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

V.M. Maslov

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^{1} 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^{1} reaction, there are no other data apart from the isomeric ratio, r, of the ^{236}Np^{1} 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]:

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

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(γ,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): $(1/T_f)\exp\left[(U_f + m\Delta_f + \delta_f)/T_f\right] \overset{I}{=} \rho_f(U_f)$.

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, $R=2\sqrt{2\pi}\sigma_{\|f}$;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 relationships 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 $< \sigma^s_{n2n} >_{Cf} = 4.66 \pm 0.47$ 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, $<\sigma^{s}_{n2n}>_U$ lies in the range of 1.97-2.43 mb. Discrepancies between measurements of the cross-section $<\sigma^{s}_{n2n}>_{cf}$ [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 $<\sigma^{s}_{n2n}>_{cf}$ [15] on the one hand, and the data in Ref. [14] for $<\sigma^{s}_{n2n}>_U$ 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.

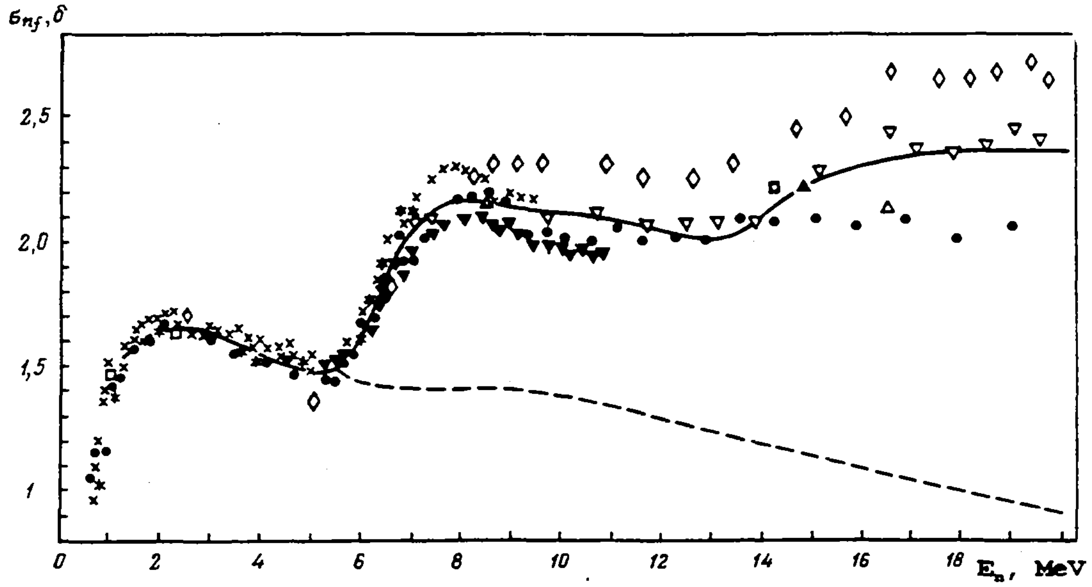


Fig. 1. Neutron fission cross-section for ^{237}Np. Continuous curve - calculation; broken curve - "first chance" fission cross-section. Experimental data from the following references: ▲ - [15], △ - [17], ▼ - [18], ● - [19], x - [20], □ - [21], ★ - [22], ▽ - [25], ◊ - [26].

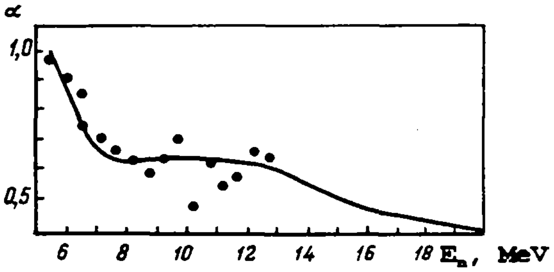
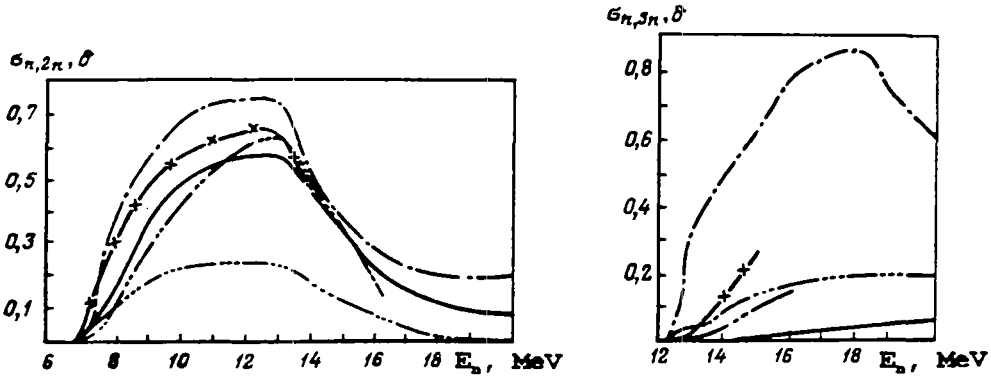


Fig. 2. Dependence of "first chance" contribution on the total fission cross-section for ^{237}Np. Continuous curve - calculation; ● - experimental data [39 and 40].



(a) (b)

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.

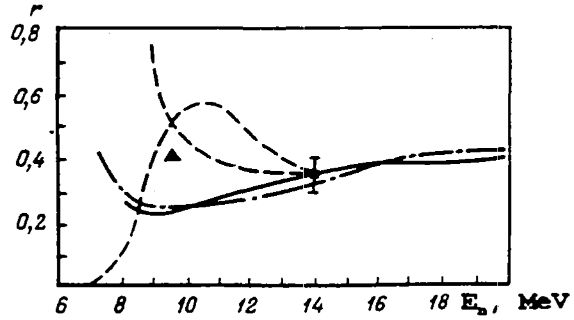


Fig. 4. Energy dependence of the isomeric ratio in the ^{237}Np(n,2n) reaction. Calculation: [9]; _._._[8];- - - [30]; Experimental data: ● - [29]; ▲ - value taken from reference [30].

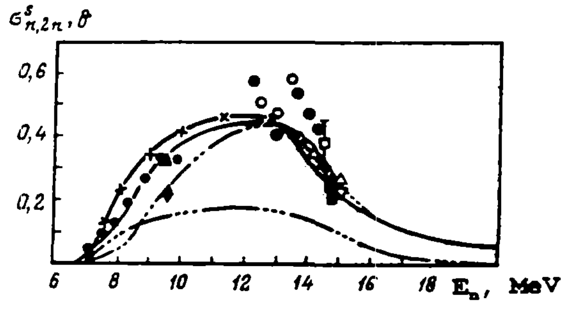


Fig. 5. ^{237}Np(n,2n) reaction cross-section. Calculation: this work;-x-x- KEDAK-4 [42]; _._._ ENDL [41];_.._.._[30];_......_ENDF/B-V. Experimental data: □ - [2]; ▲ - [3]; ▼ - [4]; ▲ - [5]; ◆ - renormalized data from Ref. [30]; ■ - [6]; ● - [7]; ○ - [28].

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