International Atomic Energy Agency

INDC(CCP)-366
Distr.: L

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

EVALUATION OF NEUTRON NUCLEAR DATA OF ACTINIDES

(Translations of selected Russian papers published in Yadernye Konstanty 1987-1991)

Translation editor: Dr. A. Lorenz

February 1994

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

Reproduced by the IAEA in Austria
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EVALUATED NEUTRON CROSS-SECTIONS OF ^{234}U IN THE THERMAL ENERGY REGION

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ABSTRACT

An analysis of the experimental cross-sections of ^{234}U has been performed up to 1 eV, and the $\sigma_t(E)$, $\sigma_\gamma(E)$ and $\sigma_n(E)$ neutron cross-sections in the 10-5 to 1 eV energy range and negative resonance parameters have been evaluated.

We need evaluated neutron cross-sections for ^{234}U because it is one of the nuclides in the thorium fuel cycle. Experimental cross-section data in the thermal energy region are sparse; the measurements are old for the most part, taken some time ago, and the scatter in the results of different authors is rather large.

The experimental information available to us can be conveniently divided into two groups: measurements of the total cross-section energy dependence [1, 2] and measurements of the capture cross-section at thermal [3-7]. This is clearly not enough to construct detailed curves for types of cross-section in the thermal region, or to obtain self-consistent values by the usual methods. In order to derive evaluated neutron cross-sections we need to apply one of the resonance formalisms so as to obtain the energy dependence of the cross-section curves with due allowance for existing experimental data. In this paper we have used the Breit-Wigner formalism, taking into account all levels in the resolved resonance region. The resonance parameters were taken from James et al. [8] even though this paper offers less than complete certainty about the magnitude of Γ_γ. In this work the authors took a value of Γ_γ = 40 meV at all levels whereas in earlier papers they took a value 25 meV. The authors give no explanation for this change. In the absence of total cross-section data in EXFOR [8] (where only values for $\sigma_f(E)$ are to be found), we were unable to carry out our own parameterization in order to clarify the issue. Calculations based on the Breit-Wigner formalism showed that in the thermal energy region the negative resonance contribution to the cross-section exceeds 90%. Accordingly, the cross-section curve in the thermal region must be determined largely by the location and parameters of this resonance.

The energy dependence of the total cross-section is plotted in papers by McCallum [1] and Block [2]; where data differ systematically by ≈ 10%. These two studies were carried out at approximately the same time. In Ref. [1] σ_t (E) was measured in the 0.01-20 eV interval, and in Ref. [2] in the 0.02-0.045 eV interval. The values obtained by the authors for the total cross-section at thermal were 121 ± 8 b [1] and 110 ± 4 b [2]. The question then arises, which total cross-section data should we take as our starting point? Mughabghab [9], after considering all aspects of the matter, gave preference to McCallum's measurements given in [1], and so, a value of 119.1 ± 1.3 b was proposed for σ_t at thermal, and yet the quality of McCallum's data [1] is questionable. The measurements in [1] were carried out on samples of different thicknesses, and the energy region of interest to us was measured on the thickest sample. If we compare the cross-sections obtained by the authors of [1] for the resonance peak at 5.16 eV, which was measured in all three experiments, we see that σ_t at the peak varies from ≈ 400 b (for the thickest sample) to ≈ 20 000 b (for the thinnest sample). This inevitably arouses suspicion. Ref.[2] on the other hand contains measurements of σ_t(E) in the thermal region for the ^{233}U, ^{235}U, ^{240}Pu, ^{234}U and ^{129}I nuclides. If we compare the values obtained by the authors of [2] for σ_t at 0.0253 eV for the first three nuclides with the values now used, we will see that they differ by 0.1, 0.27 and 0.41%, respectively. This points to a high level of accuracy in these measurements. True, the value of σ_t for ^{234}U at thermal (110 $\pm$ 4 b) given by Block et al. [2] does not agree with the values calculated by their own methods from their own experimental data, namely 108 $\pm$ 5 b, unless of course, the authors made use of additional information which they failed to mention. At any rate, σ_t for E = 0.0253 eV is considerably lower in [2] than in [1].

For the radiative capture cross-section σ_γ the only available measurements at thermal are those given in Refs [3-7]. There is no point in examining calculated values of σ_γ or, to what amounts to the thing, of σ_a, since they were obtained on the assumption that σ_n = 17.8 b [1]. Ref. [3] quotes a measured value of σ_γ = 88 $\pm$ 6 b, with $\sigma_\gamma{}^{197}$Au = 95 b used as the standard. If we take into account the latest value the radiative capture cross-section for gold-197 $\sigma_\gamma{}^{197}$Au = 98.8 b we obtain a value σ_γ ^{234}U = 92 $\pm$ 6 b.

Craig et al. [4] assigned to σ_γ^{U234} the value of 143 b (a value which was obtained from the ratio of the ^{238}U and ^{234}U α-peaks in a uranium sample). Both this value and the σ_γ = 64 b from Ref. [5] are anomalous, and neither was taken into consideration later on. Activation measurements [6,7] gave σ_γ = 100.5 $\pm$ 1.3 b and 95.6 $\pm$ 2.1 b, respectively. These values and σ_γ from Ref. [3] were used in subsequent work. The weighted average value of the three measurements indicated above, is 98.91 $\pm$ 1.09 b. Allowing for the fact that that this value is quoted for a Maxwellian spectrum, and using g_γ = 0.9903 [9], we obtain σ_γ = 99.88 b at thermal.

The value σ_n = 17.8 b [1] was calculated on the basis of parameters selected to describe the experimental curve of the total cross-section and was subsequently hen used by other authors. It corresponds to a total cross-section at thermal of ≈ 120 b, and to the radiative capture cross-sections quoted above.

It should be noted that the scatter cross-section quoted in Refs. [1, 9] appears anomalously large and extremely improbable.

Thus, the input data used to obtain our evaluated neutron cross-sections in the thermal region were: $\sigma_t(E)$ from [2], the weighted average value of σ_γ given above, a scattering radius $R = 0.89358 \cdot 10^{-12}$ cm obtained from the relation $R = 1.45 \cdot 10^{-13} A^{1/3}$, and the resonance parameters from [8]. The fit was achieved by changing the position and parameters of the negative resonance. In the absence of information on $\sigma_f(E)$ in the thermal region the value of Γ_f for the negative resonance was taken to be zero. Γ_γ for the negative resonance was subject to the usual constraint imposed previously, viz. $0.02 \leq \Gamma_\gamma \leq 0.06$ eV. The following resonance parameters were obtained after fitting: $E_r = -2.14$ eV, $g\Gamma_n = 2.544$ meV, $\Gamma_\gamma = 57.22$ meV, and so the cross-section values derived for $E = 0.0253$ eV were as follows: $\sigma_t = 110.04$ b, $\sigma_n = 11.048$ b, $\sigma_\gamma = 98.986$ b and $\sigma_f < 0.006$ b. The cross-section behavior in the energy interval 10^{-5} to 1 eV is shown in the table.

The calculated value $g_\gamma = 0.9908$ is very close to the $g_\gamma = 0.9903$ from Ref. [9], and the evaluated cross-sections in the thermal region are in good agreement with the experimental data we used as input data.

The accuracy of the evaluated data for ^{234}U could be improved further by obtaining new information, particularly on fission and radiative capture cross-sections in the thermal region.

Table

Evaluated neutron cross-sections of ^{234}U

E, eV	σ_t, b	σ_n, b	σ_γ, b
$1\cdot10^{-5}$	5089,7	5078,3	11,115
$1\cdot10^{-4}$	1617,0	1605,8	11,114
$1\cdot10^{-3}$	518,57	507,43	11,112
0,010	170,43	159,33	11,088
0,015	140,67	129,59	11,075
0,020	122,86	111,79	11,062
0,0253	110,04	98,986	11,048
0,030	101,61	90,572	11,035
0,035	94,558	83,531	11,022
0,040	88,851	77,837	11,009
0,045	84,106	73,105	10,996
0,050	80,078	69,090	10,984
0,060	73,556	62,594	10,958
0,070	68,453	57,516	10,933
0,080	64,312	53,401	10,908
0,090	60,861	49,975	10,883
0,10	57,923	47,063	10,858
0,15	47,806	37,067	10,737
0,20	41,629	31,006	10,621
0,25	37,331	26,820	10,508
0,30	34,110	23,708	10,400
0,40	29,517	19,322	10,194
0,50	26,343	16,341	10,000
0,60	23,988	14,171	9,816
0,70	22,162	12,518	9,642
0,80	20,700	11,223	9,476
0,90	19,503	10,185	9,317
1,0	18,506	9,342	9,163

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Article submitted for publication 5 April 1991

EVALUATION OF THE ^{232}Th(n,2n)^{231}Th REACTION CROSS-SECTION FROM THRESHOLD TO 20 MeV

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ABSTRACT

Experimental results for the ^{232}Th(n,2n) reaction were compiled and evaluated. Normalization of the measured cross-sections was carried out using values recently obtained for the cross-sections of standard monitor reactions. The evaluated excitation function was then obtained by Pade approximation. The accuracy of the evaluated curve was also calculated.

Investigation of ^{232}Th reaction cross-sections is interesting not only from the purely scientific standpoint but also for a practical reason, namely to establish a thorium fuel cycle. Romanian scientists produced a complete ^{232}Th cross-section file in 1979-80[1]. However, many of the cross-section evaluations, especially of the (n,2n) reaction, the authors of this evaluation used pre-1971 experimental data. New experimental results have been obtained in recent years making revision of earlier evaluations possible. The present paper is a compilation and, in some cases, a renormalization of the ^{232}Th(n,2n) reaction cross-section data. The Pade approximation was used to obtain the evaluated function of the (n,2n) reaction cross-section and its error. A few suggestions are made regarding the direction of future research.

Analysis of experimental data

Table 1 lists the experimental data considered in this evaluation and also gives the renormalized cross-section values. The considered experimental data are:

1. The data in Ref. [3] were measured with respect to the standard $^{32}S(n,p)$ reaction. The results were renormalized using the new $^{32}S(n,p)$ reaction cross-section values given in Ref. [16]. The maximum discrepancy(up to 23%) from the error increases in this energy range. It is not clear why there is such a large discrepancy between the cross-sections at the 18.52 and 20.40 MeV energy points.

2. Ref. [7] shows much lower cross-section values a all energy. The method used to measure activity is not known. These data were not included in our evaluation.

3. In Ref. [4] the neutron flux was measured relative to the $^{238}U(n,f)$, $^{27}Al(n,\alpha)$ and $^{56}Fe(n,p)$ reactions. Activity of the low-energy gamma rays was determined using a high-purity Ge detector, whose efficiency was determined by the Phillips method [13, 14]. Table 1 lists the root-mean-square errors combining the statistical and systematic errors given separately in Ref. [4].

4. The data in Ref. [9] are systematically lower for the entire energy range. Renormalization of the 84 keV gamma line intensity according to the data in Ref. [17] yields even lower cross-section values. The neutron flux was measured with respect to n-p scattering. The original cross-section values were taken for the evaluation. The data in Ref. [9] provide a complete dependence of the excitation function in the 15-20 MeV neutron energy range.

5. In Ref. [8], the neutron flux was measured using the associated alpha-particle method and with respect to the $^{27}Al(n,\alpha)$ reaction. The activity of the radiochemically purified ^{231}Th sample was determined by recording β-particles. The cross-section trend in the 13-15 MeV energy region deviates from the values obtained in Refs [9, 10].

6. In Ref. [13], the neutron flux was determined using the associated alpha-particle method. The 25 keV gamma ray was used to measure the activity. The efficiency of the scintillation detector was measured relative to the yield of gamma rays having the same energy as those from the $^{235}U \rightarrow \alpha \rightarrow {}^{231}Th$ decay.

7. The cross-sections measured in Ref. [10] for the energy range 13.5-14.8 MeV are systematically higher than all of the basic data . The experimental technique is similar to that described in Ref. [4].

8. The experimental details of Ref. [6] are not known. The data error was increased to 20%.

9. The data in Ref. [12] are considerably lower than all of the available cross-sections and were therefore disregarded in our evaluation.

10. The precise energy at which the cross-section in Ref. [11] was measured is not known. The cross-section error of approximately 4% was therefore raised to 15%.

Evaluation of the reaction cross-sections and their errors

The evaluated energy dependence of the $^{232}Th(n,2n)$ reaction cross-section was obtained using the Pade approximation method which we have used previously to evaluate the $^{238}U(n,2n)$ cross-section [15]. This method is described in detail in Ref. [2].

The cross-section was written in the form:

$$\sigma_{2n}(E) = \sigma_o + \sum_{i=1}^{k} \frac{a_i(E-\varepsilon_i)+\beta_i}{(E-\varepsilon_i)^2 + \gamma_i^2} \qquad (1)$$

When we included the full data set (with the exception of the data in Refs. [7, 11]) we obtained an "unreal" cross-section function (Fig. 1): with a drop of the cross-section at 10.5 MeV and a rise at around 14 MeV. There is no satisfactory explanation for this result. It does not follow from theoretical calculations (Fig. 1) and it is not observed in the (n,2n) cross-section for other nuclei. The shape of the excitation function corresponds on the whole to the "strange" behaviour of the experimental points in Refs [3, 7, 8, 9] in the 12-13 MeV energy region. Data in this energy range were not included in the subsequent analysis. The resulting dependence is also shown on Fig. 1. The total number of points N = 57, the number of parameters is 9, κ^2/ν = 1.5 (ν is the number of degrees of freedom) and K = 2. The parameters from Eq. (1) for the evaluated function are given in Table 2. The numerical values in the experimental points are given in Table 1.

