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EVALUATION OF THERMAL NEUTRON CROSS-SECTIONS AND RESONANCE INTEGRALS OF PROTACTINIUM, AMERICIUM, CURIUM, AND BERKELIUM ISOTOPES

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ABSTRACT

Data on the thermal neutron fission and capture cross-sections as well as their corresponding resonance integrals are reviewed and analysed. The data are classified according to the form of neutron spectra under investigation. The weighted mean values of the cross-sections and resonance integrals for every type of neutron spectra were adopted as evaluated data.

THERMAL CROSS-SECTIONS

The experimental capture and fission cross-sections, referred to energy 0.0235 eV, may be divided into several groups depending on the shape of the spectrum of the neutrons under investigation:

(1) Thermal cross-sections (let us denote them $\sigma^0(n,\gamma)$ and $\sigma^0(n,f)$), corresponding to neutron energy 0.0253 eV and measured by the time-of-flight method;

(2) Effective thermal cross-sections obtained in neutron spectra with mean energy 0.0253 eV. Two types of such effective cross-sections may be distinguished:

   (a) Thermalized cross-sections - $\sigma_\gamma(th)$ and $\sigma_f(th)$. These thermal cross-sections, averaged over the Maxwellian spectrum having a mean neutron energy of 0.0253 eV, are measured principally in thermal columns by the activation method;

(b) Effective cross-sections - σ_γ(eff) and σ_f(eff). These are also thermal cross-sections, measured in reactor neutron spectra having a mean energy of 0.0253 eV. They are obtained either by the reactivity compensation method (pile oscillation) or by the method of isotope accumulation in the reactor.

The priority of the analysed cross-sections is determined by the methods employed for obtaining them, and these take the following order:

(1) Time-of-flight method;

(2) Activation method;

(3) Reactivity compensation method;

(4) Method of isotope accumulation.

The effective cross-section can be obtained from the relationship of the reactor characteristics:

$$\sigma\ (\exp)=\sigma\ (\text{eff})\sqrt{\frac{\pi}{4}\frac{T_o}{T}} + RI\left[\frac{\phi_{epi}}{\phi_{th}} : \ln\frac{E_{th}}{E_{epi}}\right],$$

where T_0 is the reactor temperature, Φ_{epi}/Φ_{th} is the ratio of the epithermal and thermal fluxes E_{th}/E_{epi} is the ratio of the thermal and epithermal neutron energies, σ(exp) is the cross-section measured in the given experiment.

It follows from the equation that σ(eff) is very sensitive to the interface of thermal and epithermal energy, i.e. to the magnitude of E_{cd} - the cadmium shielding energy, particularly if the nucleus has levels in this region of neutron energies.

Ideally, all three types of thermal cross-sections should coincide. However, in practice considerable disparities are observed.

RESONANCE INTEGRALS

The resonance integral (RI) is the conventional term used to describe the cross-section averaged over the epicadmium neutron spectrum which has an energy distribution proportional to ~ 1/E.

$$RI = \int_{E_{cd}}^{\infty} \sigma(E) \frac{dE}{E} .$$

According to the method of obtaining it, RI can be classified as follows:

(1) RI^0 - calculated from differential data (resonance parameters);

(2) RI(eff) - obtained by the reactivity compensation method;

(3) RI(th) - measured by the activation method with a cadmium shield for more or less "pure" isotopes;

(4) RI(eff) - obtained from experiments on accumulation ("generation") of isotopes in reactor fuel.

Since the magnitude of RI depends on the integration limits, it is necessary to take detailed account of the effect of the lower, E_{cd}, and upper, E_k, boundaries of the neutron spectra.

RI is very sensitive to cadmium cut-off, particularly if the nucleus has resonances in this neutron energy region.

Table 1 presents some characteristics of the isotopes under consideration.

In the experiments, E_{cd} usually fluctuates from 0.3 to 0.68 eV.

