CONSISTENT EVALUATION OF NEUTRON CROSS SECTIONS FOR THE $^{242-244}Cm$ ISOTOPES

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It is necessary to know the neutron cross-sections for curium isotopes in order to solve the problems of the external fuel cycle. Experimental information on the cross-sections is very meagre and does not satisfy requirements. Moreover, existing evaluations of neutron cross-sections in the ENDF, JENDL and INDL libraries differ substantially, and these differences are especially large for the fission and (n,2n) reaction cross-sections. This situation requires a critical review of the entire set of evaluations of the neutron cross-sections for curium.

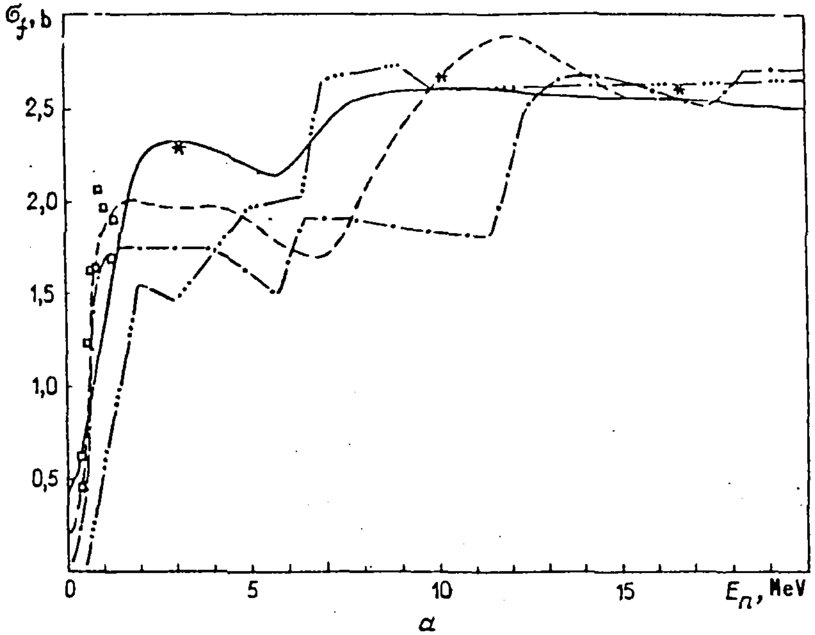
In the energy region up to the threshold of the (n,n'f) reaction the differences between the evaluations are due principally to the normalization of the calculated cross-sections to the various experimental data on the neutron fission cross-section [1-7] or on fissility in reactions with charged particles [8]. Above the threshold the discrepancies in the evaluations are due mainly to differences in the determinations of the contributions of emissive fission. The details of the theoretical models on which these evaluations are based demonstrate the need to analyse existing experimental data on the basis of a stricter theoretical approach which takes into account the whole range of contemporary concepts about the optical-statistical characteristics of deformed heavy nuclei. Existing phenomenological systematics of observed fissilities of actinides [9] and the semi-empirical descriptions of the multiple neutron emission cross-sections based on them [10] can but partly satisfy the practical requirements of neutron data evaluation. The justification for the approximations which go into such systematics also requires more consistent theoretical calculations of cross-sections.

