4		1	1	3.58	4.9
11	176.8 1	1 21.7	91.4			0.20	
11	182.9	1 42.0			H	2.11	2.3 11
1	192.5	1 152.9	141.3	1	1	1.12	3.3
1	203.	1 3.4 - 1			1		
11	216.	1 65.6 141	83.6	I I			11
	221.	1 3.9 - 1		1	1		
11	232.	1 0.19 1			1]	11
1	245.	1 27.4 - 1			1	4	1
1	252.	1 86.6 1*1	112.2	1	1	I	11
11	261.	0.45-	1	I	1	1	
	285.	1 237.0 - 1	295.6	1		1	11
11	289.	84.7 _*		1	1	l	11
23					: 3		********
	• SUM TO B	E COMPARED	IN STUBBINS	5 AND SILBERT	Г	DATA	

TABLE I

COMPARISON OF EXPERIMENTAL RESONANCE DATA

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TABLE	2	-	Resonance	parameters	in	ENDF/B	format	(E,	J,	^r t ^{, r} n'	Γ̈́Ύ́	Г _f	MAT,	MF,	MT:

-0.1000E+02	0.5000E+00	0.5960E-01	0.1580E-01	0.34006-01	0.9800E-024381	2151
-0.4000E+00	0.50002+00	0.4534E-01	0.34158-03	0.4380E-01	0.12006-024381	2151
0.2885E+01	0.5000E+00	0.3478E-01	0-7474E-04	0.36708-01	1-2100E-034381	2151
0.9976F+01	0.5000F+00	0.3701E-01	0.2085E-03	0.30105-01	0.67005-024381	2151
0.18055+02	0.50000 +00	0.4003E-01	0.30005-04	0.4000E-01	0.70005-024381	2151
0.10545+02	0.500000.00	0.46665-01	0 30605-03	0 34005-01		2121
0.10000-02	0.30002700.	V.4400C-V1	0.30000-02	0.34002-01	0.14/02-024381	2151
0.3220E+02	0.5000E+00	10-318816-01	0.00095-04	0.34002-01	0.48002-024381	2151
0.36602+02	0.5000E+00	0.3992E-01	0.2420E-04	0.3400E-01	0.5900E-024381	2151
0.5980E+02	0.5000E+00	0.3598E-01	0.1315E-02	0.3400E-01	0.67002-034381	2151
0.7010E+02	0.5000E+00	0.4391E-01	0.2512E-02	0.3400E-01	0.7400E-024381	2151
0.7770E+02	0.50002+00	Q.4343E-01	0.2644E-04	0.3400E-01	0.9400E-024381	2151
0.8300E+02	0.5000E+00	0.5809E-01	0.2059E-01	0.3400E-01	0.3500E-024381	2151
0.9620E+02	0.50002+00	0.3886E-01	0.5885E-04	0.34005-01	0.4800E-024381	2151
0.9960E+02	0.50002+00	0.3936E-01	0.25958-03	0.3400E-01	0.5100E-024381	2151
0.1101E+03	0.5000E+00	0.4377E-01	0.5666E-02	0.3400E-01	0.4100E-024381	2151
0.1112E+03	0.5000E+00	0.3723E-01	0.1265E-03	0.3400E-01	0.3100E-024381	2151
0.1136E+03	0.5000E+00	0.5166E+01	0-1226E-01	0.34005-01	0.54005-024381	2151
0 11865+03	0.50002+00	0.66625-01	0.30925-01	0 34005-01	0.16005-024381	2151
A 1004E+A3	0 50005+00	0.72485-01	0.20085-01	0 34005-01	A 45405-024001	2131
0.12005+03	0.300000+00	0.75225-01	0.21505-01	0.34000-01	0.83005-024381	2121
0.12902703	0.50002+00	0.33225-01	0.21382-03	0.34002-01	0.10002-024381	2131
0.13246403	0.50002+00	0.40136-01	0.00100-03	0.34002-01	0.53002-024381	2131
0.13912+03	0.500000+00	0.43146-01	0.203/2-02	0.34002-01	0.63002-024381	2151
0.15112+03	0.50002+00	0./2585-01	0.2938E=01	0.34002-01	0.9200E-024381	2151
0.1650E+03	0.5000E+00	0.44922-01	0.2184E-03	0.3400E-01	0.1070E-014381	2151
3.1710E+03	0.50002+00	0,81532-01	0.4681E-01	0.34008-01	0.72002-034381	2151
0.17682+03	0.5000E+00	0.8066E-01	0.2659E-02	0.3400E-01	0.4400E-014381	2151
0.1829E+03	0.5000£+00	0.69648-01	0.2854E-01	0.3400E-01	0.71002-024381	2151