Equation (1), together with the parameters from Table 1,does not satisfy the behaviour of the cross-section near the threshold. The following function is recommended for this region:

$$\sigma_{2n}(E) = 930.9(E-6,468)^2 \text{ millibarns, } E < 7.05 \text{ MeV} \qquad (2)$$

The exponent in expression (2) was determined from the behaviour of the Pade-approximation near 7 MeV. Function (2) corresponds to the theoretical near-threshold behaviour of the cross-section [15]. The difference from the ^{238}U(n,2n) reaction, where the near-threshold behaviour was described by a cubic function [15], is probably due to the lower fissionability of ^{232}Th.

In addition to the excitation function we also calculated the error S [2], assuming energy independence of the data given in (Table 3). The parameter S should be regarded as the lower error limit. The upper limit, D, can be determined from the spread of the experimental data from the evaluated curve for various energy ranges (Table 4).

Conclusions

1. The evaluation for the ^{232}Th(n,2n) reaction cross-section given in the present paper is ~ 10% higher than that proposed in Ref. [1] and ~ 20% higher than the data in Ref. [18] for the 9-14 MeV energy region. This is due to the fact that the data in Ref. [7] were disregarded as they were not substantiated by recent experiments. In addition, as a result of renormalization, the cross-sections from Ref. [3] were increased.

2. The upper and lower error limits can be established with sufficient reliability. The actual error of the cross-section lies between these values.

3. In the ≈ 7 to ≈ 10 MeV energy region, the reaction cross-section is determined with sufficient reliability by the data given in Refs. [3, 4]. The error for this range is (2-5%).

4. In the 13-15 MeV region, data from the latest studies [9, 10] show a systematic shift of ~ 200 mb. The reason for this shift is not clear. The actual error of the cross-section for this region is close to the upper limit evaluated in the present paper, that is ~ 10%. New experiments are required to measure the trend of the cross-section in order to resolve the discrepancy between Refs [9] and [10].

5. The (n,2n) reaction cross-section in the > 18 MeV energy region is determined entirely by the non-statistical primary neutron emission mechanism. Precise determination of the reaction cross-section in this region and comparison with the cross-sections for other nuclei would enable one to come to a clearer conclusion about the character of the interaction. At the present time the accuracy of the evaluated function is in the region of D ~ 22%.

Table 1

Experimental data used to evaluate the $^{232}Th(n,2n)$ reaction excitation function

E, MeV	Original: Reaction cross-sections $\sigma \pm \Delta\sigma$, mb		Renormalized: $\sigma_n \pm \Delta\sigma$, mb		Recommended: σ_p, mb	Recommended: $\sigma_p - \sigma_n$, mb	Reference
1	2		3		4	5	6
6,51	15	7	15	7	10	-5	3
6,68	36	3	36	3	38	-2	3
6,745	74	11	74	11	66	-8	4
6,79	94	8	95	8	90	-5	3
6,938	209	13	209	15	202	-7	4
7,00	270	13	270	13	262	-8	5
7,01	271	13	273	15	273	0	3
7,03	277	25	273	55	294	21	6
7,190	449	18	449	24	480	-31	4
7,28	603	28	607	34	593	-14	3
7,448	827	37	827	48	804	-23	4
7,59	976	45	984	60	973	-11	3
7,697	1021	29	1021	48	1089	68	4
7,84	1200	70	1214	80	1229	15	3
7,944	1386	57	1386	77	1318	-68	4
8,01	1390	70	1406	85	1370	-36	3
* 8,4	1420	280	1420	280	1611	(191)	7
8,457	1660	33	1660	70	1639	-21	4
8,61	1610	70	1656	88	1707	44	3
8,975	1904	79	1904	106	1837	-67	4
9,02	1750	80	1839	98	1851	12	3
* 9,1	1500	300	1500	300	1875	(375)	7
9,445	1952	45	1952	85	1967	15	4
9,63	1940	90	2168	136	2012	-56	3
* 9,8	1440	290	1440	290	2050	(610)	7
9,934	2090	62	2090	99	2079	-11	4
10,03	1830	80	2120	126	2099	-21	3
* 10,35	1600	320	1600	320	2162	(562)	7

1	2		3		4	5	6
10,450	2158	77	2158	111	2180	22	4
10,62	1910	90	2302	142	2209	-91	3
* 11,0	2100	420	2100	420	2264	(164)	7
* 11,5	1840	370	1840	370	2309	(469)	7
11,61	1720	80	2114	129	2313	199	3
* 12,1	1690	340	1690	340	2295	(605)	7
* 12,13	1760	176	1760	352	2292	(532)	8
* 12,3	1630	330	1630	330	2269	(639)	7
* 12,55	1510	80	1635	87	2224	(589)	3
* 12,99	1811	246	1811	246	2084	(273)	9
* 13,0	1750	350	1750	350	2080	(330)	7
13,33	1610	161	1610	161	1939	329	8
13,40	1680	168	1680	168	1906	226	8
13,487	1967	79	1967	79	1863	-104	10
13,52	1635	164	1635	164	1847	212	8
13,69	1630	163	1630	163	1758	128	8
13,741	1807	69	1807	69	1730	-77	10
13,83	1566	148	1566	148	1682	126	9
* 13,85	1490	300	1490	300	1671	(181)	7
13,88	1560	156	1560	156	1654	94	8
* 14,0	1330	270	1330	270	1587	(257)	7
14,09	1560	156	1560	156	1537	-23	8
14,097	1585	57	1585	57	1533	-52	10
14,1	1200	50	1200	180	1531	331	11
14,31	1520	152	1520	152	1413	-107	8
14,31	1235	118	1235	118	1413	178	9
14,45	1230	60	1251	61	1335	84	3
14,462	1399	55	1399	55	1328	-71	10
* 14,5	1400	280	1400	280	1307	(-93)	7
14,50	1440	144	1440	144	1307	-133	8
14,68	1400	140	1400	140	1211	-189	8
* 14,7	650	150	730	200	1200	(470)	12
14,79	1049	99	1049	99	1154	105	9
14,81	1280	128	1280	128	1143	-137	8
14,836	1231	47	1231	47	1130	-101	10
14,93	1255	126	1255	126	1083	-172	8
15,0	1100	100	1100	165	1049	-51	13
* 15,1	980	200	980	200	1002	(22)	7
15,32	792	107	792	107	905	113	9
15,85	552	54	552	54	707	155	9
15,97	480	60	480	96	669	189	6
* 16,5	< 480				530		8
16,57	438	42	438	42	515	77	9
17,28	369	34	369	34	396	27	9
18,13	303	27	303	27	315	12	9
18,52	459	27	469	28	293	-176	3
20,40	225	15	228	15	255	27	3

[*] Data marked with * were not included in the final analysis

Table 2

Pade-approximation parameters

i	a_i	β_i	ε_i	γ_i
1	-5309,8052	13736,850	13,39116	3,3500121
2	955,83063	-1733,7130	6,9045630	1,148528

σ_o = 583.44098 mb

[*] For calculation purposes, energy is expressed in "MeV", the cross-section in "millibarns".

Table 3

Error of the evaluated function (lower limit)

E, MeV	S, %	E, MeV	S, %
7,00	2,6	11,61	3,0
7,45	2,0	13,40	2,4
8,00	2,0	14,09	1,4
9,02	1,7	15,00	2,0
10,0	1,9	20,40	6,3

Table 4

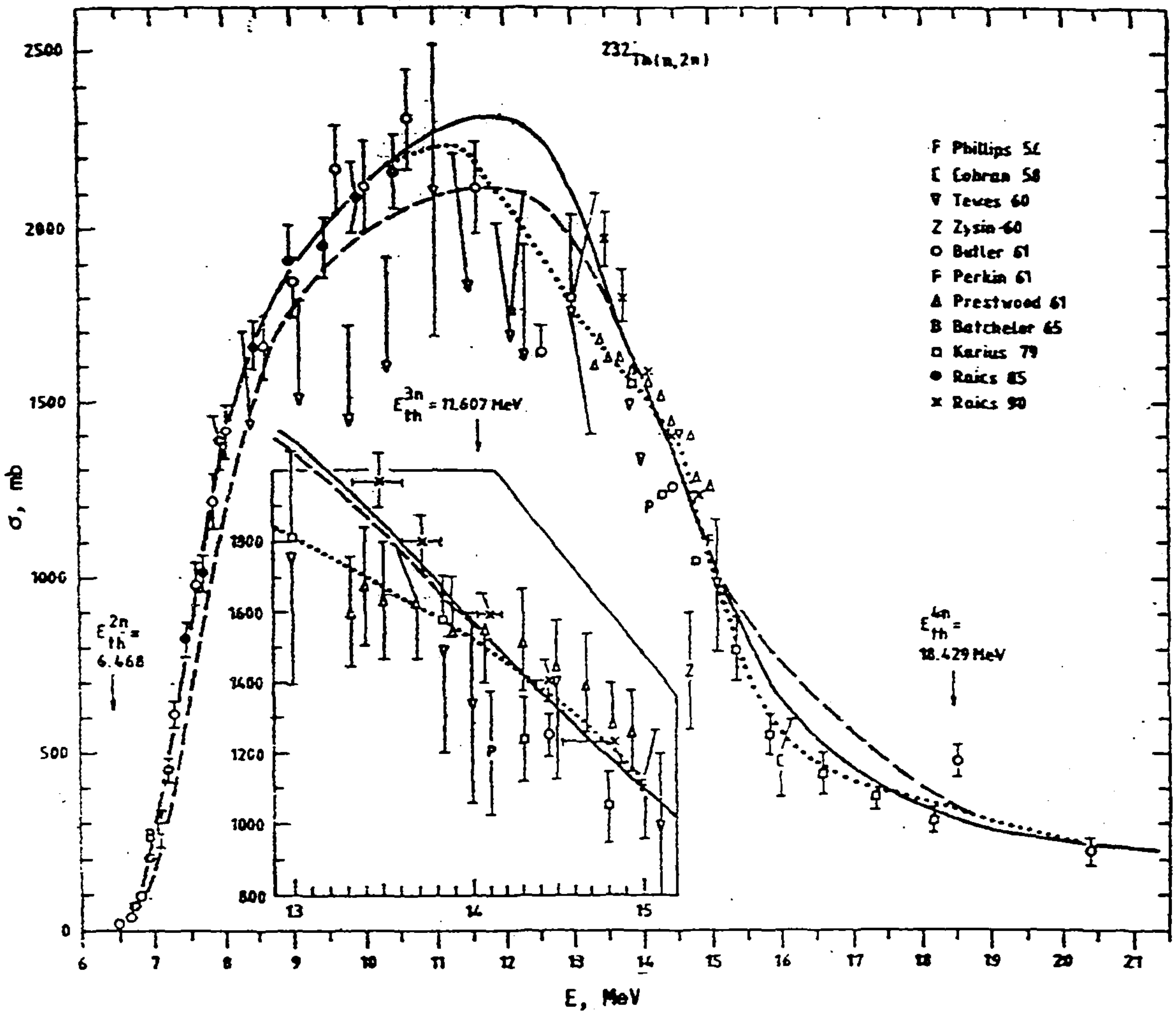
Upper error limit

$E_1 - E_2$	$\bar{\xi}$	D, %
6,51-6,94	-0,086	13,6
7,00-8,01	0,005	4,5
8,46-9,93	-0,011	3,4
10,03-11,61	0,013	5,8
13,33-13,88	0,065	9,1
14,09-14,93	-0,011	12,4
15,00-20,4	0,089	21,7

$$\xi = \sum_{i=1}^{n} \xi_i / n \qquad \xi_i = [\sigma_i^{\text{экс}} - \sigma_i^{p}] / \sigma_i^{p}$$

$$D^2 = \sum_{i=1}^{n} (\bar{\xi} - \xi_i)^2 / n$$

where n = number of points in the energy range



Experimental data for the ^{232}Th(n,2n) reaction cross-section

......: Pade approximant for inclusion of data in the 12-13 MeV energy region

———: Final version of the evaluated function, with parameters from Table 2

— — —: Theoretical estimation from Ref. [1]

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Article submitted for publication 19 July 1990

EVALUATION OF NEUTRON CROSS-SECTIONS FOR ^{242}Cm TO OBTAIN A COMPLETE FILE

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ABSTRACT

Experimental fission, capture, inelastic scattering, (n2n), (n3n) and other cross-sections are scarce or unavailable. As a consequence, theoretical models and parameter systematics have been used extensively in the calculation of these data. Data obtained in this work are compared with previous evaluations. Severe discrepancies were found.

Because of the high concentration of curium isotopes in nuclear power plant fuel, there is a need for their evaluation. The complete ^{242}Cm file described below is the first of a series of curium isotope evaluations carried out at the Nuclear Power Institute of the Byelorussian SSR Academy of Sciences for the National BROND Nuclear Data Library. Since there are virtually no experimental data available, the evaluation was based on theoretical calculations and known systematics of model parameters.