It is evident that comparison of RI is valid only in the case of uniform values of E_{cd}. The generally accepted value of E_{cd} = 0.5 eV.

As a rule, in calculating RI_γ and RI_f, infinity is replaced by a finite value of E_k in the upper part of the spectrum, no correction being introduced for the contribution to RI of energies above E_k, and the quantity E_k itself is ignored. It is true that for capture and thresholdless fission processes the contribution to RI from neutrons with energy exceeding 20 MeV amounts to several barn, which are referred in the form of an error to the values of RI obtained by the majority of authors.

For nuclei having a fission threshold, such as ^{231}Pa, ^{243}Am and ^{249}Bk, such an approach is erroneous. Here RI_f is a function strictly dependent on the upper integration limit and consists of two principal parts.

(1) A low-energy part from 0.5 eV to several keV and (2) from a threshold neutron energy value to infinity. The intermediate energy region from several keV to the fission threshold contributes a negligible amount of the order of 0.1 barn to RI_f.

Calculation of RI_f for ^{243}Am from the differential data in Ref. [27] showed that an increase of E_n from 10 to 20 MeV increases RI_f correspondingly from 3.8 to 5.4b, i.e. almost by a factor of 1.5. From experiments it follows that for the same ^{243}Am the value of E_k fluctuates from ~ 30 keV [11] to 20 MeV [27]. Thus, for isotopes with a fission threshold substitution of E_k in the upper part of the neutron spectrum and scatter in the value of E_k can be a cause of discrepancies in RI_f.

When RI_f is obtained directly in integral measurements in reactors, it is also necessary to allow for the perturbation of the relationship 1/E in the fission neutron spectrum above 100 keV (here the spectrum assumes an exponential dependence). Isotopes having a fission threshold are particularly sensitive to this perturbation. Therefore it is imperative that a correction be made to RI_f for the discrepancy between the actual neutron spectrum and the 1/E spectrum. As a result, scatter may arise in the values of the resonance integrals due to

significant differences in the neutron energy spectra of different reactors and due to the thickness and shape of the cadmium filters.

Review of publications on resonance integrals and thermal cross-sections

Resonance integrals calculated from resonance parameters as well as measured cross-sections for energy 0.0253 eV have a very high accuracy. Unfortunately, there is very little such data [10, 16-19, 25, 27, 28, 37, 38, 41, 47, 51, 68, 78, 84].

Direct measurements by the "cadmium difference" method on a Maxwellian spectrum with sufficiently pure samples have been performed in Refs [1, 2, 11, 12, 14, 15, 20, 21, 24, 26, 39, 40, 43-46, 50, 53, 54, 65, 69-73, 75, 77].

Let us now consider the data obtained by the isotope accumulation method [4-9, 13, 22, 23, 26, 29, 30, 35, 36, 42, 45, 49, 60-64, 66, 67, 74, 83, 85]. The sample being investigated, shielded with a cadmium foil, is irradiated in the reactor. The quantity of isotopes accumulating in it is determined on a mass spectrometer after the actinides (elements) have been chemically separated. Then nuclear data taken from the literature are fitted with the aid of the computer so as to reproduce the experimentally found isotopic composition of the irradiated sample. The ratio of the thermal to the epithermal flux (Cd-ratio) is also varied, in order to obtain optimum correspondence between experiment and calculation. The values of σ and RI are the quantities fitted to experiment in these measurements.

However, the isotopes accumulating in the sample appear as result of multiple neutron absorption in competition with different forms of decay of the intermediate nuclei. Matching of the isotope decay scheme and the corresponding self-consistent set of nuclear constants with the quantity of accumulated isotopes requires very precise knowledge of these constants for all the intermediate processes which is virtually unavailable at the present time. It

follows therefore that the accuracy of the accumulation method is low and the data obtained, particularly the values of RI, should be treated with caution.