0.1925E+03	0.5000E+00	0.1795E+00	0.1554E-01	0.3400E-01	0.13002+004381	2151
6+2030E+03	0.5000E+03	0.4119E-01	0.4987E-02	0.3400E-01	0.2200E-024381	2151
0.2160E+03	0.5000E+00	0.7464E-01	0.1764E-01	0.3400E-01	0.2300E-014381	2151
0.2210E+03	0.5000E+00	0.9422E-01	0.5902E-01	0.3400E-01	0.12002-024381	2151
0.2320E+03	0.5000E+00	0.35568-01	0.7159E-03	0.3400E-01	0.8400E-034381	2151
0.2450E+03	0.5000E+00	0.65736-01	0.6731E-02	0.3400E-01	0.25005-014381	2151
0-2520E+03	0.5000E+00	0.10665+00	0-1556E-01	0.3400F-01	0.5700E-014381	2151
0.26105+03	0.50002+00	0 41265-01	0.25855-03	0.34005-01	0.70005-024381	2151
0.20102-03	0.500002+00	0 35605+01	0 26005-01	0 34005+01	0 35005+014381	2151
0.20002+03	0.500000+00	0.05575-01	0.2000E-01	0 34005-01	0 34005-014381	2151
0.20702703	0.30000000	0.33316-01	0.01010-01	0.34002-01	10305-004301	2121
0.300000703		0.11005.00	10-20436-01	0-34005-01	0 1020E7004301	2131
0+30502+03	0.5000E+00	0.11002+00	0.00346-02	0.34002-01	V.0000C-V14381	2131
0.32002+03	0.50002+00	0.21046+00 7 74475 AT	0.1/892+00	0.34002-01	V.3500E-024381	2121
0.32702+03	0.5000E+00	0./00/2-01	0.2/0/E-01	0.34002-01	0.15002-014381	2151
0.33/0E+03	0.50002+00	0.5/822-01	U-1542E-01	U.3400E-01	0.84002-024381	2121
0.3610E+03	0.50002+00	0.41502-01	0-7980E-03	0.34002-01	U. /UUUE-024381	2151
0.36802+03	0.5000E+00	0.55066-01	U-1726E-01	0.3400E-01	0.44002-024381	2151
0.38202+03	0.5000E+00	0.5139E-01	0.3909E-03	0.3400E-01	0.1700E-014381	2151
0.3910E+03	0.5000E+00	0.4985E-01	0.1305E-01	0.3400E-01	0.2800E-024381	2151
0.4080E+03	0.5000E+00	0.5508E-01	0.18586-01	0.3400E-01	0.2500E-024381	2151
0.4190E+03	0.50002+00	0.1162E+00	0.5322E-01	0.3400E-01	0.2900E-014381	2151
0.4260E+03	0.5000E+00	0.9298E-01	0.4768E-01	0.3400E-01	0.1130E-014381	2151
0.4480E+03	0.5000E+00	0.1116E+00	0.6561E-02	.0.3400E-01	0.7100E-014381	2151
0.4610E+03	0.5000E+00	0.9030E-01	0.4960E-01	0.3400E-01	0.6700E-024381	2151
0.4650E+03	0.5000E+00	0.1263E+00	0.8561E-01	0.3400E-01	0.6700E-024381	2151
0.4730E+03	0.50002+00	0.5935E-01	0.23058-01	0.3400E-01	0.2300E-024381	2151
0.4960E+03	0.5000E+00	0.5015E-01	0.9354E-02	0.3400E-01	0.6800E-024381	2151

323		***************	****************	***************	========================	11
11	ENERGY	AVERAGE	AVERAGE	I AVERAGE I	DIFFERENCE	11
11	(KEV)	(FISSION (EXP.)	CAPTURE (EXP.)	ICAPTURE (CALC.) I	CAPTURE	11
11		1 REF.(5)	REF.(5)	t		11
11-					*************	• • • •
11	· · · · · · · ·					
11	0.050- 0.300		23.43	1 19-90 (1)	4.02	
		1 2 60	} • • • • • •		4 94	11
	0.000- 1.000	1 3+70	1 12+11		4+00	
11	1 00 6 00		1 7 07	2.67 (2)	1.30	11
11	1.00 - 4.00	1 L+CC			1.000	-11
	4.00 -10.00	n.98	2.25	i 1.35 (2) i	0.90	ii
- i i	4800 -10800	1		1		11
	10.00 -20.00	0.752	1.744	0.950 (2)	0.79	11
-ii	10000	1	1	1 1 1		11
ii	20.00 -40.00	0.803	1.152	1 0.675 (2) 1	0.48	11
11		F 1	1	1 1		11