Resolved resonance region (10^{-5}-155 eV)

The basis for evaluating the resolved resonance parameters of this nuclide was based on the neutron widths given in Ref. [1]. Although ^{242}Cm resonances were measured in this study up to an energy of 265 eV, no resonances were found in the 155-235 eV region, where they were probably omitted. The resolved resonance region extends to 155 eV. In the measurement of the total widths of the first three resonances, which were reported in Re. [1], the total width of the 37.49 eV resonance is anomalously high. This contradicts the systematics of the isotopic dependence of radiative widths. We believe that the high value of Γ_t is attributable to insufficient experimental resolution and to a lack of detailed knowledge about the resolution function. Reference [2] reports measurements in the energy region below the first four fission resonances. Using the Γ_t and Γ_n values of the first two resonances from [1] we are able to evaluate their fission and radiative widths. The radiative width of the remaining resonances is equal to the average of the first two. This determined the fission widths of the 37.49 and 60.1 eV resonances. For the remaining resonances, Γ_f was taken to be equal to the average value. The parameters of the negative resonance were selected such that they agreed with the values of the evaluated capture and fission cross-sections at thermal, derived from the results obtained in Ref. [3]. The potential scattering radius was taken from calculations which were carried using the coupled channel model with the potential obtained earlier in Ref. [4]. The evaluated cross-sections in the 10^{-5}-155 eV region can be obtained from the evaluated resonance parameters (Table 1) using the single-level Breit-Wigner formalism.

The evaluated cross-sections at thermal are almost identical to the values obtained by other authors and are given in Table 2. The average parameters for the resolved resonance region are:

$$\langle D \rangle = 8{,}0^{+2{,}0}_{-1{,}2}\ \text{эВ}; \qquad S_0 = (0{,}84 \pm 0{,}39) \cdot 10^{-4};$$

$$\langle \Gamma_f \rangle = 4{,}45 \pm 1{,}5\ \text{мэВ}; \qquad \langle \Gamma_\gamma \rangle = 33{,}7 \pm 8{,}0\ \text{мэВ}.$$

In determining < D > and < Γ^0_n > we made allowance for the fact that the resonances were measured on a sample with a low concentration (8.7%) of the isotope under investigation. Thus, omission of the ^{242}Cm levels can be a consequence of not only their small values and tight groupings but also by the fact that they may coincide with those of other isotopes contained in the sample.

Unresolved resonance region (0.155-42.1 keV)

The upper limit of the unresolved resonance region is determined by the position of the first excited level of ^{242}Cm. The average resonance parameters are obtained taking into account the contribution of s,p and d-waves, where the contribution of the d-wave to the calculated cross-section values is ~2%.

The average distance between the levels is considered to be energy-dependent and its value for E_n = 155 eV is equal to the average of the average distance taken from the resolved resonance region for J = 1/2. The strength functions $S_0 = 0.925 \times 10^{-4}$ and $S_1 = 2.95 \times 10^{-4}$ were obtained from calculations using the generalized optical model. The width of the radiative capture $< \Gamma_\gamma > = 33.7$ was considered to be energy independent for all reaction channels.

In the calculations to determine the energy-dependence of the fission widths, we assumed that the fission barrier parameters (height and curvature) were constant for all channels, and that their total numbers equalled 2J + 1. From the calculated and experimental data given in Ref. [5] it follows that one of the fission barriers of the ^{243}Cm compound nucleus is smaller than neutron binding energy. Thus, the average fission width were calculated using the single-hump approximation. In the region up to 1.5 MeV, the fission barrier parameters obtained from experimental σ_{nf} data given in Ref. [6] were slightly modified so as to describe the average value of $< \Gamma_f > = 4.45$ meV from the resolved resonance region. Using the results thus obtained, the calculational results agree on the average with the data given in the only measurement of σ_{nf} in the considered energy region. In order to describe the structure of the data in Ref. [2] in the adopted energy grouping used in the evaluation the fission widths were renormalized and taken as evaluated.

Fast neutron energy region (42.1 KeV-20 MeV)

With the exception of the fission cross section in the narrow energy region up to 1.5 MeV, there are no experimental data . Evaluation was therefore based on calculations using generalized optical and statistical nuclear models. The optical potential given in Ref. [4] was used in the calculations. The ^{242}Cm deformation parameters β_2 = 0.2 and β_4 = 0.053 were determined taking into account the isotopic dependence of these values, predicted by microscopic calculations, and the values of the strength function S_o, evaluated in the resolved resonance region. The evaluated values of the total cross section, the cross-section for the formation of a compound nucleus, of the direct elastic and inelastic scattering and their angular distributions, as well as neutron penetration were obtained using the above-mentioned potential. Up to the energy of 1.5 MeV, the fission cross section was evaluated using experimental data [6]. All other cross sections, those that went through the interim formation of a compound nucleus and the fission cross section above 1.5 MeV were calculated according to the statistical model. The level density and the transitional fission stages required for the calculations was determined using a superfluid nucleus model taking into account rotational and oscillational modes, and using the parameters obtained earlier for nuclei groups in Ref. [7] and taking into account the difference in the symmetry of transitional configurations at the first and second fission barriers. The fission barrier parameters of the compound ^{242}Cm and ^{241}Cm nuclei, required for calculation of the reaction cross sections (n,nf) and (n,2nf), were determined taking into account data on the fissioning ability of charged particles [5, 8].

Radiative capture transmissions were calculated using a γ-quantum cascade emission model with an energy dependent spectral factor f(E, σ_γ) in the form of a double-humped Lorentz curve.

At incident neutron energies greater than ~5 MeV, the contribution of the pre-equilibrium neutron emission process becomes significant. The proportion of this contribution was determined using data for ^{238}U data,for which this process has studied extensively. The amount by which it differs from ^{242}Cm was calculated taking even-odd effects into account.

Comparison with the results of other evaluations

Unlike the ENDF\B-V [9] evaluations and those by Maino et al. [10] our resolved resonance parameters include fission widths obtained from experimental data [2] and are in our opinion more reliable. In the unresolved resonance region the basic differences in the evaluations lie in the magnitudes of the average fission widths: our values for $< \Gamma_f >$ are approximately ten times greater and agree with the experimental data given in Ref. [2], which were published after the evaluations carried out in Refs [9] and [10]. A comparison of σ_{nf} and $\sigma_{n\gamma}$ evaluations in the fast energy region is shown on Figs 1 and 2. From Fig. 1 it can be seen that our evaluation is in good agreement with the evaluation given in Ref. [10] and are practically identical in the 0.7-7 MeV range since both used fissionability data from Refs [5, 8] to obtain σ_{nf}. In the region above the (n,n'f) reaction threshold, differences in the evaluations are apparently caused by the use of different values for the evaluated cross sections for compound nucleus formation and for the thresholds of the ^{242}Cm and ^{241}Cm compound nuclei.

The greatest differences are observed in the evaluated radiative capture cross sections (Fig. 2). Our data for $\sigma_{n\gamma}$ lie above the evaluations of other authors which resulted from taking a lower value for $< D >$.

Table 1
Evaluated resonance parameters for ^{242}Cm

Eo, eV	Γ_n, meV	Γ_f, meV	Γ_γ, meV
-3.0	1.817	10.44	33.7
13.62	1.82	1.36	32.84
30.33	3.1	7.25	47.65
37.5	4.4	7.25	33.7
60.1	23.6	1.93	33.7
89.3	12.5	4.45	33.7
103.4	5.4	4.45	33.7
130.7	3.6	4.45	33.7
148.7	24.0	4,45	33.7
154.6	11.5	4.45	33.7

Table 2
Evaluated values of ^{242}Cm cross-sections
at 0.0253 eV (barn)

σ_{tot}	$\sigma_{n\gamma}$	σ_{nf}	σ_{nn}
33.43	16.66	5.0	11.77

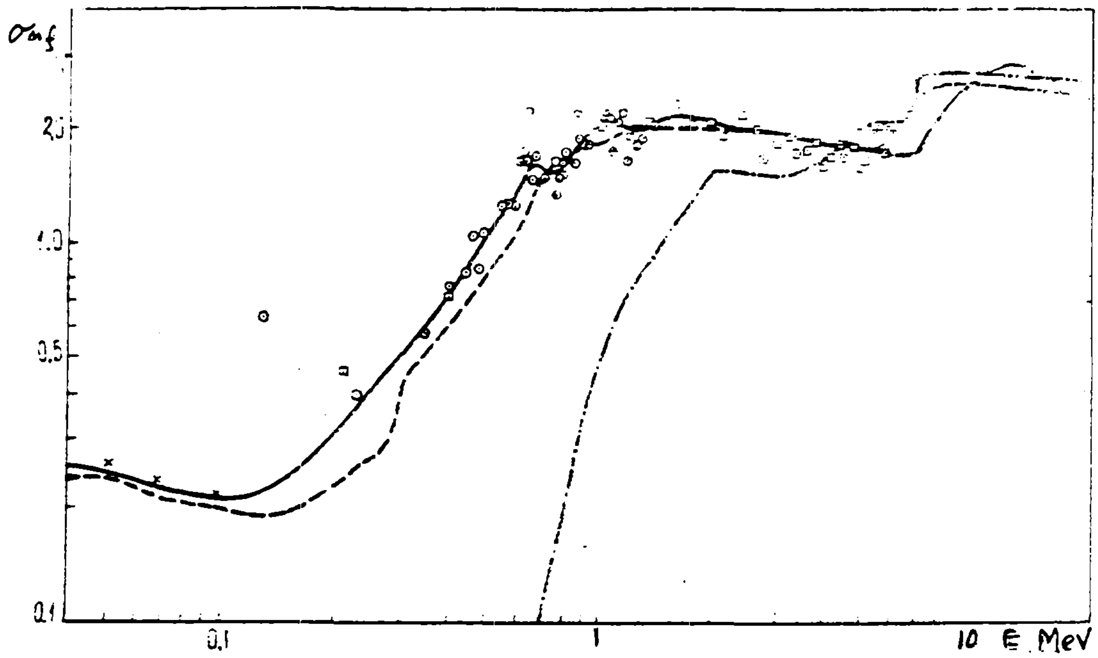

Fig. 1. Comparison of σ_{nf} evaluations with experimental data. Present work : , Ref. [9] -·-·-·- and [10] ------ Experimental data: [2] - x ; [5, 8] - □ ; [6] - ⊙.

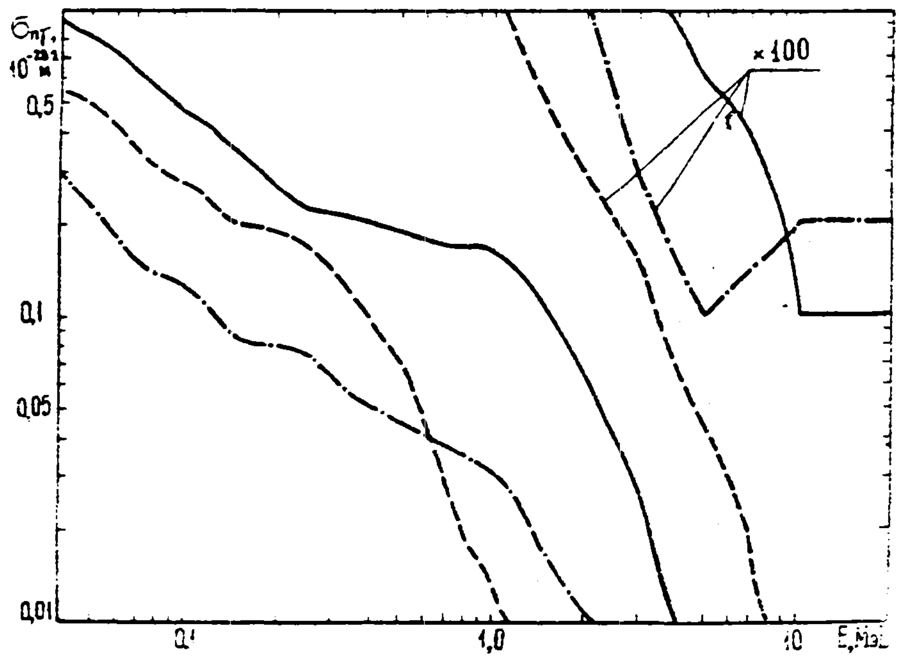

Fig. 2. Comparison of various evaluations of $\sigma_{n\gamma}$ for ^{242}Cm. Legend (See Fig. 1).

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Submitted for publication 10 September 1988

ANALYSIS OF THE ^{237}Np FISSION CROSS-SECTIONS AND THE (n,xn) REACTIONS

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ABSTRACT

Experimental and evaluated cross-section data on fission, (n,3n) and (n2n) reactions leading to the short-lived state of the ^{236}Np nucleus is analyzed using a self-consistent statistical approach. Integral and differential (n,2n) reaction data are compared. Earlier evaluations appear to be inconsistent with recent experimental data.

In order to evaluate the accumulation of ^{232}U in spent fuel from nuclear reactors, it is necessary to have a fairly accurate knowledge of certain nuclear physics constants. Of particular importance is the cross-section for the $^{237}Np(n,2n)$ reaction which produces short-lived $^{236}Np^{s}$ and the long-lived $^{236}Np^{l}$ states of the ^{236}Np isotope with the half-lives of 22.5 hours and 1.55 x 10^5 years respectively [1]. The available experimental cross-section data for the $^{237}Np(n,2n)^{236}Np^{s}$ reaction [2-7] do not cover the whole neutron energy range of 6.8-20 MeV which is of interest. For the $^{237}Np(n,2n)^{236}Np^{l}$ reaction, there are no other data apart from the isomeric ratio, r, of the $^{236}Np^{l}$ and ^{236}Np yields for 14 MeV neutrons. Therefore, the existing evaluations of the cross-section σ^{s}_{n2n} are based on model calculations of the σ_{n2n} cross-section, and the σ^{s}_{n2n} cross-section is determined from $\sigma_{n2n}/(1 + r)$ on the assumption that r does not depend on the energy of the incident neutron. As shown in Refs [8 and 9], the latter assumption is not justified. Moreover the model calculations for the cross-section σ_{n2n} have the disadvantage that the fission cross-section σ_{nf} is used in these calculations only as a parameter.