In many publications there are data on total-RI_{tot}, and absorption resonance integrals, RI_{α}, as well as on neutron absorption cross-sections, σ_{α}. When there is a lack of data on capture, it is possible to use the quantity $\sigma_{\alpha} = \sigma(n,\gamma) + \sigma(n,f)$, if in this case $\sigma(n,f) \ll \sigma(n,\gamma)$, and to consider as a first approximation that $\sigma_{\alpha} \approx \sigma(n,\gamma)$ [6, 23, 26, 29, 30, 35, 44, 48, 61, 70]. If for the resonance integrals the condition $RI_f \ll RI_{\gamma}$ is also fulfilled, it can be assumed as a first approximation that $RI_{\gamma} = RI_{\alpha} = RI_{tot}$. Thus, for even isotopes of curium $RI_{\gamma} < RI_f$ by a factor of 10-50, for ^{241}Am by a factor of 100-150, and for ^{243}Am by a factor of 200-300. This circumstance makes it possible to employ for RI_{γ} the values of RI_{α} and RI_{tot} obtained in Refs [5, 6, 22-25, 28-30, 38, 51].

To obtain absolute values of cross-sections measured by relative methods, reference cross-sections (standards) of such reactions as ^{59}Co(n,γ), ^{197}Au(n,γ), ^{232}Th(n,γ), ^{237}Np(n,γ), ^{238}U(n,γ), ^{235}U(n,f) and ^{239}Pu(n,f) were used in Refs [1-16, 19-24, 29, 30, 33-36, 39-42, 46, 50, 52-57, 60, 62-67, 69-75]. In the course of time the standards have been changed and harmonized systems of reference cross-sections for these reactions have emerged. In the process of analysis part of the experimental data in Refs [3, 4, 7-10, 12, 13, 20, 24, 35, 39, 40, 57, 62-67, 72-74] have been subjected to renormalization, with the cross-sections and the resonance integrals from BNL-325 [31] being used as standards.

As a result of the analysis, the values of the cross-sections and the resonance integrals for certain isotopes have been shown to be invalid in a number of works.

1. Gavrilov, et al. [2, 46]. For ^{241}Am the values of RI_{γ} and RI_f are too high due to uncertainty in the allowance for E_{cd}. Having checked the detector capabilities of the method

with the aid of ^{239}Pu (first resonance at 0.296 eV), the authors evidently retained this value in all their measurements during recording.

Thus, the levels 0.307 eV of ^{241}Am and 0.416 eV for ^{243}Am (see Table 1) serve to make the values of RI_γ and RI_f too high; for ^{241}Am they ought to be excluded from the evaluation. In the case of ^{243}Am the level 0.416 eV is very weak, so that its contribution to RI_γ and RI_f may be neglected and these quantities themselves used in the evaluation.

Since the first levels for isotopes of Cm lie above 0.6 eV, the values obtained for the resonance integrals in this work are quite correct and suitable for evaluation.

2. Zhuravlev, et al. [11]. Here, RI_f of ^{241}Am is almost two times higher than the RI_f obtained from differential data in Ref. [10]. Even if E_{cd} is reduced to the extremely low value of 0.3 eV, it is impossible to approximate RI_f for ^{241}Am in Ref. [11] to the data in Ref. [10]. Evidently the calculation of the integrals contains some hidden error associated with E_{cd} resulting in the value of RI_f for ^{241}Am being too high, so that it cannot be used in the evaluation. The data for ^{243}Am and isotopes of Cm are quite suitable for evaluation.

3. Bak, et al. [1]. In this paper no information is provided on the "purity" of the samples and the value of E_{cd} (the thicknesses of cadmium are given). Analysis has shown that the authors had $E_{cd} \sim 0.3$ eV, so that the lower levels of ^{241}Am made a contribution to RI_γ and RI_f, and these values are left out of consideration. RI_γ and RI_f for ^{243}Am may be used for evaluation in virtue of the fact that the contribution of the very weak level 0.416 eV is negligible.