(1) CALCULATED FROM RESONANCE PARAMETERS
 (2) STATISTICAL MODEL CALCULATIONS REPRODUCING THE AVERAGE EXPERIMENTAL FISSION VALUES

-

TABLE	3
•	•

32323 ² 33332 ² 33222			**********
11	I THIS WORK	ENDF/8-5	I KEDAK II
233222332322	==================		= = = = = = = = =
11	l	1	1 11
II TOTAL	583.75	1 590.0	1 575.55 11
11		1	11 11
II CAPTURE	546.74	1 552.4	I 541.5 II
IT FISSION	17.15	17.0	17.02
	10.44	70 (0	
11 SCALLERING	19.30	20.60	17.03 1
	 322=============	,	

TABLE 4

CROSS-SECTION (BARNS) AT 0.0253 EV

33:					=====
11	POTENTIAL	DEPTH (MEV)	RADIUS (FM)	DIFFUSENESS	(FH) []
11					
11		i 1	·		11
11	REAL	47.2-0.3E	1.244	0.62	i i
11		i			11
11	SURFACE				i i
11	IMAGINARY	2.7+0.4E	1,280	0.58	
11					i i
Ϊİ.	REAL SPIN		i		ii
11	ORSIT	7.5	1.240	59-0	11
11					ii
33					
11	DEFORMATION	PARAMETERS B	2 = 0.219 84	= 0.089	t t
==:			************		******

TABLE 5

OPTICAL MODEL PARAMETERS

ENERGY MEV	ECIS	OPTMOL	ECIS LAGRANG MODIFIED	E I OPTMDL I	FISENGA (1) STATMOL
	TOTAL	COMPOUND	I TOTAL I	COMPOUND I	TOTAL I COMPOUND
0.01	1 15.35	4.58	1 15.63 1	5.20	15.88 5.34
0.04	13.14	3.14	13.21	3.57	13.30 3.52
0.10	11.73	2.97	11.92	3.37	
0.40	8-87	3.19	9.06	3.47	(1) FROM THE
0.70	7.60	3•28	7.70	3.37	I FOLLOWING
1.00	7.12	3.32	7.10	3.29	S0 = 1.17E10-4
2.00	7.54	3.40 .	7.44	3+34	SI = 2.00E1J=4 <d>L=0 = 7.7EV</d>
4-00	7.95	2.98	7.81	2.90	$R^{*} = 0.936$ $R^{\infty} = -0.198$
6.00	7.21	2.93	7.11	2.87	
8.00	6.43	2.97	6.33	2.90	
10.00	6-09	3.07	5.89	2.91	
14.00	5.89	2.83	5.86	2.79	