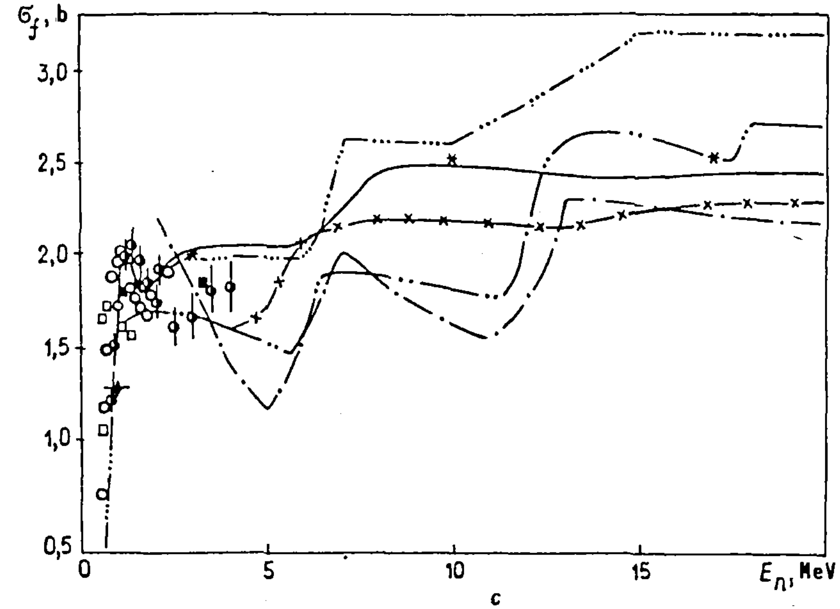
In order to calculate the neutron cross-sections, we used the statistical approach, which takes into account the pre-equilibrium emission of neutrons in the initial stages of compound nucleus formation and the maintenance of the angular moment at all stages of decay of the compound nucleus. The parameters of the pre-equilibrium neutron evaporation model were obtained on the basis of the consistent description of neutron spectra, the (n,2n) and (n,3n) reaction and also the neutron fission cross-sections for ^{238}U [11], for which the fullest experimental information is available for all the data considered. It has been shown that such an approach also ensures a good description of the neutron cross-sections for the neighbouring odd ^{235}U isotope [11].

The level density in the neutron and fission channels was calculated with the use of the phenomenological model, which consistently takes into account shell, superfluid and collective effects [12]. The model parameters for the neutron channel were determined from the systematics obtained by combined analysis of the neutron resonance density and the cumulative sums of low-lying levels [13]. It has been shown that for all actinides the density of the low-lying levels can be described satisfactorily by the constant temperature model with parameter T = 0.388 MeV common to all actinides and odd-even differences determined by the value of the correlation function $\Delta_o = 12/\sqrt{A}$ MeV. The selection of the level density parameters for the fission channel is considered in detail in Ref. [14], where, using neutron reactions as an example, we demonstrated the need for taking into account the collective effects associated with the non-axial deformation of fissile nuclei on the internal barrier and the mirror deformation on the external barrier. In that case, the correlation functions of the fission channel $\Delta_o + 0.08$ will be systematically higher than the similar values in the neutron channel, while the shell corrections needed to describe the observed fission cross-sections at the internal hump $\delta\varepsilon_A = 2.5$ MeV and at the external hump $\delta\varepsilon_B = 0.6$ MeV will remain practically unchanged for the whole uranium and plutonium isotope chain [14]. Such an evaluation of shell corrections is in good agreement with the phenomenological systematics of the two-humped fission barrier parameters for actinides, and consequently the parameters in question can also be used in the calculations of the neutron fission cross-sections for curium isotopes.

The analysis of the neutron cross-sections in curium isotopes is complicated by the fact that the experimental data obtained for nuclear-explosion neutrons [2, 4, 5] exhibit poor agreement with each other both in absolute value and in the energy dependence of the cross-sections. They also fit poorly into the existing systematics of the isotopic dependence of fission cross-sections at the first plateau [15, 16]. In these circumstances, as reference cross-sections the authors used, for the first plateau, the evaluations of the 3-MeV neutron fission cross-sections for curium obtained within the framework of the consistent systematics of fissilities of actinides in neutron reactions and in reactions with charged particles [9]. Such reference cross-sections make it possible to determine the parameters of the fission channel for the whole curium isotope chain, and further calculations of the energy dependence of the fission cross-sections and also the (n,2n) reaction cross-sections are no longer associated with any variations in the parameters. To calculate the cross-sections for compound nucleus formation and the corresponding neutron transmission coefficients, we used the non-spherical optical model with the potential parameters recommended in Ref. [17].