4. Draper, et al. [14]. No information is provided on the value of E_{cd} so that the values of RI_f for americium-241, 242m and 243, being of illustrative character, are not used in the evaluation.

5. M. Darouzet, et al., [52]. $\sigma(n,\gamma)$ were determined in the neutron spectrum of the "Melusine" swimming-pool type reactor by the activation method. Analysis of the method indicates that the neutron spectrum deviates considerably from the Maxwellian, although a mean energy of 0.0253 eV was assigned to it, which excludes $\sigma(n,\gamma)$ from consideration for americium-241 and 243 and curium-244. (The cross-sections themselves deviate from similar cross-sections in other works by 40-75%).

6. Schuman, et al., [5, 6, 29, 30]. Samples of Am and Cm were irradiated in cadmium cans 1, 3 and 7 mm thick but the numerical values of E_{cd} are not given and its effect on the experimental values of RI_α is not analysed. Moreover, the isomer ratio of 0.773 found for ^{241}Am [5] is much lower than the generally accepted value. Therefore the values of RI_α for Am in Refs [5, 6, 30] are not used. The values of RI_α for Cm isotopes in Refs [5, 29, 30] are quite suitable for evaluation, since the first levels of these isotopes are greater than $E_{cd} = 0.5$ eV.

7. The values of RI_γ for ^{231}Pa in publications [69, 72] are left out of consideration, since they were obtained for a cadmium cut-off energy from 0.1 to 0.3 eV and consequently were not shielded from the effect of levels 0.4 and 0.497 eV (see Table 1).

8. The values of RI_γ for ^{231}Pa in Ref. [76], calculated from the resonance parameters for neutrons with energy from 0.1 to $2 \cdot 10^3$ eV were not used, since a non-generally accepted lower boundary of E_{cd} was selected by the authors.

9. In Refs [61-66, 70, 83] an unjustifiably high accuracy of the cross-sections (from 3% [63] to 10% [65]), obtained by the isotope accumulation method, is observed. It is well known that this method can provide 15-30% accuracy of results, and the data of the above-mentioned works were in fact analysed with such accuracy.

10. Certain omissions and inaccuracies in the experiment on isotope accumulation in a graphite reactor as well as some confusion in the values of the standard - RI_α for ^{59}Co - made it impossible to use the results of Ref. [64].

11. The values of RI_f were measured incorrectly in Ref. [39]. The authors did not introduce a correction for scattering of neutrons by the hydrogen contained in the capsule with the curium and californium powders.

The thermal cross-sections and resonance integrals of the isotopes Pa, Am, Cm and Bk isotopes, selected as a result of analysis and appropriately classified, are listed in Table 2. The weighted mean values of these quantities that are recommended for use as evaluated values are also given in the table.

It should be noted that the limitations imposed on the use of RI_γ and RI_f do not extend to the thermal fission and capture cross-sections given in the same works [1, 2, 11, 14, 24].

DISCUSSION OF THE RESULTS

Protactinium isotopes

Evaluation of the neutron data of protactinium isotopes is complicated for the following reasons:

1. The process of neutron fission of ^{231}Pa has been investigated very little, so that very little data is available on σ(n,f) [71, 80, 81], and no work at all has been published on RI_f;
2. For ^{233}Pa only evaluated values of σ(n,f) and RI_f have been published [31, 58]. Also it is not known whether this isotope has a fission threshold or is not fissioned at all by neutrons;

3. Where there is a dearth of neutron data, $\sigma(n,\gamma)$ for energy 30 keV is used for the evaluation in the case of many isotopes. In the case of isotopes 231 and 233 such a possibility does not exist, because $\sigma(n,\gamma)$ for them has not been measured at all and the values of $\sigma_\gamma \sim \sigma_{tot}$ (for $\sigma_\gamma \ll \sigma_f$), obtained from the total cross-sections, have been measured on a selector only up to 10 keV [68, 76].