In view of the above circumstances and in view of the appearance of new experimental fission cross-sections data which differ significantly from previous evaluations [10 and 11] it is necessary to establish a consistent analysis of the latest experimental fission cross-sections data , data on the $^{237}Np(n,2n)^{236}Np^{s}$ reaction and on the isomeric ratio.

The absolute value of σ^{s}_{n2n} can be obtained by normalizing the energy dependence σ^{s}_{n2n} [10 and 12] to the experimentally measured integral cross-section for the fission spectrum $<\sigma^{s}_{n2n}>$. Therefore, it is also necessary to analyse the consistency between the differential and integral data on the cross-section for the $^{237}Np(n,2n)^{236}Np^{s}$ reaction obtained for the ^{235}U fission spectrum [13 and 14] (which differ by a factor of about 2.5) and for the ^{252}Cf spontaneous fission neutron spectrum [15].

EXPERIMENTAL DATA

Fission cross-section for ^{237}Np for neutrons above the (n,nf) reaction threshold. The experimental data in the energy range under consideration can be divided into two groups: absolute measurements [16] and measurements of the ratio of the ^{237}Np fission cross-section to the $^{235}U(\sigma^{7}_{nf}\sigma^{5}_{nf})$ [15-21] or $^{239}Pu(\sigma^{7}_{nf}/\sigma^{9}_{nf})$ [22] fission cross-sections . The results of the absolute measurements carried out using the time-correlated associated particle method for E_n = 14.7 MeV are significantly different from the results of the relative measurements carried out using the "threshold cross-section" method. In the region of the (n,nf) reaction threshold, the experimental data [17-19] are in good agreement with the data in Ref. [16]. The systematically higher values of the data in Ref. [20] as compared with the data in Refs. [18 and 19] is evidently associated with the absolutization of the ratio $\sigma^{7}_{nf}/\sigma^{5}_{nf}$ in Ref. [20], which was based on a comparison of the α-activities of the ^{237}Np and ^{235}U shells which is in itself very unreliable, since the half-life of ^{237}Np is measured only in one reference. The higher levels in Ref. [22] as compared with Refs [18 and 19] may, to some extent, be attributed to the fact that for the absolutization of the cross-sections for the $\sigma^{7}_{nf}/\sigma^{9}_{nf}$ ratio, data on the cross-section σ^{9}_{nf} from Ref. [23] were used.

Thus, in the data given in Refs [16-22], there are discrepancies both between the relative measurements of the different authors as well as between the absolute and relative data normalized to the cross-section σ^5_{nf} [10]. In the latter case the discrepancy is approximately equal to the value of σ^5_{n2n} for E_n = 14.7 MeV. The situation is complicated by the fact that the energy dependence of the cross-section σ^7_{nf} from the data in Ref. [19], covering the whole energy range of interest to us, shows that the (n,2nf) reaction makes an extremely small contribution to the fission cross-section studied which is not consistent with the isotopic fissibility dependence of neptunium isotopes [24]. These discrepancies may be associated with experimental errors in the measurement of the $\sigma^7_{nf}/\sigma^5_{nf}$ ratio and with the fact that the evaluation of σ^5_{nf} in the ENDF/B-V library [10] is used to obtain the cross-section σ^7_{nf} for E_n > 14 MeV.

In order to resolve the contradictions between the data of the different authors on the cross-section σ^7_{nf} for E_n > 14 MeV, let us turn to the data in Refs [25-27]. The measurement of the energy dependence of the fission cross-section in the 9-22 MeV range is reported in Ref. [25]. When these results are normalized to the data in Ref. [16] at E_n = 14.7 MeV, the data for $E_n \leq$ 14 MeV agree with the data in Ref. [19] and for E_n > 14 MeV they show that the (n,2nf) reaction makes a significant contribution to the observed fission cross-section . In Ref. [26] the fission cross-section is measured in the 5-22 MeV range; however, these data are normalized to the value of σ^7_{nf}, equal to 1.62 b (E_n = 3.4 MeV) . Renormalization of the data in Ref. [26], on which the ENDF/B-V [10] and KEDAK-4 [11] evaluations are based, to the value of $\sigma^7_{nf}(E_n$ = 3.4 MeV) equal to 1.56 b [19] does not significantly change the cross-sections in the high neutron energy region, and after normalization of these data to the data at E_n = 14.7 MeV [16], they more or less agree with the data for E_n > 9 MeV [25]. The data in Ref. [27] are not taken into account since they are twice renormalized in Refs. [25 and 26] in order to improve the fission fragment recording efficiency.

Thus, as reference values for $E_n \leq 14$ MeV we have selected data from Refs [17-19, 25 and 26] and for $E_n > 14$ MeV, we have selected data from Ref. [16] and renormalized data from Refs [25 and 26] (Fig. 1).

Cross-section for the $^{237}Np(n,2n)^{236}Np^2$ reaction. The measurement of this cross-section in the 13.8-15 MeV energy range was reported in Refs [2-6] and in the threshold region at E_n = 7.10 MeV in Refs [5 and 7]. All the measurements were made using the activation method by recording the α-activity of the ^{236}Pu nuclei. They differ only in the methods used to determine the neutron flux. In Refs [3, 4 and 7] the flux was measured relative to the $^{27}Al(n,\alpha)$ reaction and was also monitored [7] with respect to the $^{238}U(n,f)$ and $^{238}U(n,2n)$ reactions. In Refs [4 and 6], one of the methods used to determine the flux involved evaluating the accumulation of ^{97}Zr nuclei during fission of ^{237}Np. However the use of the fission cross-section, which was 10% higher than the data in Ref. [16], resulted in an overestimation of the $\sigma^s_{n,2n}$ cross-section. Therefore, the data obtained in this way in Ref. [4] were not taken into account. The data which resulted from the measurement in which the flux was determined with respect to the $^{238}U(n,f)$ and $^{237}Np(n,f)$ reactions [6] need to be renormalized to the corresponding cross-sections given in Ref. [16]. As a result, the difference in the cross-sections obtained using the two methods of determining the neutron flux [6], was reduced from 5 to 1%. The value of $\sigma^s_{n,2n}$ obtained from measurements of the γ-activity of ^{236}U [6], is 15% lower than the data in Refs [3-6] for the corresponding energy and therefore we will not take it into account.

In the neutron energy region 10-13.8 MeV there are no neutron reaction data available. Information on the $\sigma^2_{n,2n}$ cross-section may be derived from the measurements results of the cross-sections for the $^{235}U(t,2n)^{236}Np^s$ and $^{236}U(d,2n)^{236}Np^s$ [28] reactions. By assuming that the probability of two neutrons being emitted is not dependent upon the way in which the compound nucleus is formed, the reaction cross-section $\sigma^w(n,2n)$ may take the form [28]:

$$\sigma s_{n2n} = [\sigma^7_{nf}/\sigma_{t(d)f}]\sigma^s_{t(d)2n} \quad (1)$$

In Ref. [28], data from Ref. [26] were used to determine the σ'_{nf} cross-section; as a result, $\sigma^s_{n,2n}$ was over-valued. In this work the calculated σ_{nf} cross-section was used to calculate $\sigma^s_{n,2n}$ in accordance with this expression. Below we discuss the agreement of the data obtained in this way with the results in Refs [2-7] and the present work.

Isomeric ratio in the $^{237}Np(n,2n)$ reaction. In Ref. [29] the isomeric ratio r = 0.35 was obtained in a thermonuclear explosion at an average neutron energy of 14 MeV. In Ref. [30] the measurements r = 0.41 in the $^{237}Np(\gamma,n)$ reaction are given for an excitation energy corresponding to E_n = 9.6 MeV. From these data it follows that for E_n = 9.6-14 MeV, $r(E_n)$ should decrease as the neutron energy increases. This tendency is confirmed by data from Ref. [31], obtained during the study of the $^{238}U(d,4n)$ reaction at E_d = 21 MeV, which showed that the states of the ^{236}Np compound nucleus with spin J = 1 are approximately seven times more frequent than for states with spin J = 6. This means that $r(E_n \approx 19$ MeV) $\approx$ 0.14. No direct or indirect information on cross-sections for the interaction of neutrons with the ^{237}Np nucleus is available.

CALCULATION OF THE CROSS-SECTIONS FOR FISSION AND FOR (N,XN) REACTIONS.

The Hauser-Feshbach statistical theory was used to calculate the cross-sections for the (n,f) and (n,xn) reactions, taking into account conservation of spin and parity for all nuclear reaction cascades [32].

In view of the lack of experimental data which would make it possible to determine the optical potential parameters for ^{237}Np, the neutron attachment coefficients necessary for the statistical calculations were calculated with the potential [33] for ^{238}U. This approximation is justified on the basis of the weak isotopic dependence of the neutron absorption cross-section in the energy range studied.

The level density in the neutron and fissile channels $\rho_{n(f)}(U,J)$ was calculated in the following way. For excitation energies U, which is smaller than energy $U_{n(f)} = (10.7 - m\Delta_{n(f)}) - 0.028A$ MeV, where m is 0,1,2 for even-even, odd-even and odd-odd nuclei respectively, A is the mass number, $\Delta_{n(f)}$ is the correlation function in the (strongly deformed) ground state, $\rho_{n(f)}(U,J)$ is determined using the constant temperature model [34]. In the neutron channel

$$\rho_n = \frac{1}{T_n} exp\left(\frac{U+m\Delta_n}{T_n}\right)\frac{2J+1}{2\sigma^2}\, exp\left[-\frac{J(J+1)}{2\sigma^2}\right], \qquad (2)$$

where $\Delta_n = 12/\sqrt{A}$ MeV; $T_n = 0.385$ MeV. The parameter for spin dependence of σ^2 at excitation energies $U < U_x$, where $U_x = 1.2-0.3\ (m + \delta_{2m})$ MeV, is the boundary of reliable identification of the spin levels and δ_{2m} is the Kronecker δ-symbol determined by the expression $\sigma^2_n = 0.156A - 26.76$. For $U > U_x$, σ^2 is determined by the linear extrapolation between σ_n and $\sigma^2 F\ t(U_n)$. Here $F_\perp$ is the perpendicular inertia moment and $t(U_n)$ is the thermodynamic temperature at excitation energy U_n.

In the fissile channel the level density is determined from the expression:

$$\rho_f(U,J) = \frac{R}{T_f} exp\left(\frac{U+m\Delta_f+\delta_f}{T_f}\right)\frac{1}{2\sigma_f^2}\sum_{K=-J}^{J} exp(-K^2/2K_0^2)\ \ exp\left[-\frac{J(J+1)}{2\sigma_{\perp f}^2}\right].$$

Here $K^2_0 = (1/\sigma^2_{\parallel f} - 1/\sigma^2_{\perp f})$, where $\sigma^2_{\parallel f} = F_{\parallel f}t$ ($F_{\parallel f}(F_{11f}$ is the parallel inertia moment). The parameter T_f is determined from the condition

$$T_f = \left\{\frac{d}{dU}\left[\ln \rho_f(U)\right]_{U=U_f}\right\}^{-1},$$

where $\rho_f = \sigma^2_{\perp f}\,\omega_f(U)/\sqrt{2\pi}\,\sigma_{\parallel f}$. The δ_f parameter is determined from the continuity condition of the level density $\rho_f(U)$ for the excitation energy $U = U_f$ (the corresponding parameter in the neutron channel equals zero): $(1/T_f)exp\left[(U_f + m\Delta_f + \delta_f)/T_f\right] \stackrel{!}{=} \rho_f(U_f)$.

The coefficient R reflects the effect of the saddle configuration asymmetry on the level density. For the internal hump where there is axial and mirror asymmetry, $R = 2\sqrt{2\pi}\sigma_{\parallel f}$; for the external hump only the mirror symmetry is violated and R = 2 [35]. The density of the internal states $\omega_{n(f)}(U)$ and the spin dependence parameters σ^2_{11} and σ^2 are determined from the relationships given in Ref. [36], and the correlation function $\Delta_f = \Delta_m + 0.08$ MeV is determined from the description of the fission cross-section energy dependence in the first plateau region. The shell corrections δW_f for the internal and external humps are taken from Ref. [23]. The main level density parameter $a_{f(n)}$ is determined from the relationships in Ref. [36] and its asymptotic value $a_{f(n)}$ from the expression given in Ref. [34] $a_{f(n)} = 0.473A - 1.619 \times 10^{-3}A^2$. The value of the parameters T_f and δ_f for the internal A and external B humps are: $T^A_f = 0.38$ Mev, $T^B_f = 0.39$ Mev, $\delta^A_f = 0.001$, $\delta^B_f + 0.24$.

For excitation energies $U > U_{n(f)}$ $\rho_{n(f)}(U,J)$ is determined from the relàtionships of the superfluid model [36]. A more detailed model for calculating the level density and the fissile channel permeability, together with the necessary parameters are described in Refs [34, 36, 37], and the method used to calculate the radiation widths is described in Ref. [34].