The results of theoretical calculation of the fission cross-sections, together with available experimental data [1-7], are shown in Fig. 1. For comparison we have also given the results of the various evaluations. From the data presented it will be seen that there is a considerable difference between evaluations both in absolute value and in the description of the energy dependence of the fission cross-sections. Substantial differences exist also between the experimental data (see Fig. 1,c) so that the fission cross-section evaluations based on the systematics of fissility of nuclei by charged particles are preferable [9]. It should be noted that, although we





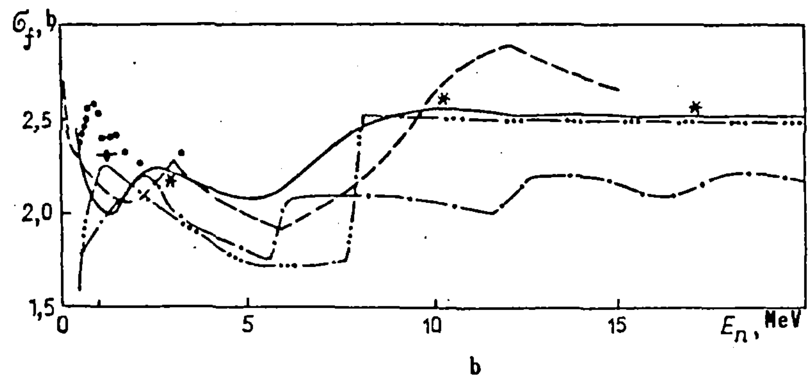
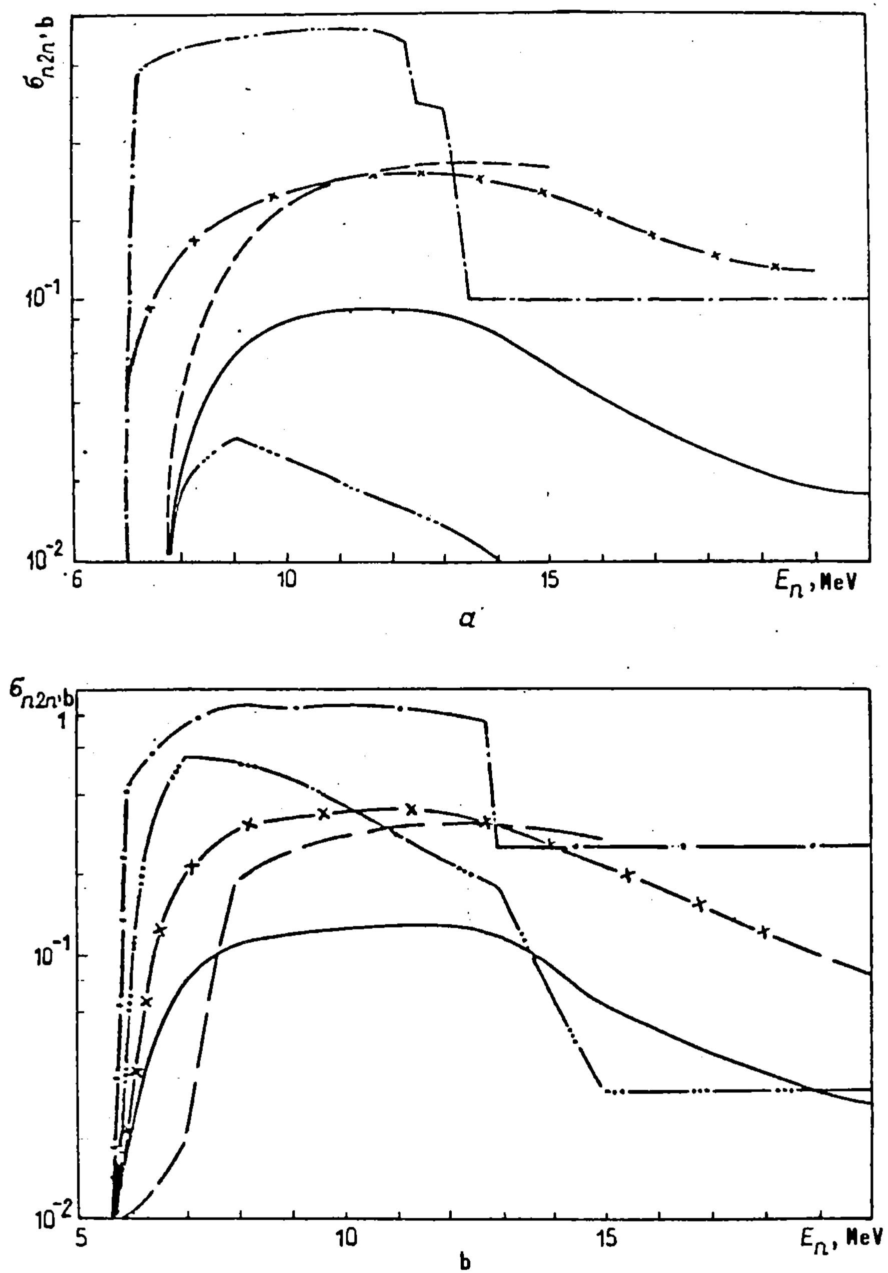