Protactinium-231

1. The mean values of all types of capture cross-sections agree with each other within the range $\pm$ 10%. Scatter in σ_γ(eff) ranging up to 40% [69, 71, 74] is most often caused by the nature of the reactor neutron spectra.

2. It is evident that when E_{cd} = 0.4-0.414 eV the strong level is shielded, and the contribution of the weak level to the value of RI_γ can be neglected as a first approximation and use made of the data in Refs [73, 78]. The fact that the values of RI_γ from Refs [73, 78] are $\sim$ 30% above the evaluated values of RI^0_γ [31, 58] cannot be explained simply by the contribution of the weak level because the value of RI_γ(th) = 775b [72], obtained for E_{cd} = 0.512 eV is completely shielded from the effect of both levels, and it agrees well with RI_γ [73, 78]. A possible cause of RI^0_γ in Refs [31, 58] being too low could be the basic assumptions of the theory used in these evaluations.

3. The very low values of $\sigma(n,f)$ compared with $\sigma(n,\gamma)$ [71, 80, 81] are explained by the presence of a fission threshold at neutron energy $\sim$ 400 keV.

4. Values of RI_f for ^{231}Pa have not been published.

Protactinium-233

1. The capture of neutrons in ^{233}Pa results in the formation of two isomers ^{234g}Pa (6.75 h) and ^{234m}Pa (1.18 min) for which the cross-sections have been obtained only by integral methods [65, 69]. The data in Refs [61, 64] are excluded (see our survey above).

For each of the isomers σ_γ(th) [65] and RI_γ [65, 69] are in agreement with the analogous quantities of the evaluation in Ref. [31].

2. There is agreement of the total capture cross-sections in the Maxwellian neutron spectrum and disagreement by a factor of approximately 3.5 for σ_γ(eff) obtained in reactor spectra [60, 66]. The fact that σ_γ(eff) [60] agrees with the mean value of σ_γ(th) allows σ_γ(eff) [66] to be excluded from the analysis. Evidently the neutron spectrum of the MTR reactor [66] differs appreciably from the Maxwellian.

3. The total capture cross-section for isomeric states as well as the total capture integral practically agree with the total $\sigma(n,\gamma)$ and RI_γ which were measured independently.

4. For the ^{233}Pa (n,f) reaction there are no experimental data available.

Americium Isotopes

Americium-241

1. Capture of neutrons in ^{241}Am occurs with formation of two isomers - ^{242}Am (16 h) and ^{242m}Am (152 yr). There exist only integral experiments giving σ(th) and σ(eff). For each isomer, agreement is observed between σ(th) and σ(eff) within the range 7-15%, but they differ by 23-43% from analogous cross-sections from BNL-325 [31].

The total capture cross-section of the isomeric states agrees well with the total capture cross-section measured independently.

All this leads to the conclusion that the values of $\sigma(n,\gamma)$ for ^{241}Am recommended in Ref. [31] are much too low.

2. The ^{241}Am fission process was investigated using both differential and integral methods. The values of $\sigma(n,f)$ obtained agree very well with each other and also with the evaluated values from Ref. [31].

3. Differential measurements of RI_γ do not exist. References [1, 2, 5] were excluded from consideration due to indeterminacy in the value of E_{cd}. As recommended values, it is proposed that RI_γ(th) and RI_γ(eff) from publications [3,8] be employed, since these agree with an accuracy of $\pm$ 10% and are in a good agreement (within the range 3-12%) with the data of Ref. [31].

4. The values of RI_f from Refs [1, 2, 11, 14] were excluded (see survey). The value of RI_f = 14.1b [10], calculated from data from differential measurements for the energy range 0.55 eV-18 MeV, is in good agreement with analogous values from the majority of evaluations [31, 32, 58]. However, there is a 33% disagreement with RI_f (eff) in Ref. [8].