Let us assume that the main parameter of the pre-equilibrium decay model, the two quasi-particle interaction matrix element $M^2 = 10/A^3$, taken from the description of the spectra for inelastically scattered neutrons for the ^{238}U nucleus [38], can also be used in the case of ^{237}Np. This assumption fixes the behavior of the "first chance" fission cross-section. The barrier parameters of the compound nucleus ^{237}Np, which is fissile in the (n,nf) reaction, are taken from the description of the experimental data for the cross-section σ_{nf} below the (n,2nf) reaction threshold, and the barriers of the ^{236}Np nucleus are taken from the description of σ_{nf} above the (n,2nf) reaction threshold. Comparison of the experimental and calculated data for the cross-section σ_{nf} is given in Fig. 1, showing the "first chance" fission cross-section. The energy dependence of the contribution of the "first chance" fission cross-section σ^1_{nf} to the observed fission cross-section σ_{nf}, i.e. $\alpha = \sigma^1_{nf}/\sigma_{nf}$ can be compared with the data for α obtained from the analysis of the dependence of the total average energy of the prompt gamma radiation emitted during fission on the average number of prompt fission neutrons [30 and 40]. As can be seen from Fig. 2, these data agree well with our evaluation of α. The cross-section $\sigma_{n2n} = \sigma^1_{n2n} + \sigma^s_{n2n}$ for the ^{237}Np(n,2n) reaction, calculated at the same time as the fission cross-section, agrees with data from Refs [2-6] (Fig. 3(a)) provided that the isomeric ratio at E_n = 14-15 MeV is virtually constant and equal to 0.35 [29]. When $E_n \leq 13.5$ MeV our cross-section differs significantly from the evaluations in the ENDL [41], KEDAK-4 and ENDF/B-V [30] libraries and when $E_n > 15$ MeV it differs from the evaluations in the ENDL and ENDF/B-V libraries. All the evaluations for the σ_{n2n} cross-section in the 14-15 MeV energy range agree (with the exception of the ENDF/B-V evaluation) because they are normalized to the experimental data for the cross-section σ^s_{n2n} taking into account the isomeric ratio [29]. In the 9-13 MeV energy range the discrepancy between the ENDL evaluation and the KEDAK-4 evaluation may be linked to the fact that the ENDL evaluation for the fission cross-section is based on the data in Ref. [19], and the KEDAK evaluation is based on data in Ref. [26] (see Fig. 1). The evaluation of the fission cross-section in the ENDF/B-V library is also based on the data in Ref. [26]; however, the evaluation for the cross-section σ_{n2n} is significantly lower than the KEDAK-4 evaluation. This is related to the fact that in the ENDF/B-V library, the cross-section for the ^{237}Np(n,2n) reaction is determined as $\sigma_{n2n} = 1.35\ \sigma^s_{n2n}$ and σ^s_{n2n} by normalization of the dependence $\sigma^s_{n2n}(E_n)$ [12] on the integral data for $\langle\sigma^s_{n2n}\rangle_U$ [13]. The calculated curve for σ^s_{n2n} in Ref. [30] is lower than the data of our work and the data of Ref. [7]. The differences in the cross-sections for the (n,3n) reactions are still more significant. They are caused by differences both in the fission cross-section evaluations and in the cross-sections for formation of the compound nucleus (Fig. 3(b)).

Now let us examine the process for obtaining $\sigma^{s}_{n2n}(E_n)$ from the calculated dependence $\sigma_{n2n}(E_n)$ as $\sigma^{s}_{n2n}(E_n)=\sigma_{n2n}(E_n)/[1+r(E_n)]$. In order to determine $r(E_n)$ the results of the calculations in Ref. [9] were used where the isomeric ratio is obtained by simulating the low-lying level structure of the ^{236}Np nucleus. The results of Ref. [9] agree well with the data from Ref [8], obtained using a method which is very different from that used in Ref. [9], but differ significantly from the evaluation of $r(E_n)$ in Ref. [30], based essentially on the data from Ref. [5] which are 30% too low and the consequent tendency in Refs [29-31] for $r(E_n)$ to decrease as the energy increases. The evaluation of $\sigma^{s}_{n2n}(E_n)$ in the present work agrees well with the data from Refs [2-7] whereas the experimental data in Ref. [28], even after the renormalization described above, do not agree well with the data in Refs [2-6] and the present evaluation. When $E_n < 7.5$ MeV the calculated curve is lower than the experimental data in Ref. [7], however, as can be seen from Refs. [9] the excitation of the residual of ^{236}Np nucleus is here so small that statistical modelling of the gamma transitions becomes scarcely justified, therefore, in this energy range we will determine σ^{s}_{n2n} by interpolation of the values given in Ref. [7] when E_n equals 7.09 and 7.47 Mev. The evaluation for σ^{s}_{n2n} in KEDAK-4 obtained with the assumption of the independence of the isomeric ratio on energy i.e. $r(E_n) = 0.38$ [3] is higher than the data in Refs. [5 and 7] and the use of $r(E_n)$ [9] only intensifies the differences. The evaluation in Ref. [30] is significantly lower than the experimental data [5 and 7] and this fact is associated with the evaluation of $r(E_n)$ (Fig. 4).

COMPARISON OF THE INTEGRAL AND DIFFERENTIAL DATA FOR THE CROSS-SECTION OF THE REACTION $^{237}Np\ (n, 2n)^{236}Np^{s}$

The integral cross-section for the reaction $^{237}Np\ (n,2n)^{236}Np^{s}$ averaged over the fission neutron spectrum is directly involved in calculations of the ^{232}U accumulation in reactor fuel. This can be represented in the form:

$$<\sigma^{s}_{n2n}> = \int_{6,8}^{20} \sigma^{s}_{n2n}(E_n)\chi(E_n)dE \Big/ \int_{0}^{20} \chi(E_n)dE_n ,$$

where $\chi(E_n)$ is the fission neutron spectrum. In Refs [13 and 14] the values 1.05 and 2.4 mb were obtained respectively for $< \sigma^s_{n2n} >_U$. The difference between these values is significantly greater than the errors ascribed to them by the authors. Essentially in Ref. [13] the ratio of ^{236}Pu and ^{238}Pu concentrations in fuel was measured by comparing the α activities and the cross-section $<\sigma^s_{n2n}>_U$ was determined by solving the kinetic equations. In Ref. [14] the value of $<\sigma^s_{n2n}>_U$, obtained by averaging the cross-section $\sigma^s_{n2n}(E_n)$ [42] over the spectrum [43], was used to evaluate the dependence of accumulation of ^{236}Pu in the fuel on a result of burnup. If these data are averaged over the fission spectrum [44] which was used to simulate the reactor neutron spectrum in Ref. [13], the cross-section $<\sigma^s_{n2n}>_U$ [14] increases to 2.67 mb. The curves for $\sigma^s_{n2n}(E)_n$ [10] and [42] and the corresponding data for $< \sigma^s_{n2n} >_U$ [13] and [14] are shown in Fig. 5. The result of averaging the dependence for $\sigma^s_{n2n}(E_n)$ [30] virtually coincides with the data in Ref. [13]. As has already been pointed out, the curves in Refs [10 and 42] do not agree with the data in Ref. [7] for $\sigma^s_{n2n}(E_n)$, however, in Ref. [14], it is shown that $<\sigma^s_{n2n}>_U$ = 2.43 mb which gives a higher evaluation of the dependence of accumulation of ^{236}Pu on burnup, i.e. there is a possibility of reducing the value $<\sigma^s_{n2n} >^U$ by 20%. This tendency corresponds to the dependence $\sigma^s_{n2n}(E_n)$ obtained in the present paper, its averaging over the spectra [43 and 44] gives 2.02 and 1.82 mb respectively and taking into account the modification of the calculated dependence $\sigma^s_{n2n}(E_n)$ for $_n \leq 7.5$ MeV, it gives 2.17 and 1.97 mb.

It is interesting to compare our data on the $\sigma^s_{n2n}(E_n)$ dependence with the measurements which used the ^{252}Cf spontaneous fission neutron spectrum. Using the recommendations in Ref. [45] for the cross-section $<\sigma^s_{n2n}>_{Cf}$ in the ratio $\chi(E_n)$ for ^{252}Cf we obtain the values 3.23 and 3.47 MeV, taking into account the modification in $\sigma^s_{n2n}(E_n)$ for $E_n \leq 7.5$ MeV i.e. values less than $< \sigma^s_{n2n} >_{Cf}$ = 4.66 ± 0.47 mb from Ref. [15].

Thus we can conclude that our data on the $\sigma^s_{n2n}(E_n)$ cross-section agree with the recommendations in Ref. [14] but do not agree well with the data in Ref. [15]. In order to obtain agreement with them, the value of $\sigma^s_{n2n}(E_n)$ close to the threshold would have to be significantly increased, at least to the level of the curve in Ref. [42], averaging of which over the ^{252}Cf spontaneous fission neutron spectrum gives 4.24 mb.

Thus, $\langle\sigma^s_{n2n}\rangle_U$ lies in the range of 1.97-2.43 mb. Discrepancies between measurements of the cross-section $\langle\sigma^s_{n2n}\rangle_{cf}$ [15] and the evaluation for the dependence $\sigma^s_{n2n}(E_n)$ in the present work may be caused by measurement errors and inaccurate approximations of the ^{252}Cf spontaneous fission neutron spectrum [45].

An analysis of the experimental data on the cross-sections and the ^{237}Np (n, 2n)^{236}Np^s reactions makes it possible to evaluate the energy dependence of the fission cross-section above the threshold of the (n,nf) reaction. Within the framework of the consistent optical-statistical approach, cross-sections were also obtained for the reactions (n,2n) and (n,3n).

The differences found between the measurements for $\langle\sigma^s_{n2n}\rangle_{cf}$ [15] on the one hand, and the data in Ref. [14] for $\langle\sigma^s_{n2n}\rangle_U$ and the evaluation in this work on the other hand, leaves the problem of the consistency of integral and differential data on cross-sections for the reaction ^{237}Np (n,2n) unresolved.

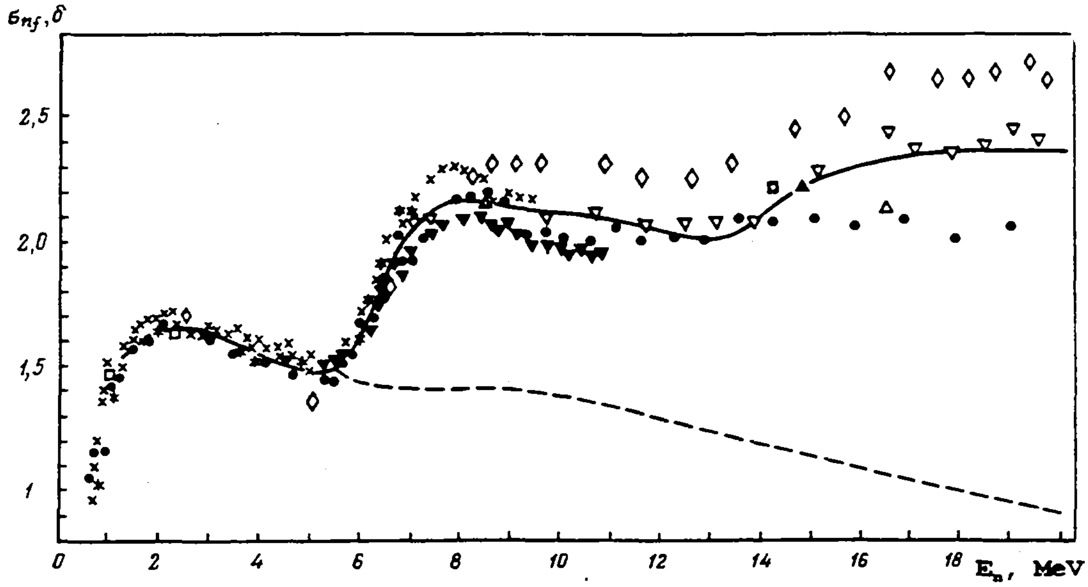

Fig. 1. Neutron fission cross-section for ^{237}Np. Continuous curve - calculation; broken curve - "first chance" fission cross-section.
Experimental data from the following references:
▲ - [15], △ - [17], ▼ - [18], ● - [19], x - [20],
□ - [21], ★ - [22], ▽ - [25], ◇ - [26].

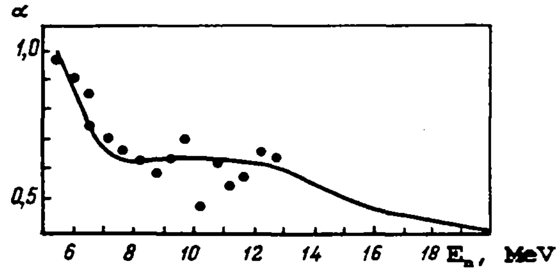

Fig. 2. Dependence of "first chance" contribution on the total fission cross-section for ^{237}Np. Continuous curve - calculation; ● - experimental data [39 and 40].

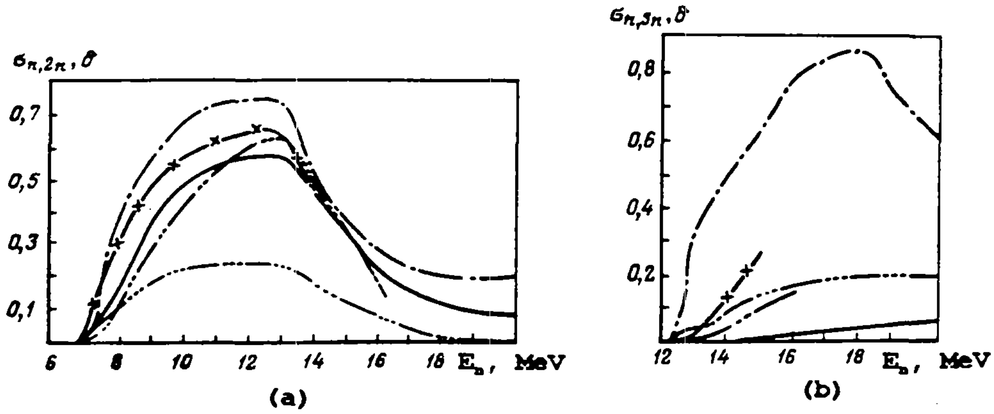

Fig. 3. Cross-section for the reactions: (a) - ^{237}Np(n,2n), (b) - ^{237}Np(n,3n). Calculation:——— this work; x—x—x KEDAK-4 [42];.— . — . — . ENDL [41]; —. . — . . — [30]; —. . . — . . . — ENDF/B-V.