Fig. 1. Fission cross-sections for ^{242}Cm (a), ^{243}Cm (b) and ^{244}Cm (c). Evaluations: —— — present work; —·—— ENDL; —·· ——— JENDL-II; —··· —— ENDF/B-V; - - - - INDL/A (Bologna); —x— [10]. Experimental data: ■ – [1]; 0 – [2]; ◐ – [3]; ● – [4]; ◆ – [5]; □ – [7]; * – phenomenological systematics [9].

used such systematics only for the neutron energy of 3 MeV, no substantial differences occur between the theoretical calculations and the systematics of the fission cross-sections [9] for the second and the third plateau region (see Fig. 1,a-c). We can therefore regard the theoretical calculations and the phenomenological systematics of the neutron fission cross-sections for the nuclei [9] as sufficiently consistent for the whole region of neutron energies above 3 MeV.

Figure 2 shows the results of the present calculations and the set of available evaluations of the (n,2n) reaction cross-sections. For this reaction there are no experimental data, and the differences between the various evaluations are a direct consequence of the models on which they are based. Since in all evaluations the sum of cross-sections is normalized practically always to the cross-section for compound nucleus formation, a considerable part of the differences in the evaluations of the (n,2n) reaction cross-sections is due directly to discrepancies between the evaluations of the fission cross-sections and, in the neutron energy region above 14 MeV, also to discrepancies between the evaluations of (n,3n) reaction cross-sections. The non-physical nature of the energy dependence of the (n,2n) reaction cross-sections in the evaluations of the ENDL and ENDF libraries is obvious. At the same time, the evaluations of Ref. [10], which used a model conceptually close to our approach, have a cross-section energy dependence similar to our calculations, and the differences in the absolute value of the cross-sections are due to the error of the evaluations of the fissility of nuclei and to the more approximate modelling of the cross-sections for compound nucleus formation.

Because of the above differences in the evaluations of the (n,2n) reaction cross-sections, the evaluations of this reaction for uranium and plutonium isotopes deserve attention. Figure 3 shows available evaluations of the (n,2n) reaction cross-sections in the region of their maximum value, i.e. for neutron energies of 10-12 MeV. We have given the results of our



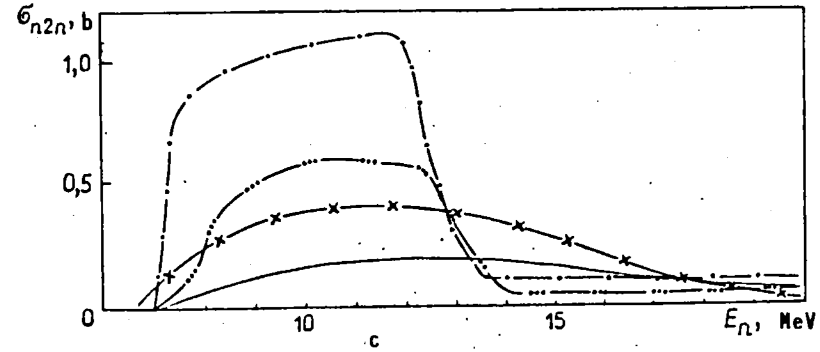


Fig. 2. Reaction cross-sections for: (a) ^{242}Cm(n,2n); (b) ^{243}Cm(n,2n); (c) ^{244}Cm(n,2n). Evaluations: ——— present work; —·— ENDL; —··— JENDL-II; —···— ENDF/B-V; – – – INDL/A (Bologna); — x — [10].

