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Translation of a Reprint from
Vestsi Akad. Navuk BSSR, Ser. Fiz.-Energ. Navuk 3(1974)

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NUCLEAR DATA FOR ^{239}Pu IN THE UNRESOLVED RESONANCE REGION OF NEUTRON ENERGIES

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The unresolved resonance region of neutron energies for ^{239}Pu extends from 600 eV to 25 keV. In this energy region the contribution of states other than the S- and P-states can be neglected.

The mean resonance parameters can be obtained by averaging the resonance parameters in the resolved resonance energy region and by fitting the calculated values of the cross-sections to the available experimental data.

Both these approaches were used in the present work.

As energy-dependent parameters we took the quantities $\langle\Gamma_n^o\rangle$ for $\ell = 0$, J = 0 and 1 and $\langle\Gamma_f\rangle$ for $\ell = 0$, J = 1, which were determined from the experimental data on σ_t and σ_f.

The following were the statistical parameters assumed to be independent of neutron energy:

$$\langle\Gamma_f\rangle \text{ for } l=0,\ J=0;\ l=1,\ J=0;\ l=1,\ J=1;\ l=1,\ J=2;\ \langle D\rangle,$$
$$\langle\Gamma_\gamma\rangle,\ \langle\Gamma_n^0\rangle \text{ for } l=1,\ J=0;\ l=1,\ J=1;\ l=1,\ J=2.$$

These parameters are given in Table 1.

We obtained the average distance between levels $\langle D\rangle$, equal to 2.38 ± 0.06 eV, by considering the resolved resonance energy region. It shows satisfactory agreement with the latest Saclay experiments (2.36 ± 0.10 eV) [1].

Considering that the dependence of $\langle D\rangle$ on J can be described by the Fermi gas model, and neglecting the parity dependence, we can determine $\langle D\rangle_{J=0}^{\ell=0}$ and $\langle D\rangle_{J=1}^{\ell=0}$. For $\ell = 1$, the average distance $\langle D\rangle_{J=0}^{\ell=1}$ was taken to be 9.0 eV, $\langle D\rangle_{J=1}^{\ell=1}$ to be 3.1 eV and $\langle D\rangle_{J=2}^{\ell=1}$ to be 2.1 eV.

The average radiative $<\Gamma_\gamma>$ was taken to be constant in the energy region under consideration. We obtained this value from the data on the resolved resonance parameters.

$<\Gamma_f>$ for $\ell = 0$, J = 0 was obtained from the resolved resonance parameters. $<\Gamma_f>$ for $\ell = 0$, J = 1 was taken to be energy-dependent and determined from the experimental data on σ_f, while the values of $<\Gamma_f>$ for $\ell = 1$ were taken as: $\langle \Gamma_f \rangle_{J=0}^{l=1} = 0$, $\langle \Gamma_f \rangle_{J=1}^{l=1} = 1{,}0$ eV $\langle \Gamma_f \rangle_{J=2}^{l=1} = 1{,}0$ eV.

The neutron widths $<\Gamma_n^o>$ for $\ell = 0$, J = 0, 1 were taken as energy-dependent and determined from the experimental data on σ_t.

$<\Gamma_n^o>$ for $\ell = 1$ and J = 0, 1, 2 were obtained from the force function for the P-wave and the value of $<D>$ for $\ell = 1$, J = 0, 1, 2.

In experimental work, Uttley [2] and Ryabov and Fenin [3] determined the force function for the P-wave as $S_1 = (2.5 \pm 0.5) \times 10^{-4}$ $(eV)^{-\frac{1}{2}}$ [2], and $S_1 = (1.99 \pm 0.48) \times 10^{-4}$ $(eV)^{-\frac{1}{2}}$ [3].

Otter [4] estimated the contribution of resonances with $\ell = 1$ to the ^{239}Pu fission cross-section. A better comparison is obtained for $S_1 = 1.5 \times 10^{-4}$. In his calculations Otter did not, however, take into account competition with inelastic scattering; had he done so, S_1 would have been larger. In our calculations we used the value $S_1 = 2.0 \times 10^{-4}$ $(eV)^{-\frac{1}{2}}$.

The experimental values of σ_t and σ_f estimated in Ref. [5] were used to obtain $<\Gamma_n^o>$ for $\ell = 0$, J = 0 and 1 and $<\Gamma_f>_{J=1}^{\ell=0}$.

We chose 24 points in the energy region from 300 eV to 30 keV which acceptably describe the cross-sections in this region. Between 1 and 2 keV, where $<\Gamma_f>_{J=0}^{\ell=0}$ changes especially sharply, the experimental data on σ_f obtained with good resolution by Blons and co-workers [1] were used for the detailed behaviour of the curve.