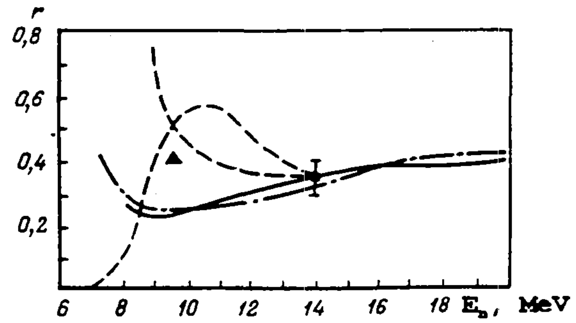

Fig. 4. Energy dependence of the isomeric ratio in the ^{237}Np(n,2n) reaction. Calculation: [9]; —. — . — [8]; - - - [30]; Experimental data: ● - [29]; ▲ - value taken from reference [30].

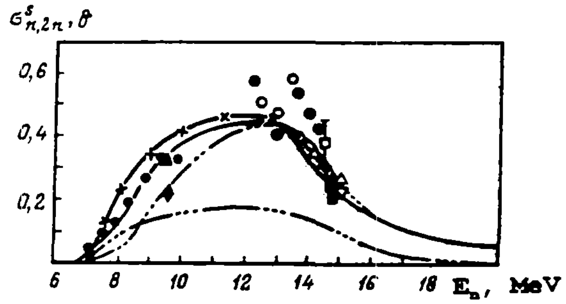

Fig. 5. ^{237}Np(n,2n) reaction cross-section. Calculation: this work;-x-x- KEDAK-4 [42]; — . — . — ENDL [41]; — . . — . . —[30]; — . . . — . . . —ENDF/B-V. Experimental data: □ - [2]; ▲ - [3]; ▼ - [4]; ▲ - [5]; ♦ - renormalized data from Ref. [30]; ■ - [6]; ● - [7]; O - [28].

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Submitted for publication 17 July 1986

COMPARISON BETWEEN CALCULATED AND EXPERIMENTAL NEUTRON DATA AND GROUP CONSTANTS FOR ^{238}U IN THE UNRESOLVED RESONANCE REGION

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ABSTRACT

The available experimental data on the transmission and capture self-indication functions for the unresolved resonance region for ^{238}U and the results of the latest radiative capture cross-section measurements are compared with two sets of average resonance parameter evaluations ([4], [6, 17]). It is concluded that the experimental data are described equally well by both sets. It is suggested that the level density dependence on parity assumed in the evaluation of Refs [6, 17] has no theoretical validity. The group evaluations obtained on the basis of the average resonance parameters [4]) are comparable to the ABBN-78 tabulated data. The errors of the results are discussed.

The study of the ^{238}U neutron cross-sections is of practical value since this nuclide is a component of nuclear fuel. There have been attempts to describe the numerous experiments on ^{238}U in the framework of a unified theoretical approach. The unresolved resonance region has plenty of room for experimental and theoretical studies - for the further refinement of the radiative capture and inelastic scattering cross-sections, and of resonance self-shielding factors and their temperature dependences. It is important to analyse all experimental data together and to perform group constant evaluations based on calculations in the framework of a unified theoretical model which is utilized for the analysis.

Unlike the total and partial neutron cross-sections, the resonance self-shielding factors are not measured directly but are obtained from the analysis of the transmission and self-indication functions. This class of experiments is geared specifically to the study of the resonance structure of the neutron cross-section. Theoretical analysis of such data, obtained usually at room temperature, enables the resulting evaluations of the group constants to be extended to the region of high temperatures, which are characteristic of fast power reactor cores. This is how the problem of measuring he transmission and self-indication functions at high temperature is resolved. Analysis without theoretical model of these experiments (i.e., evaluation of the self-shielding factors by integration with respect to the thickness of the sample-filter) is not a fruitful exercise at the present time.

In this paper our purpose is to analyze within the framework of a calculational and theoretical model the experimental transmission and self-indication function data for the capture reaction in the unresolved resonance region of ^{238}U. Such experiments have been carried out at the Institute of Physics and Power Engineering, at the Joint Institute of Nuclear Research as well as abroad.

BRIEF DESCRIPTION OF THE EXPERIMENTS

Measurements of V.N. Kononov and co-workers [1-3]

The transmission functions were measured with a time-of-flight neutron spectrometer in the EhG-1 accelerator with a resolution of about 7 ns/m. A ^{6}Li-glass detector (glass thickness 0.8 mm) was used for neutron counting. The self-indication function of the radiative capture process was measured with a gamma ray scintillation detector. The metallic ^{238}U sample had a thickness of 6.47 nuclei/kb, the ^{235}U impurity being not more than 3.5×10^{-3}%. The metallic uranium filters samples were 9.1, 23.7, 47.4, 70.7, 94.3 and 190 nuclei/kb thick, ensuring a variation range within an order of magnitude for neutron flux attenuation. The instrumentation enabled the measurements to be carried out in the energy region from a few to hundreds of kiloelectron-volts. The authors noted the problem presented by the background at low neutron energies.

Measurements of A.A. Van'kov and co-workers (Institute of Physics and Power Engineering, FEI) [4, 5]

At the Neutron Physics Laboratory of the Joint Institute for Nuclear Research a device was designed for the measurement of transmission functions over a wide neutron energy range using the time-of-flight technique. Collaborators from FEI, from the Central Institute of Nuclear Research (German Democratic Republic) and the Joint Institute of Nuclear Research [5] participated in the work. The pulsed sources was the IBR reactor operating in pulsed mode (burst width a few tens of microseconds) and in the so-called booster mode (with an electron accelerator) with a microsecond burst, was used as the neutron source.

The microsecond technique was justified by the high power of the source and the large flight path (up to 1000 m). The moderate energy resolution suited the problem of measuring the transmission function over a fairly wide energy range comparable to the range covered by the ABBN group constants [6]. Banks of ^{3}He counters and liquid scintillators were used as highly efficient neutron detectors, which made it possible to measure the transmission functions for attenuations of the incident neutron flux by four orders of magnitude. The background was measured with the help of resonance filters. The neutron energy region studied was 1-100 keV. The set of filter samples had thicknesses starting from 0.5 mm and then doubled up to 128 mm. The sample consisted of depleted metallic ^{238}U; the thickness of 1 mm corresponded to 0.00477 nuclei/b with an error of less than 1%. The measurement error for transmission was within 1-3% for thicknesses up to 8 mm, 5-8% for the medium thicknesses and 10-20% for the maximum thickness. Reference [5] deals with the temperature dependence of transmissions. The measurements at room temperature were repeated a number of times subsequently in order to reduce the errors.

Measurements of V.V. Filippov (FEI) [7, 8]

The measurements were performed in an EhG-2.5 Van de Graaff electrostatic generator using the $T(p,n)^3He$ reaction. Reliable data could therefore be obtained at energies above 3-40 keV. Although the author reports data at lower energies (up to 4 keV, however, with reservations about their reliability), these data are not informative because of the high uncertainty of the resolution function. A bank of boron counters in paraffin were used for neutron detection. Among the distorting factors, the author mentions the influence of background. Only data having a background value which did not exceeding 40% were selected for data analysis. For the existing background condition, the use of the metallic samples available for the experiment, enabled transmissions to be measured with neutron flux attenuations up to two order of magnitude.

Measurements of R. Block and co-workers [9, 10]

Measurements using ^{238}U samples were carried out at the Renselaer Polytechnic Institute (USA) in 1973 [9]. The purpose of the experiment was to determine the transmission and self-indication functions for the capture reaction in the energy range of approximately 100 eV-100 keV. The time-of-flight technique was used with a pulsed neutron source consisting of the target of a linear electron accelerator. Neutrons were recorded with a liquid scintillation detector and a NaI scintillator with a ^{10}B indicator. The electron pulse width was 1 ns and the path length 25-28 m. The thickness of the metallic filter samples varied within 0.1-1 mean-free-paths . This means that the initial sector of the transmission curve was measured. An important feature of the experiment was that the filter sample temperature was varied. The measurements were performed at three temperatures - at room temperature, cooled by liquid nitrogen and heated to 970 K. In the self-indication measurements the authors used a metallic indicator sample with a thickness of 0.00379 nuclei/b, i.e. about 0.8 mm. Unfortunately, the measurements of the self-indication function were unreliable, since no allowance was made for a satisfactory account of the different statistical sources of errors, such as the influence of background, fluctuation of the resolution and intensity and lastly the effect of multiple scattering in the indicator sample. Results of a subsequent analysis of part of the old measurement are described in Ref. [10]. The corresponding self-indication function data obtained at room temperature have been included in the present paper for comparison.

Measurements of de Saussure and co-workers [11]

The capture self-indication function for ^{238}U at 4-10 keV was measured at the Oak Ridge National Laboratory (USA). The measurement method was similar to that used at the Renselaer Polytechnic Institute (time-of-flight spectrometry technique and linear electron accelerator source). The thickness of the metallic indicator sample was 0.0031 nuclei/b and a flight path of 40 m. The filter sample thicknesses were 0.0038, 0.0124, 0.0341 and 0.0521 nuclei/b. As a result of the measurements, corrections were made for multiple scattering in the sample (up to 3% for the largest filter thickness). It should be noted that the background was responsible for an appreciable uncertainty in the final results. Unfortunately, the data were obtained for a narrow energy range, namely 4-10 keV.

In the same laboratory Poenitz and co-workers [12] measured the total and partial cross-sections of heavy nuclei employing a neutron gènerator with lithium and tritium targets [12]. A quasi-monoenergetic source and time-of-flight spectrometry were used in combination in order to take correct account of the background. In particular, transmissions were measured in samples at a neutron energy of 60 keV.

THE ACCURACY NEEDED FOR MEASURED AND CALCULATED ^{238}U NEUTRON DATA IN THE LIGHT OF REACTOR CALCULATION REQUIREMENTS

Nuclear data evaluators proceed from the specific accuracy requirements for fast reactor calculations - i.e., the error in k_{eff} should not exceed 1%, and in the breeding ratio 2%. In reality, the problem of design requirements is more complex and involves an extensive list of parameters relating to the economic, physical and safety characteristics (in particular, a built-in excess reactivity and a non-uniform power generation coefficient). It follows from all these requirements that the ^{238}U group data should be known to an accuracy of better than 2% for the σ_γ cross-section and 1% for the resonance self-shielding factors of the resonance capture cross-section in the unresolved resonance region, and should be better than 5% for the transport cross-section and the corresponding self-shielding factors [13, 14]. The accuracy requirements for the transport cross-section come up in the analysis of the calculated uncertainty of the power density profile. Thus, in order to satisfy the above requirements for the resonance self-shielding factors and the transport cross-section, one has to ensure the measuring accuracy of the integrals over the thickness as a function of T(n) and $T_\gamma(n)$ and also as a function of (1 - T(n)) at small thicknesses of n. Since systematic errors are possible in these measurements, it is desirable to ensure 1% accuracy in the measurements for each thickness and 3-5% accuracy in the value of (1 - T(n)) for small thicknesses.

THE THEORETICAL MODEL AND ITS PARAMETERS

In the unresolved resonance region, the simplest average functional cross-sections are those that can be expressed in terms of the average resonance parameters using the Hauser-Feshbach formalism. The corresponding formulae can be obtained easily (for low energies) by simple averaging of the Breit-Wigner formulae. The averaging procedures are described, for example, in Ref. [15].

The cross-section for a reaction of type x is determined by the formula

$$\langle \sigma_x \rangle = 2\pi^2 \lambda\!\!\!^{-2} \sum_{J\pi} g(J) \frac{\bar{\Gamma}_n^J \bar{\Gamma}_x^J}{\bar{\Gamma}^J \bar{D}^J} \langle F_{nx}^J \rangle \ ;$$

and the total cross-section by

$$\langle \sigma_t \rangle = \sigma_p + 2\pi^2 \lambda\!\!\!^{-2} \sum_{J\pi} g(J) \frac{\bar{\Gamma}_n^J}{\bar{D}^J} \ .$$

Here λ is the neutron wavelength, g(J) the statistical factor, J, π are the total moment and the parity of the compound nucleus, $\bar{\Gamma}^J_n$ is the average neutron width in the J state, $\bar{\Gamma}^J_x$ the average width by the x-type reaction in the J state, $\bar{\Gamma}^J$ the average total width in the J state, $\bar{D}^J$ the average level spacing in the J state, $\langle F^J_{nx} \rangle$ the so-called fluctuation factor and σ_p the potential scattering cross-section

$$\sigma_p = 4\pi \lambda\!\!\!^{-2} \sum_{\ell} (2\ell+1) \sin^2 \varphi_\ell \ ,$$

where φ_ℓ is the scattering phase equal to kR_o for s-neutrons (k being the wave number and R_o the potential scattering radius for s-neutrons). Thus, the parameters of any R-matrix model are $\bar{D}^J$, $\bar{\Gamma}^J_n$ (or the so-called strength functions $S^J_n = \bar{\Gamma}^J_{no}/\bar{D}^J$, where $\bar{\Gamma}^J_{no}$ is the reduced neutron width), $\bar{\Gamma}^J_x$ and the scattering radii R_ℓ for various orbital moments ℓ.