Americium-242g

1. In the only experimental work [13], performed in a reactor at Chalk River as far back as 1951 by the accumulation method, a value of $\sigma(n,\gamma)$ = 5500b was obtained - after renormalization 5100b - which is recommended with 30% accuracy. A sole evaluation exists - JENDL-3 [58] - in which a non-renormalized cross-section from Ref. [13] is given as the recommended value.

2. Values of $\sigma(n,f)$ have been measured only by integral methods [1, 4, 13, 21] and agree satisfactorily both with each other and with data of the evaluations in Refs [31] and [58].

3. There are no experimental data for RI_γ and RI_f, and evaluation of these quantities has been performed only in JENDL-3 [58].

Americium-242m

1. A value of σ(eff) = 1650b has been obtained solely in an experiment on isotope accumulation [4]. The evaluation of this quantity in BNL-325 [31] is acceptable.

2. The fission process was investigated both by differential and integral methods. From Table 2 it can be seen that all types of cross-sections agree well both with each other and with evaluated data from Ref. [31].

3. Experimental data for RI_γ do not exist, and evaluated values are given in four libraries with maximum scatter of 45% [32].

4. For RI_f the integral data in Refs [11, 14] are excluded. As result of analysis of the differential data in Refs [16, 17, 19] we recommend the value $RI_f = 1677 \pm 85$b which agrees (in the range 7-12%) with the same data in other libraries [31, 32, 58].

Americium-243

1. Values of $\sigma(n,\gamma)$ have been measured only by integral methods and have 10% agreement. The values of σ(th) and σ(eff) put forward as recommended values agree very well with the data of the majority of evaluations [31, 32, 58].

2. In the case of ^{243}Am the values of $\sigma(n,f)$ were divided into two groups. The values for σ_f in Refs [2, 34] exceed those in Refs [11, 12, 33] by almost a factor of three. In Ref. [2], the error is great ($\pm$ 55%) and it enables the fission cross-section to be used in a very wide range of dispersion of σ_f (from 90 to 310 mb). Moreover, the fission cross-section from Ref. [11] which is close to zero makes it possible to recommend a cross-section

σ_f(th) = 74 ± 4 mb [33] (a 1989 work), which agrees with the evaluations of UKNDL-81 [32] and JENDL-3 [58].

3. For RI_γ the data in Refs [1, 2] are excluded. The disparity between RI_γ^0 = 1825b [25], calculated from parameters for the neutron energy range 0.532 eV-350 eV and RI_γ(eff) = 2263b [22-24] amounts to 24%.

4. The values for RI_f in Refs [2, 14] are excluded. The value RI^0_γ = 8.45b [27], calculated from differential data in the neutron energy range 0.5 eV-20 MeV, and the directly measured value RI_f(th) = 9.0b [11] agree with each other and with corresponding data of the evaluations in Refs [31, 32, 58].

Curium Isotopes

Curium-242

1. There exists only a single experimental value for σ_γ(eff) = 25b [4], recalculation of which to the results σ_f = 5b and RI_f = 190b in Refs [57, 59] gives σ_γ(eff) = 20 ± 5b (with allowance for the accuracy of the method), which agrees with the values for $\sigma(n,\gamma)$ in other evaluations [31, 32, 58].

2. Only the effective fission cross-sections have been measured [4, 13], and they are cited in all evaluations [31, 32, 58].

3. RI_γ(eff) has been measured in just one work on isotope accumulation [5]. In this situation, RI^0_γ may be replaced by RI_{abs} [38] obtained by calculation from the resonance parameters, since for ^{242}Cm $\sigma_f < \sigma_g$ by a factor of 4-5.

4. In 1988, as a result of calculation from the resonance parameters, a value of RI_f = 12.9 ± 0.7b was obtained [37]. Only two libraries have evaluated this quantity: JENDL-3 [58] and ENDL-82 [32], and their results exceed the value of RI^0_f in Ref. [37] by a factor of 1.5-3 respectively.