COMPARISON OF CALCULATED TOTAL AND COMPOUND NUCLEUS FORMATION CROSS-SECTION

= =		4 2 -	.======================================	**********	*=====									
11	5	11	τοτ	AL (BARNS)		1	FIS	SION (BARNS)		CAPTURE (BARNS)				
-11	ENERGY	-!!				-!!							-11	
- ! !	(IIEV)		THIS WORK	ENDE78-5	I KEDAK		1112 MORV	EIIUF /13-5	KEDAK I	THIS WORK	I ENDEZB-5	KEDAK	11	
		- []		*********			A 300					=============	-	
- ! !	0.040	-11	13.211	1 16 21	11.55		0.708			1 0,660	0.105	0./68		
	0.000		12.911	14,31			0.010	0+038	0.540	0.603	0.112	0.081		
	0.000		12.250				0.007	0+001	0.523	0,458	0.010	0.483		
	0.100		11.915	12.33	1 12.39	1	0.01J	820.0	0.532	0.397	1 0.202 1	0,401		
	0.200		10.000	11.13	10.83	11	0.116	0.728	0.704	0.264	0.410	0.262	11	
	0.275	11	9.983	9.90	10.53		0.916	0.932	0.860	0.224	0.365	0,232	11	
11	0.350	11	9.400	9.10	9.79	11	1.060	1.061	0.959	0.199	0.325	0.211	11	
11	0.450	11	8.759	8.46	1 3-11	11	1.297	1,286	1,220	0.173	0.275	0,196	11	
11	0.550	11	8.263	7.90	8.67		1.570	1,524	1 1.410	1 0.149	0.259	0.190	11	
11	0.700	11	7.699	6.07	8.14	11	1.840	1,781	1 1.694	0,104	0.210	0.167	11	
11	0.800	11	7.431	6.74	7.89	11	1,915	1.953	1.450	0.084	0.196	0.157	11	
11	0.900	11	7.237	6.67	7.68	1	1.990	2.002	1 1.980	0.072	1 0,190	0.154	11	
11	0.985	11	7.121	6.64	1 7.47	1	2.040	2.044	2.030 1	0.061	1 0.187 /	0.153	11	
11	1.100	11	7.032	6.61	1 7.40	11	2,092	2,066	2.060	0.052	1 0.175	0.152	11	
11	1.300	11	7.003	6.59	7.20	1	2,150	2.095	2.111	0.044	0.149	0.150	11	
11	1.500	11	7.079	6.80	1 7.11	11	2.189	2.120	2,131	0.042	0.122	0.150	11	
11	2.000	11	7.454	7.46	1 7.08	11	2.250	2.180	2.180	0.038	0.087 /	0.087	11	
11	2.500	11	7.727	7.60	7.20	11	2,280	2,225	2,228 1	0.033	0.065	0,073	11	
11	3.000	11	7.857	7.77	7.40	11	2.210	2.255	2.222 1	0.029	1 0.044	0.057	11	
11	4.000	11	7.814	7.55	7.56	- İ İ	2.082	2,336	2.120	0.024	0.025	0.026	11	
11	5.000	11	7.522	7.10	7.40	i	2.032	2.170	2.033 1	0.018	•	0.020	11	
11	6.000	11	7.111	7.00	7.05	11	2.283	2.366	2.176 1	0.013	1 0.019	0.014	ii.	
ii	7.000	11	6.692	6.76	6.70	ii	2,725	2.577	2.546	0.009	1	0.012	ii	
11	8.000	11	6.331	6.73	6.31	ii	2.823	2.685	2.680	0.007	1 0.020	0.010	ii	
11	9.000	11	6.074	6.80	5.98	1	2.789	2.703	2.680	1 0.005	• • • • • • •	0.009	-ii	
ii	10.000	ii	5.885	6.87	5.78	-11	2.722	2.721	2.680	0.004		0.008	11	
11	11.000	11	5.774	6.92	5.66	1	2.660		2.680	0.003		0.007	11	
ii	12.000	5.5	5.75	6.97	5.57		2.626		2.680	0.003	, , , , , , , , , , , , , , , , , , ,	0.006		
ii	13.000	11	5.787	7.02	5.51	-11	2.654		2.680	0.002	i i	0.005		
11	14.000		5.865	7.08	5.51		2.702	2-668	2.680	1 0.002	1 0.030	0.005	11	
		•••									1 4+448			