CALCULATIONAL METHOD

In the calculations of the cross-section parameters we used the R-matrix parametrization scheme in a single-level Breit-Wigner approximation, which is fully justified in the case of heavy even-even nuclei at energies between 100-200 keV. The problem of error introduced by the use of a single-level approximation was studied by comparing the results of the single-level and multi-level (in the Reich-Moore approximation) calculations. The difference in the average cross-sections did not exceed 0.5% and that for values of moments $\langle 1/\sigma^2_t \rangle$ at zero dilution was not above 4%, which is much lower than the error due to the uncertainty of such parameters as R_1 and S^{0}_{n}.

The cross-section parameters were calculated by modelling the energy dependence of the cross-sections using pseudo-resonances, whose parameters were obtained from the sequence of random numbers obeying the Porter-Thomas and Wigner distributions (Monte Carlo method). The methods of cross-section calculation and statistical analysis of experimental data are described in detail in Ref. [16].

AVERAGE RESONANCE PARAMETERS

Earlier we had obtained an evaluation of the average resonance parameters [4] from the results of a combined analysis of the average cross-sections and transmission function experiments [5]. That evaluation was aimed at obtaining a more reliable prediction of the resonance self-shielding factors for the ^{238}U cross-sections, while retaining the qualitative description of the average cross-sections. In the present work, we intended to verify how well one could describe the wider set of experimental data with these parameters, especially new data on the transmission and self-indication function data and the radiative capture cross-section [1-3]. Moreover, it is of interest to compare the obtained results with calculations using the parameters given in Refs [6, 17]. In this evaluation the debatable question is the dependence of level density on the parity of the compound nuclear state at a specified instant [18]. The evaluation of the average resonance parameters are compared in Table 1.

DISCUSSION OF THE RESULTS OF ANALYSIS

The authors carried out Monte Carlo calculations of all quantities measured - average total and partial cross-section, transmission functions $T(n) = 1/\Delta u \int_{\Delta u} exp[-\sigma_t(u)n]\, du$ and capture self-indication function $T_\gamma(n) = 1/\langle\sigma_\gamma\rangle \int_{\Delta u} \sigma_\gamma(u)\, exp[-\sigma_t(u)n]\, du$, where n is the thickness of the filter sample and u the lethargy variable. The experimental conditions described in Refs [1-4] (energy intervals of averaging and sample thicknesses) were reproduced in these calculations. At the same time, all the group constants defined in the ABBN system in the 4-100 keV region were calculated by the Monte Carlo method within the same calculational model. All calculations were performed for two separate evaluations of the average resonance parameters [4 and 6, 17] (see Table 1). Both evaluations included results of the analysis of experimental data for several different model representations. Moreover, an important point in evaluation [4] was that it took into account the experimental values of transmission for large thicknesses.

It can be seen from Fig. 1, which gives the calculation results for the transmission functions T(n), that the difference in the calculations for the largest of the thicknesses does not exceed 10% (this is comparable to the uncertainty in the measurement). Both calculations describe with equal validity the experimental data [1, 9, 12] for medium and large thicknesses. However, on the scale of Fig. 1, it is difficult to discern the actual value of the experimental points - for small sample thicknesses. The "envelope" of the $(-1/n)\ln(T(n,E))$ function is plotted in Fig. 2, where the quantity plotted along the vertical axis represents the "intersecting" self-shielded total cross-section. On this scale we can see the systematic deviations of the experimental points from Ref. [1] from the calculational results for thicknesses 4.7 and 9.7 nuclei/kb, deviations that are evidently due to the systematic measurement errors. We assume that the errors in this instance are such that the calculated curves lie within the range of these errors.

Figure 3 shows the self-indication functions for the capture reaction on the same scale as the transmission functions in Fig. 1. With regard to the calculations the comments made in the case of Fig. 1 also apply here. In the 12-100 keV region the experimental points from Ref. [2, 10] are described satisfactorily by the calculated curves if we disregard the difference for the largest thickness at lower energies, which seems to be associated with the systematic measurement errors (e.g., influence of the background with increasing thickness). In the 4-12 keV region the measurements in Ref. [10] (for a thickness of 15.5 nuclei/kb) and Ref. [11] (for 12.4, 34.1 and 52.1 nuclei/kb) show an irregular energy dependence, which is due to the fact that the averaging of the resonance structure at low energies was not sufficiently satisfactory. It is obvious that the calculation shows, in principle, a monotonic dependence. The evaluations of the fluctuations of calculated points based on nuclear statistics indicate that below 10 keV the irregularities revealed by the experiments are fully corroborated.

It should be noted that in Refs [4, 7-9, 12] the averaging intervals for the measured transmission functions were different from those in Ref. [1]. Therefore, a comparison of all those studies can be made by re-averaging the data of the different studies over the same wide intervals, that is, over the energy range of the ABBN groups [6]. Such a comparison has been made in Fig. 4 for the self-shielded total cross-section. It can be seen that calculations using the parameters from Refs [4, 6, 17] describe the whole set of experimental points equally satisfactorily. The transmission measurements for the smallest thicknesses (of the order of a millimeter) were carried out in Refs [1, 4, 9]. As was to be expected, the errors of measurement of the total cross-section for the smallest thicknesses are large.

In Fig. 5 we compare the experimental values of the radiative capture cross-section $\sigma_\gamma(E)$ for ^{238}U [3] with the corresponding calculated data. The comparison with the data of other authors is given in Ref. [3]. It is this study which is of interest since $\sigma_\gamma(E)$ was measured using the same methodology as the transmission and self-indication functions. We confined ourselves to comparing experiment with calculation up to 50 keV since analysis at higher energies requires a careful study of the influence of inelastic scattering and the energy dependence of the average resonance parameters. In the energy range under consideration we observe that the experimental points are described satisfactorily by calculation. The slightly higher value for the experimental points in comparison with calculation in the low-energy region can be attributed to the fact that sufficient allowance was not made for the effect of the multiple scattering of resonance neutrons in the sample [19].

Thus, we can state that a satisfactory description has been achieved of the experimental data for the transmission and self-indication functions of the capture reaction and capture cross-section for ^{238}U in the unresolved resonance region 4-50 keV. The difference between calculations using the evaluations of the average resonance parameters of Refs [4, 6, 17] does not exceed experimental errors.

GROUP CONSTANTS

In Ref [4] we presented some preliminary data on the evaluation of group constants. Table 2 shows the evaluations of group cross-sections and Tables 3 and 4 the resonance self-shielding factors and their temperature increments. The results of calculations using the parameters of Ref. [4] are compared with the tabulated data of Ref [6].

Comparison of the evaluated group constant with the ABBN-78 tabulated data [6] shows that there are systematic deviations beyond the errors given above. Of the most substantial ones, we note the following trends [6] in comparison with the results of the present work: there is an underestimate of $< \sigma_\gamma >$ and a systematic overestimate of the resonance self-shielding factors, and their temperature increments (i.e., insufficient allowance is given for the effects of resonance self-shielding and Doppler broadening). This conclusion was also drawn earlier [4] on the basis of preliminary evaluations of group constants (the Doppler effect was not considered in Ref. [4]). After testing the evaluations of the average resonance parameters [4] using new experimental data, we can finally conclude that the differences between our group constant evaluations and the tabulated data of Ref. [6] are systematic in character. The differences show similar trends obtained in the case of the calculations that used the parameters given in Refs [6, 17]. The higher Doppler increment values obtained by us imply that the corresponding correction of the Doppler reactivity coefficient for a fast reactor improves the safety characteristics of the design.

ERROR ANALYSIS

We should, first of all, compare the methods used to calculate the function parameters, namely, the method of stochastic modelling based on the R-matrix theory [16] developed by us in collaboration with the Joint Institute for Nuclear Research, and the method of numerical integration over the statistical distributions of nuclear parameters (GRUKON program [6]). We have made this comparison which is shown in Table 5, for the average cross-sections, the resonance self-shielding factors, and the transmission and capture self-indication functions. The results are shown for the neutron energy range of 30-40 keV (by the GRUKON program); a similar calculation was performed at the 35 keV energy point.

It will be seen that the differences between the results are small (about 1%), which indicates that the two methods are physically close. The advantage of the Monte Carlo method lies in its much higher efficiency and versatility. It provides extensive information from a single calculation - the distribution $P(\sigma_t)$ and correlation $\sigma_x(\sigma_t)$ functions, variety of parameters (including their dependence on temperature) and their dispersions due to the statistics of nuclear levels for a given energy range. Moreover, what is very important is that from these related correlating calculation we obtained all the sensitivity coefficients of the parameters needed for the analysis (quantities to be measured and such functionals as group constants, moments of cross-sections, etc.). The fundamental advantage of this method is that it is based on the generalized R-matrix theory, which takes into account inter-level interference,and is therefore applicable to fissioning nuclei, where these effects dominate. This is not possible with the numerical integration method where no account is taken of the effects of inter-level interference in the form the Breit-Wigner formalism corrections. As for the ^{238}U nuclide, it should be stated that in this case the methods virtually coincide.

There is thus no error due to the calculational methodology in comparable results. We can only speak about differences in the model parameters obtained from the evaluations reported in Refs [4, 6, 17] which were used in the two sets of calculations. The corresponding differences in the group constants are such that they are regarded as statistically insignificant from the standpoint of the experimental neutron data considered above. These differences are overlapped by the a posteriori error evaluations.

Tables 6 and 7 give the a priori and a posteriori evaluations of the average resonance parameters and, consequently, of the group constants obtained in the analysis of experimental data on transmission in Ref [4]. The a priori error of the average radiative width Γ_γ was taken to be 10% and did not change because in the statistical optimization procedure based on sensitivity coefficients the experimental data on cross-section σ_γ were not taken into account. Therefore, the uncertainty of the absorption cross-sections in groups 10-12 is about 10% (in accordance with the existing notions about the measuring accuracy of this quantity).

From the data given here, it can be concluded that the a posteriori error attained at present (i.e. after taking into account the transmission experiments) for the resonance self-shielding factor approaches the required level. It is important to note that the obtained evaluations for the whole set of group constants are self-consistent (determined within the framework of a single theoretical model on the basis of the same experimental material). Attempts to apply a non-statistical approach without a model can lead to unsubstantiated physical conclusions. For example, in Ref. [8] it is concluded that the empirical evaluations agree with the tabulated data of Ref. [6] on the resonance self-shielding factors of the total cross-section $f_t(0)$ to within 2-3% for the same claimed accuracy of the evaluations. This is not substantiated by the present analysis.

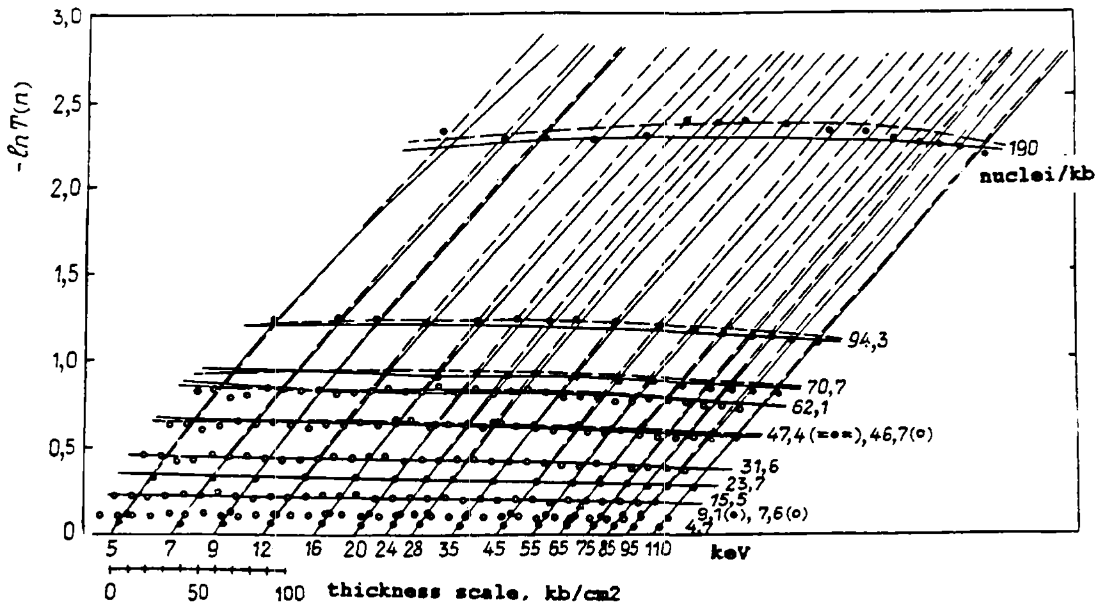

Fig. 1. Transmission function T_n for ^{238}U as a function of incident neutron energy and sample thickness at room temperature; the solid line represents calculation results using parameters from Ref. [4], and the dashed line using parameters from Ref. [17]. Experimental data are denoted as follows: ● - [1]; O - [9]; ▲ - [12].