The values obtained for the average energy-dependent resonance parameters are given in Table 2.

The cross-sections in the unresolved resonance region were calculated by the formula

$$\bar{\sigma}_X = \frac{K}{E_0} \sum_s \frac{g_s}{\langle D \rangle_s} \cdot \frac{\langle \Gamma_n \rangle_s \cdot \langle \Gamma_X \rangle_s}{\langle \Gamma \rangle_s} \cdot \langle S_X \rangle_s ,$$

where s is a state with given (ℓ, J), $g_s = \frac{2J+1}{2(2I+1)}$ the statistical weight for state J, K a constant equal to 4.09×10^6 barn-eV, E_0 the neutron energy in eV, $<D>_s$ the average distance between levels for the S-state, $<\Gamma_X>_s$ the average width for the reaction (n,X) for the S-state (ℓ,J) in eV, $<\Gamma>_s = <\Gamma_n>_s + <\Gamma_f>_s + <\Gamma_\gamma>_s$ the average total width for the S-state (ℓ,J) in eV, and $<S_X>_s = <\frac{\Gamma_n \Gamma_X}{\Gamma}>_s \Big/ \frac{<\Gamma_n>_s <\Gamma_X>_s}{<\Gamma>_s}$ the average value of the S-factor which takes into account the statistical distributions of $<\Gamma_X>_s$ and $<\Gamma_n>_s$.

The S-factors were calculated with the help of so-called representation parameters [6], each of which is a given fraction in the χ^2 distribution for the corresponding widths:

$$\langle S_f \rangle_s = \frac{\frac{1}{I_s K_s} \sum_i^{I_s} \sum_k^{K_s} \frac{\Gamma_{n,s,i} \Gamma_{f,s,k}}{\Gamma_{n,s,i} + \Gamma_{f,s,k} + \Gamma_{\gamma,s}}}{\frac{\langle \Gamma_n \rangle_s \cdot \langle \Gamma_f \rangle_s}{\langle \Gamma \rangle_s}},$$

where I_s is the number of terms used in representing the distribution of neutron widths and K_s the number of terms used in representing the distribution of fission widths; I_s and K_s are chosen in accordance with the number of degrees of freedom for the χ^2 distribution.

For the widths of reactions with one or two degrees of freedom, ten intervals were used. When the degrees of freedom were three or four, five intervals were used to represent the distribution.

The resonances used to represent the distribution were determined by calculating the quantities

$$\Gamma_{n,s,i} = f_{n,s,i} \langle \Gamma_n \rangle_s,$$
$$\Gamma_{f,s,k} = f_{f,s,k} \langle \Gamma_f \rangle_s,$$

where $f_{n,s,i}$ and $f_{f,s,k}$ were obtained from Ref. [7] by averaging the parameters over the corresponding parts of the distribution which they represent.

In this analysis inelastic scattering was not considered in the energy region above 8 keV, and consequently $<\Gamma_f>^{\ell=0}_{J=1}$ is low in that energy region.

Figures 1 and 2 show the fission cross-sections and the total cross-section, calculated from the parameters given in Tables 1 and 2, which enable us with satisfactory accuracy to calculate the value of α in the 0.3–30.0 keV region. Comparison of the experimental and calculated values of α shows (see Fig. 3) that the calculated values are slightly higher in the energy region above 9 keV, as would be expected from the somewhat low value of $\langle\Gamma_f\rangle^{\ell = 0}_{J = 1}$.

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Table 1

Unresolved resonance parameters for ^{239}Pu

l	J	$\langle D\rangle$, eV	$\langle\Gamma_f\rangle$, eV	$\langle\Gamma_\gamma\rangle$, eV	$\langle\Gamma_n^0\rangle$, (eV)$^{1/2}$	No. of degrees of freedom: Fission	Scattering
0	0	9,0	2,019	0,0433	depends on E_n	2	1
0	1	3,1	depends on E_n	0,0433	depends on E_n	1	1
1	0	9,0	0,0	0,0433	$1{,}8 \cdot 10^{-3}$	0	1
1	1	3,1	1,0	0,0433	$0{,}62 \cdot 10^{-3}$	2	2
1	2	2,1	1,0	0,0433	$0{,}42 \cdot 10^{-3}$	3	1