calculations of the cross-sections for ^{246}Cm and ^{248}Cm, together with those for the light isotopes of curium. The analysis of the isotopic dependence of the cross-sections for compound nucleus formation [17] shows only comparatively small variations in these cross-sections for the incident neutron energies considered. Hence it can be concluded that changes in the (n,2n) reaction cross-sections at the maximum are determined almost entirely by changes in the fissility of nuclei. Since for all uranium, plutonium and curium isotopes the fissility decreases monotonically the heavier the isotopes are, the (n,2n) reaction cross-sections should exhibit the inverse dependence - a monotonic increase in the cross-sections. This result is, of course, confirmed by the experimental data available for ^{235}U and ^{238}U [11]. In the consistent theoretical calculations a monotonic isotopic increase in the (n,2n) reaction cross-sections is observed for all actinides (see Fig. 3), but the ENDF/B-V and JENDL-II evaluations do not show this trend, indicating inconsistency between the evaluations for the different isotopes.

A similar pattern of isotopic changes appears also in the (n,3n) reaction cross-sections. However, these need not be discussed in the present work since for the curium isotopes considered the (n,3n) reaction cross-section is very small (not greater than 20 mb for ^{244}Cm).

The results of theoretical calculations of the main neutron reaction cross-sections for curium isotopes, together with the results of the phenomenological systematics of the fission cross-sections [9] based on an analysis of the fissility of transactinides in reactions with charged particles, indicate the unsatisfactory nature of the majority of the evaluations included in the INDL/A files. Existing evaluations cannot be recommended to neutron data users for one single isotope. A considerable amount of work must be carried out on the revision of the cross-section evaluations in the neutron energy region above 1 MeV. It is evident that the necessary degree of reliability of such evaluations can be ensured only by the use of coherent theoretical models which are consistent with the whole set of

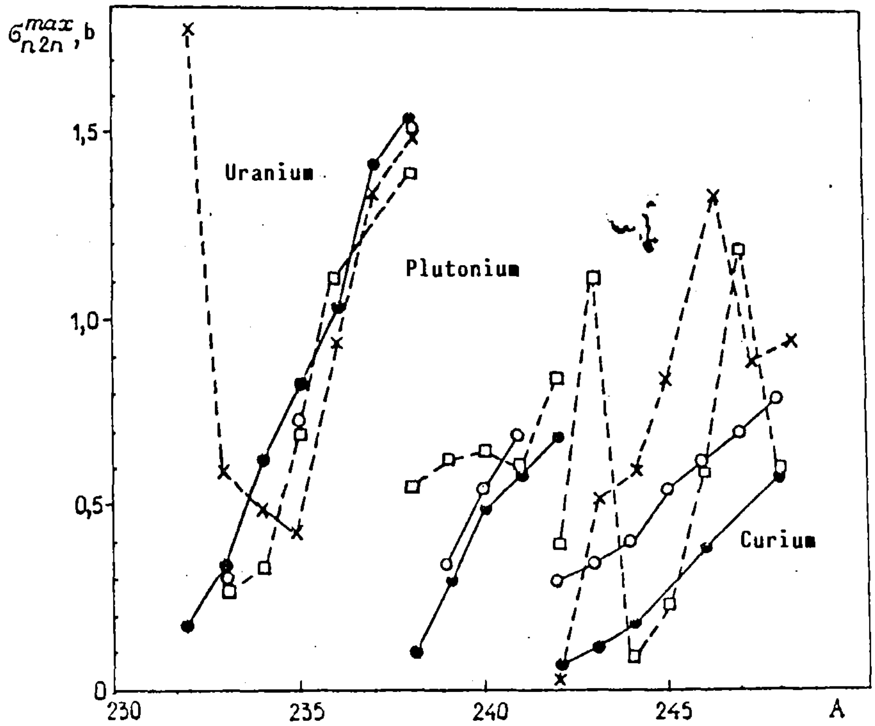


Fig. 3. Isotopic dependence of cross-sections $\sigma_{n,2n}$ at the maximum according to the data of: ● - Present work; x - ENDF/B-V; □ - JENDL-II; ○ - [10].

concepts relating to neutron reaction mechanisms and with the statistical description of the properties of the competing decay channels of fissile nuclei. We hope that the results of the present work will provide the necessary basis for the practical re-evaluation of the neutron cross-section files for $^{242-244}$Cm.

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