TABLE 7

SELECTED VALUES OF EVALUATED TOTAL + FISSION AND CAPTURE CROSS-SECTIONS COMPARED TO ENDF/B-V AND KEDAK 3

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T	AUL	E	8

11		11			1	ι τα	TAL	I ELASTI	С	1 F1	SSION	I CAPTU	IRE	I INELAST	IC
11					1 I	SCATTERING			1				I SCAT	TERING	
11	GROU	P 11	ENERGY	INTERVAL	S	1				1		+	****		!
11		- 11	- '		i	BARIIS	I ERR. %	BARHS	1. ERR. %	BARNS	ERR. %	I BARNS I	ERR. %	I BARNS I	ERR %
11	====	==	=======		=====	=======	=======	======	=========	======		====== =	======	=====	======[
11	1	11	14.5	- 3.68	MEV I	1 7.45	8	4.14	1 10	2.20	9	1 0.02 1	200	1 1.09 1	30 1
11	2	- i i	3.68	- 2.23		1 7.79	1 8	4.15	1 10	1 2.14	1 7,	1 0.03 1	200	1 1.46 1	30 1
11	3	- 11	2.23	- 1.35	- +	1 7.25	i 8	3.47	1 10	2.18	1 7	0.04 1	200	1 1.56	30
11	4	- 11	1.35	- 0.82		1 7.13	8	1 3.70	1 10	2.13	1 7	0.06 1	100	1 1.24 1	30
11	5	i i	821.	- 498.	KEV I	1 7.97	i 8	5.17	1 10	1 1.74	1 12	0.12 1	50	0.93	40
ii	6	i i	498.	- 302.		9.08	1 8	6.88	1 10	1 1.17	1 12	0.19 1	50	0.84 1	40 1
11	7	- ii	302.	- 183.	- + ÷ - į	1 10.33	8	8.51	1 10	0.85	1 12	0.24 1	50	0.72	50 (
ii	8	11	183.	- 111.	- ++ j	1 11.34	1 8	9.81	1 10	0.68	1 12	0.32 1	30	0.52	60
11	9	- İİ	111.	- 67.4	- 11 j	1 12.13	1 8	1 10.80	1 10	1 0.61	1 12	0.44 1	30	0.28	100 1
11	10	i i	67.4	- 40.9	- ++ j	1 12.85	1 13	11.54	1 10	0.66	6	0,59 1	25	0.06 1	100 1
11	11	- 11	40.9	- 24.8	• • • j	1 13.54	1 12	12.11	1 12	0.78	6	0.65 1	2 5	1 1	1
ii	12	— i i	24.8	- 15.0	- • • j	1 14.37	1 12	12.02	1 11	1 0.81	6	0.75 1	22	1 1	i
ii	13	i i	15.0	- 9.12	- + i j	1 15.37	1 12	13.31	1 11	0.77	6	1.29 1	22	i i	i
ii	14	i i	9.12	- 5.53	11	1 16.63	1 12	14.55	1 12	1 0.97	6	1 1.11 1	22	1 1	1
11	15	i i	5.53	- 3.36	i j	1 16.78	i i3	1 13.86	1 11	1 1.00	6	1 1.92 1	18	1 1	1
11	16	ii	3.36	- 2.04	••• 1	22.63	1 13	18.67	1 13	1 1.41	6	2.55	18	1 1	1
11	17	11	2.04	- 1.23	j	1 25.6)	i i3	22.35	Í 13	1 1.23	6	2.03 1	18	1 1	1
11	18	- 11	1.23	- 0.75	i j	1 25.30	1 15	19.72	1 13 .	1 1.93	6	3.66 1	18	1 1	1
ì	19	- i i	748.	- 454.	EV İ	1 31.13	1 15	22.52	1 13	1 2.46	1 15	6.15 1	18	1 1	1
11	20	11	454.	- 275.		1 44.34	1 15	27.84	1 14	7.30	1 10	9.19	15	1	i
ii	21	i i	275.	- 101.	- + + i	1 54.87	1 14	1 28.31	1 14	1 5.77	1 9	20.77	13	1	i
ii	22	- 11	101.	- 22.6	101	1 25.68	1 14	1 13.95	i ii	1 1.19	9	1 10.53 1	13	i i	i
- 11	23		22.6	- 3.06		65.34	1 14	1 14.69	1 11	2.67	i 9	47.95 1	13	i i	i
	24		3.06	- 0.41	4 + • i	1 81.48	1 14	1 12.74	1 10	1 2.16	9	1 66.32 1	13	i i	i
	25	- 11	3100	тн 🗸		1501.93	4	1 19.41	6	1 14.75	1 10	467.77	5	i i	i
= =							, , ,					**********	=======		



Fig. 1 - ²³⁸Pu total and capture cross-sections from BNL-325. The curves show the cross-sections calculated from the resonance parameters.



Fig. 2 - The evaluated data compared to the experimental cross-sections in the thermal region.



Fig. 3 - Distribution of the reduced neutron widths.



Fig. 4 - Number of levels as a function of energy.



Fig. 6 - Distribution of the fission widths from SILBERT et al. (4), (5).

Fig. 5 - The fission widths fro SILBERT et al. (4), (5



Fig. 7 - Statistical model calculations in the unresolved region.







Fig. 9 - The fission cross-sections in the energy range 0,1 MeV to 3 MeV.



Fig. 10 - The fission cross-sections in the energy range 0,1 MeV to 14 MeV.

XX	KNITTER AND BUDTZ-JORGENSEN data
-0-1-0-	SILBERT et al. data
	Statistical model calculations
	Evaluated data



Fig. 11 - Evaluated data in the 5 MeV to 14 MeV energy range. The dashed total fission and the dashed (n, 2n) crosssections are from ENDF/B-V.





X	Experimental	values	(référence	29)
	Calculated v	alues		











Fig. 16 - Evaluated capture cross-sections. CAD corresponds to the present evaluation.