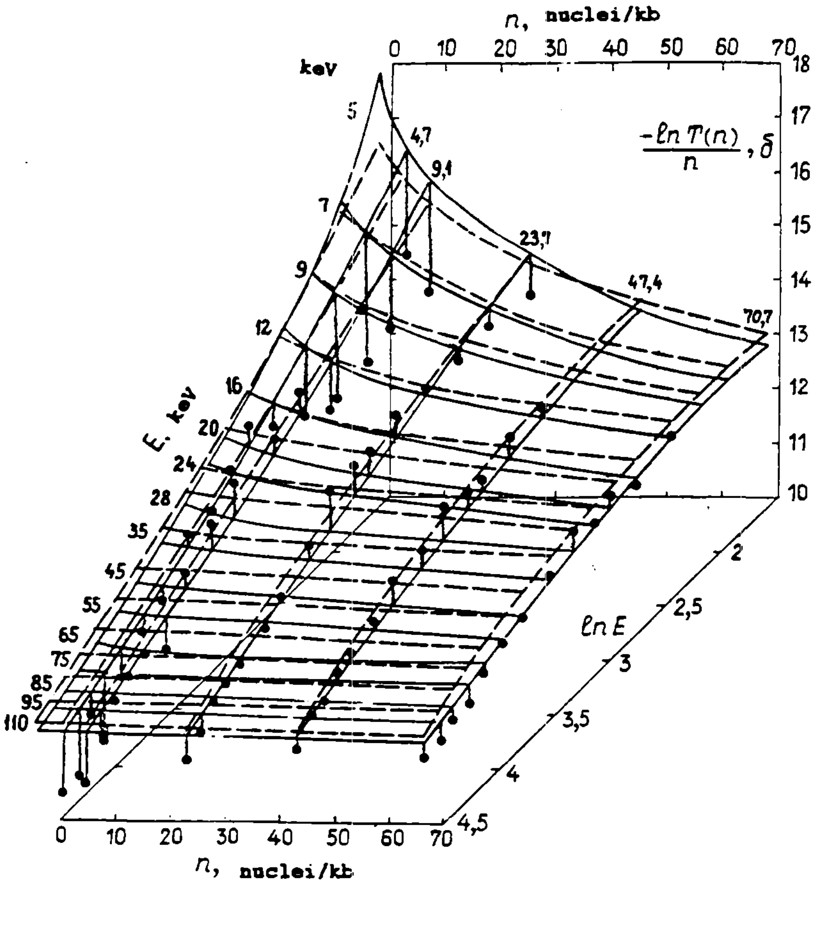

Fig. 2. Self-shielded ^{238}U total cross-section: solid curve - calculated with parameters from Ref. [4]; dashed curve - with parameters from Ref. [17]; experimental data are taken from Ref. [1].

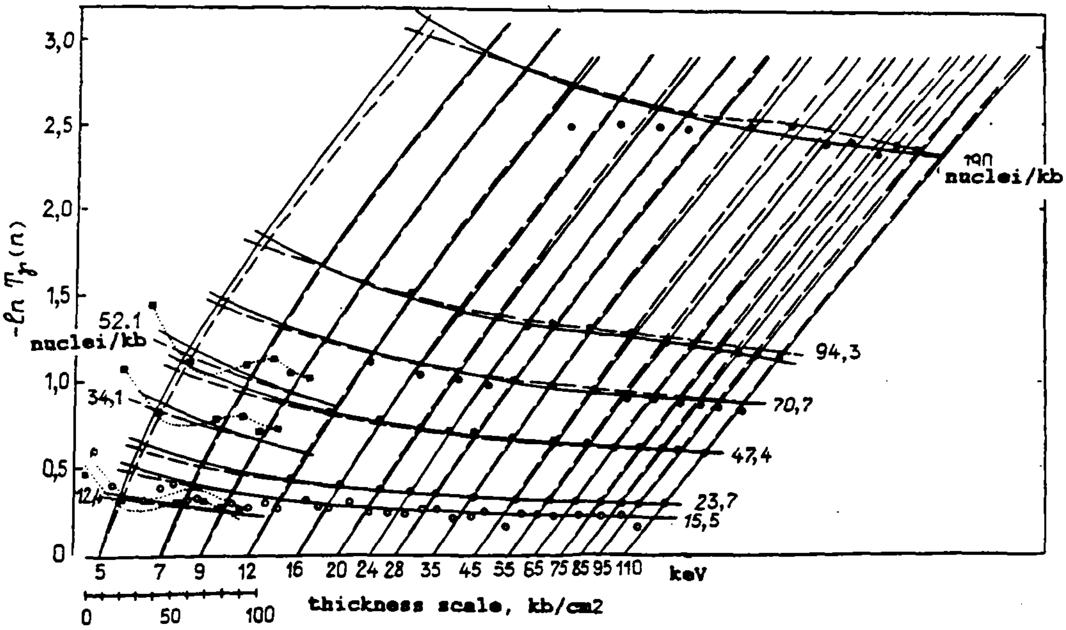

Fig. 3. Self-indication function of the capture reaction as a function of neutron energy and sample thickness; solid curve - calculation with parameters from Ref. [4]; dashed curve - with parameters from Ref. [17]; experimental data: ● - [2]; ○ - [10]; ■ - [11].

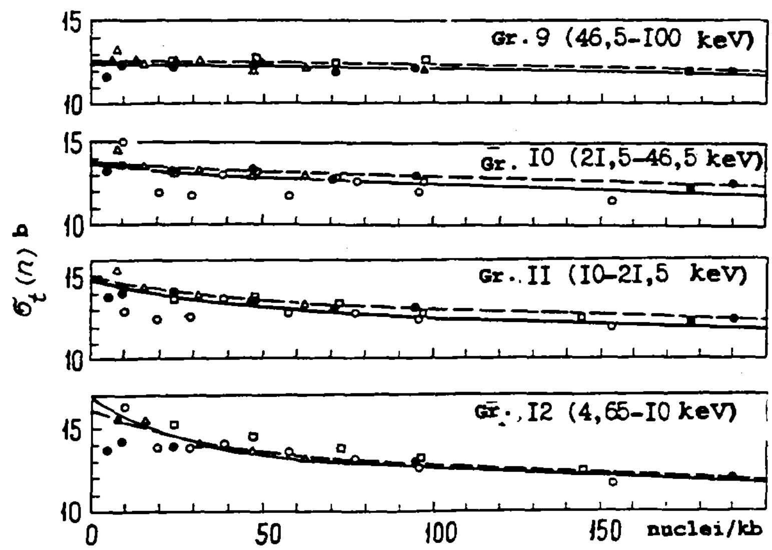

Fig. 4. Total ^{238}U self-shielded cross-section in four BNAB groups; solid curve - calculation using parameters from Ref. [4]; dashed curve - using parameters from Ref. [17]; experimental data ● - [7]; ○ - [4]; ■ - [7]; □ - [8]; ▲ - [9]; ▴ - [12].

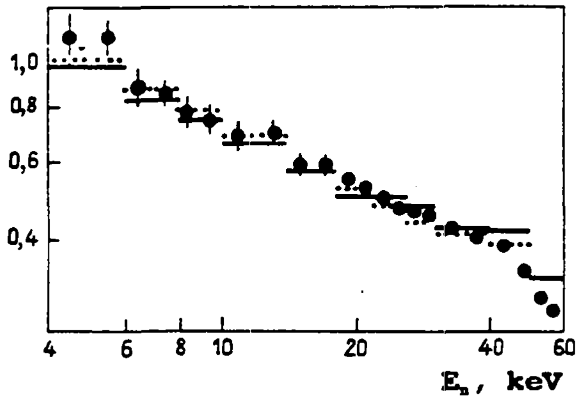

Fig. 5. ^{238}U radiative capture cross-section in the 4 to 60 Kev energy range; solid histogram lines - calculation using parameters from Ref. [4]; dotted lines - using parameters from Ref. [17]; experimental data are taken from Ref. [3].

Table 1

Average ^{238}U resonance parameters for orbital moments equal to 0, 1, 2

Eval. Ref.	$\bar{D}$, eV			R, fm			$S_n \cdot 10^4$			$\bar{\Gamma}_\gamma$, meV		
	0	I	2	0	I	2	0	I	2	0	I	2
[4]	2I,6	7,2	4,3	9,I3*	9,I3	9,I3	I,I4	2,0	3,0	22,2	22,2	22,2
[6,I7]	20,8	4,4	4,I	9,35	6,70	9,35	0,93	2,3	3,0	22,9	I0,6	I6,6

*** For E<10 keV, the radius value used was 9.28 fm**

Table 2

^{238}U group cross-sections, b

Group No.	E, keV	σ_t		σ_γ		σ_e	
		A	B	A	B	A	B
I0	2I,5-46,5	I3,4	I3,4	0,43I	0,445	I3,0	I3,0
II	I0,0-2I,5	I4,8	I4,5	0,6I5	0,597	I4,2	I3,9
I2	4,65-I0,0	I6,5	I5,9	0,863	0,8I4	I5,6	I5,I

Note: A - data from this work, calculation with Ref. [4] parameters; B - BNAB-78 data [6]

Table 3

Resonance self-shielding factors
for various dilution cross-sections σ_o for T=300°K

Group No.	$f_t(\sigma_0)$				$f_\gamma(\sigma_0)$				$f_e(\sigma_0)$			
	0	I0	I00	I000	0	I0	I00	I000	0	I0	I00	I000
	Calculation with parameters from Ref. [4]											
I0	774	885	965	996	879	927	983	998	893	934	982	998
II	544	787	9I2	990	78I	860	960	995	794	86I	950	993
I2	472	709	846	966	659	753	9I0	787	724	794	907	984
	BNAB-78 data [6]											
I0	855	907	974	997	9I0	948	988	998	9I2	946	986	998
II	755	828	936	99I	830	884	968	996	844	880	963	995
I2	668	756	882	978	7I9	795	929	990	780	832	930	989

Note: All numbers are multiplied by 10^3

Table 4

Temperature increments of resonance self-shielding factors

Group No.	Increment	Δf_t for σ_0, equal to				Δf_γ for σ_0, equal to				Δf_ℓ for σ_0 equal to			
		0	I0	I00	I000	0	I0	I00	I000	0	I0	I00	I000
		Calculation with parameters from Ref. [4]											
I0	Δ_1	I024	382	I28	I6	450	279	7I	7	388	23I	70	9
	Δ_2	395	23I	7I	II	239	I4I	34	4	2I2	I35	38	4
II	Δ_1	223I	597	306	II3	856	566	I86	25	679	42I	I84	29
	Δ_2	640	34I	I58	78	4I2	268	77	I0	336	233	92	I4
I2	Δ_1	I0I7	585	42I	I48	I005	835	373	62	599	469	276	58
	Δ_2	I705	380	258	I09	664	462	I73	26	444	298	I68	33
		BNAB-78 data [6]											
I0	Δ_1	456	275	82	II	32I	I9I	44	5	252	I58	43	5
	Δ_2	264	I7	47	6	I49	88	20	2	I52	97	25	3
II	Δ_1	682	395	I8I	30	585	39I	II5	I5	373	265	I04	I5
	Δ_2	374	272	I09	I6	327	2I3	57	7	243	I76	6I	8
I2	Δ_1	7I8	45I	33I	8I	807	649	276	44	457	370	2I4	42
	Δ_2	467	356	222	45	573	433	I58	22	334	272	I36	23

Note: Δ_1 = f(900°K) - f(300°K; Δ_2 = f(2100°K) - f(900°K);
all numbers are multiplied by 10^3

Table 5

Comparison of results of calculations by different methods (parameters from Ref. [6,17], E = 30 to 40 keV, T = 300°K)

Group constants

Method	σ_t, б	σ_γ, б	σ_p, б	$f_t(\sigma_0)\cdot I0^3$			$f_\gamma(\sigma_0)\cdot I0^3$		
				0	I0	I00	0	I0	I00
Monte-Carlo This work	I3,5	0,4I5	I3,I	87I	922	980	934	96I	99I
GRUKON	I3,4	0,4I4	I3,0	888	926	979	934	957	989

Self-indication $T_\gamma(n)\cdot I0^3$

Method	$n\cdot I0^3$ **nuclei/b**						
	4,70	9,I0	23,7	47,4	70,7	94,3	I90
Monte-Carlo This work	934	877	7I2	5I2	373	273	8I,I
GRUKON	936	879	7I7	5I8	379	277	80,6

Transmission $T(n)\cdot I0^3$

Method	$n\cdot I0^3$ **nuclei/b**						
	4,70	9,I0	23,7	47,4	70,7	94,3	I90
Monte-Carlo This work	938	885	729	535	398	296	94,3
GRUKON	939	886	73I	538	899	296	9I,4

Table 6

A priori (A) and *a posteriori* (B) errors of the average resonance parameters for ^{238}U, %

Error	S_o	S_1	R_o	D
A	15	15	5	15
B	8	10	1.5	13

Table 7

A priori (A) and *a posteriori* (B) errors of group constants for ^{238}U, %

Group	Error	σ_t	σ_ℓ	$f_t(\sigma_o)$		$f_\gamma(\sigma_o)$		$f_\ell(\sigma_o)$	
				0	10	0	10	0	10
10	A	9	9	11	3	2	1	3	2
	B	2	2	8	2	1.5	0.8	2	1
11	A	9	9	15	4	3	2	5	3
	B	3	3	12	3	2.5	1.5	3	2
12	A	9	9	18	7	4	2	8	5
	B	4	4	14	4	2.5	1.5	5	3.5

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Submitted for publication 2 February 1987