Table 2

Average energy-dependent resonance parameters

E_n, keV	$<\sigma_t>$ barn	S_0	$<\Gamma_n^0>_{J=0}^{l=0}$	$<\Gamma_n^0>_{J=0}^{l=0}$	$<\Gamma_n>_{J=0}^{l=0}$	$<\Gamma_n>_{J=1}^{l=0}$	$<\Gamma_f>_{J=1}^{l=0}$
		$eV^{-1/2} \cdot 10^{-4}$			$eV \cdot 10^{-3}$		
0,3—0,4	33,867	1,0689	9,6197	3,3134	1.7997	0.6199	2,486
0,4—0,5	26.519	0,8341	7,5070	2,5857	1,5925	0,5485	18,500
0,5—0,6	45,988	2,0290	18,2609	6,2899	4,2826	1,4751	7,430
0,6—0,7	24,550	0,8808	7,9268	2,7303	2,0209	0,6961	1,103
0,7—0,8	24,010	0,9009	8,1083	2,7928	2,2205	0,7649	3,761
0,8—0,9	22,300	0,8372	7,5351	2,5954	2,1968	0,7567	2,980
0,9—1,0	29,380	1,4179	12,7607	4,3953	3,9331	1,3547	5,020
1,0—2,0	21,944	1,0773	9,6961	3,3398	3.7553	1,2935	3,080
2,0—2,1	19,831	1,0240	9,2163	3,1745	4,1729	1,4373	0,010
2,1—2,2	18,239	0,8667	7,7999	2,6866	3,6167	1,2457	1,260
2,2—2,5	18,299	0,9129	8,2164	2,8301	3,9831	1,3720	4,500
2,5—2,8	22,306	1,4798	13,3181	4,5873	6,8559	2,3615	1,350
2,8—3,0	19,621	1,1903	10,7127	3,6899	5,7690	1,9871	4,200
3—4	18,245	1,1059	9,9529	3,4282	5,8882	2,0282	2,974
4—5	17,210	1,0810	9,7290	3,3511	6,5264	2,2480	1,650
5—6	17,570	1,2643	11,3783	3,9192	8,4384	2,9065	0,860
6—7	16,540	1,1657	10,4917	3,6138	8,4587	2,9136	1,060
7—8	15,892	1,1105	9,9946	3,4426	8,6556	2,9814	2,054
8—9	15,630	1,1221	10,0986	3,4784	9,3104	3,2069	3,350
9—10	15,100	1,0539	9,4853	3,2672	9,2451	3,1844	2,040
10—15	14,864	1,1483	10,3347	3,5597	11,5545	3,9799	0,553
15—20	13,930	1,0415	9,3735	3,2287	12,4000	4,2711	1,380
20—25	14,050	1,2621	11,3585	3,9124	17,0377	5,8685	0,750
25—30	13,865	1,3467	12,1201	4,1747	20,0989	6,9229	0,622

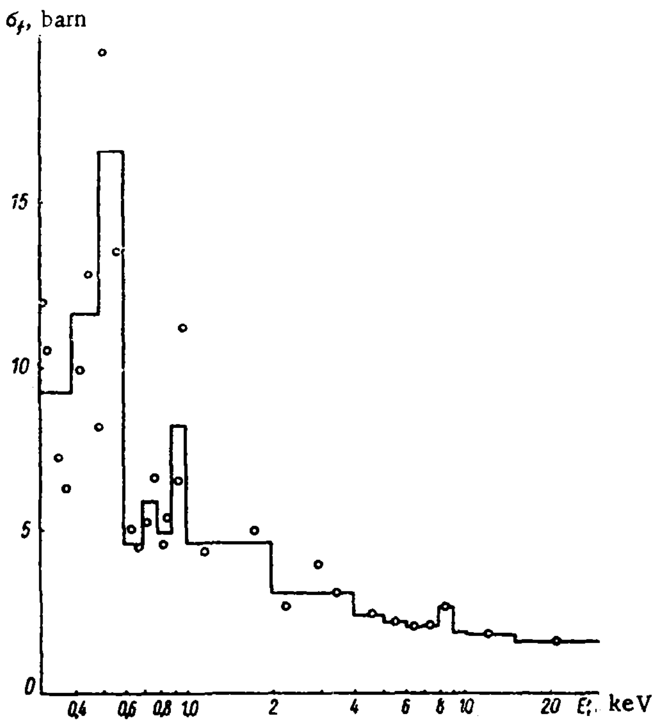

Fig. 1. Comparison of calculated and experimental values of $\sigma_f(^{239}Pu)$

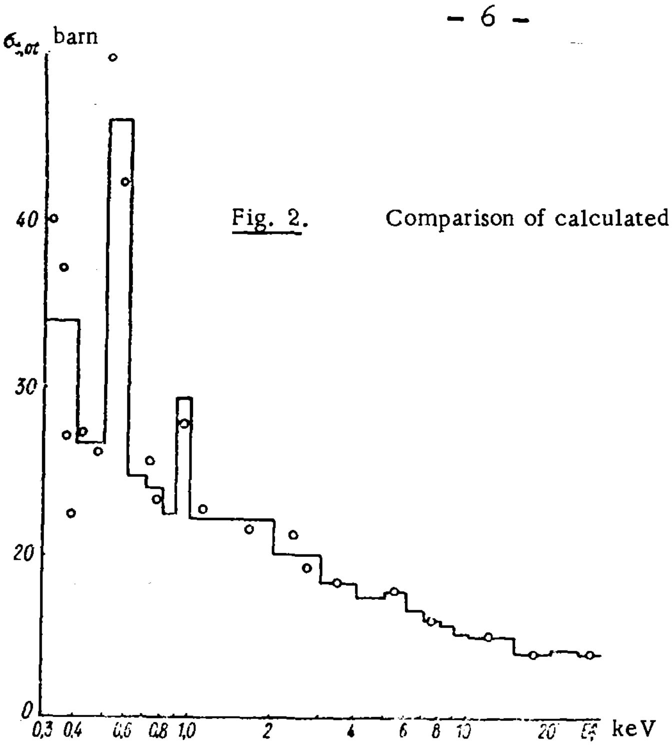

Fig. 2. Comparison of calculated and experimental values of $\sigma_t(^{239}Pu)$

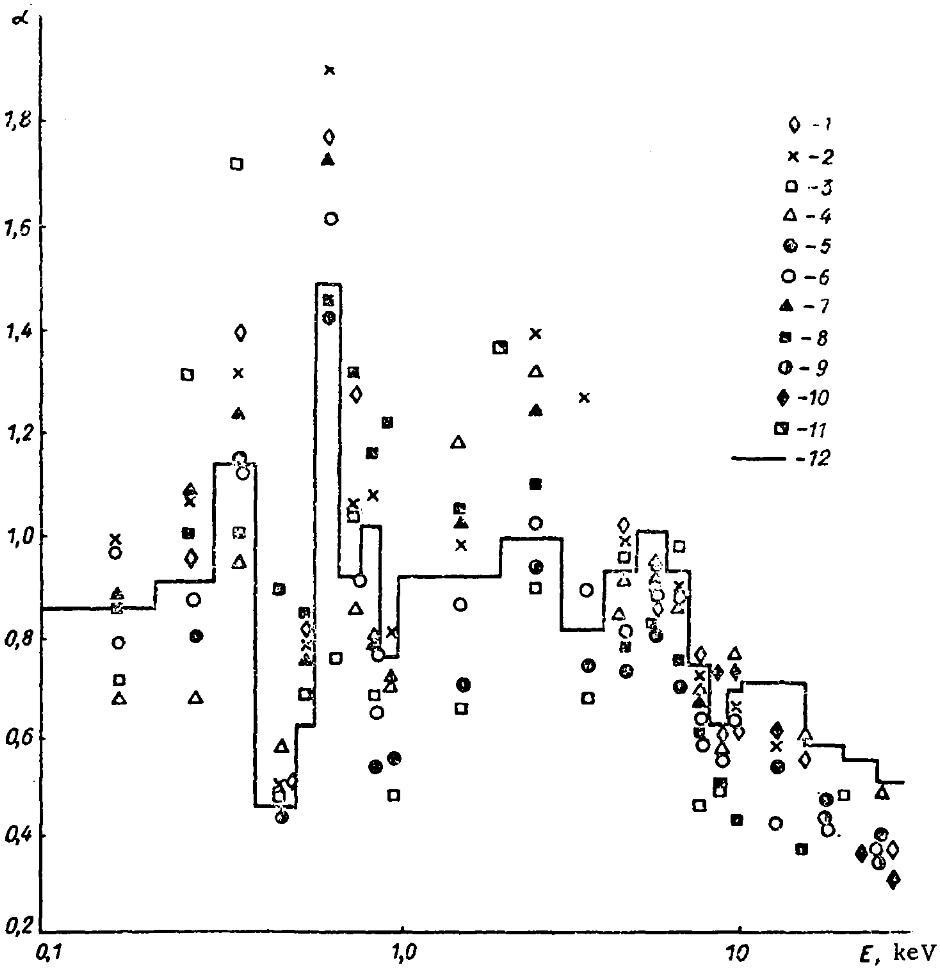

Fig. 3. Comparison of calculated and experimental values of $\alpha(^{239}Pu)$: (1) Gwin et al.; (2) Gwin et al. (fission chamber); (3) Kirov et al. (15 nsec/m); (4) Farrell et al.; (5) Schomberg et al.; (6) Czirr and Lindsey; (7) Belyaev et al.; (8) Ryabov et al.; (9) Lottin et al.; (10) Bundle et al.; (11) Dvukhsherstnov et al.; (12) calculation