Curium-243

1. The values for $\sigma(n,\gamma)$ and RI_γ are published in Ref. [54] and agree well with analogous data of BNL-325 [31].

2. Values for σ_f(th) and σ_f(eff) have been obtained in integral measurements, and the values recommended by us for these agree well with each other and with the data in Ref. [31].

3. Measurements of RI_f have been carried out only by integral methods and the scatter of the mean values amounts to only 8%.

Curium-244

The capture cross-sections have been obtained by integral methods and agree with each other within the limits of the above experimental errors. The absence of data from differential measurements of RI_γ is compensated by the value $RI_{abs} = RI^0_\gamma$ calculated from the parameters [28], since for curium-244 $\sigma_f < \sigma_g$ by a factor of 10-15.

Curium-245

This isotope has been described in a large number of works with satisfactorily consistent data (see Table 2).

Curium-246

1. σ_γ(eff) [35] is left out of account since it has a preliminary character and exceeds by an order of magnitude the remaining cross-sections which agree with each other within the limits of the above experimental errors.

2. The fission process has not been investigated very much but the values for σ_f and RI_f that do exist are in good agreement.

Curium-247

1. The scanty data on neutron capture is subject to great uncertainty (of the order of 50%). The value for σ_γ(eff) = σ_γ(th) = 60b measured in Refs [42, 46] is confirmed indirectly by the value σ_γ(eff) = 48b [22] obtained as the difference in the cross-sections $\sigma_{abs} - \sigma_f$, and is recommended by us for evaluation.

2. The available values of RI_γ(th) = 490 ± 100 [46] and RI_γ(eff) = 800 ± 400 [42] differ by 40% in absolute value but agree within the above error limits and do not contradict analogous data from evaluations [31, 32, 58].

3. The values of σ(n,f) measured in the Maxwellian spectrum decay in two groups, the cross-sections in which differ by 26-33%. On the basis of analysis of the integral experiments in Refs [11, 39, 40, 43] it is considered that the accuracy of σ_f(th) should be from 5-10% to 20% and the normal mean fission cross-section taken as the recommended value.

4. The values of RI_f, which are presented in the form of preliminary values in Ref. [39] are left out of consideration. The recommended values for RI_f(th) and RI_f(eff) are not inconsistent with each other, although they differ in absolute value by 17%.

Curium-248

Reference [46] is not taken into account owing to the indeterminacy in E_{cd}.

Curium-249, 250

These two isotopes are investigated in passing mainly in accumulation experiments, and thus data is available only on the effective thermal capture cross-sections (see Table 2).

To date, only one library [58] has offered evaluated data for these curium isotopes, taking as a basis the values $\sigma(n,\gamma)$ and $\sigma(n,f)$ from Refs [55, 56].

It should be noted that in Ref. [59] the mean cross-sections σ(th) and σ(eff) for isotopes of curium are also evaluated separately.

Berkelium isotopes

Berkelium-249

1. The fission process has hardly been investigated at all. The only experiment gives σ_f(eff) < 6 barn [86]. Evaluated values of $\sigma(n,f)$ and RI_f exist only in the libraries ENDL-82 [32] and JENDL-3 [58] and differ from each other by a factor of 2.5-3.

2. No direct measurements of $\sigma^0(n,\gamma)$ exist. There are available integral data with large scatter of σ_γ(eff) and measurements of the total cross-sections at the thermal point, which enable us to evaluate the order of magnitude of $\sigma^0(n,\gamma)$. In fact, knowing σ_{tot}, measured by the time-of-flight method with good accuracy, and allowing for the relationship $\sigma_f \ll \sigma_\gamma$ for ^{249}Bk, we can consider as a first approximation that $\sigma_{tot}^0 \approx \sigma^0(n,\gamma)$. The value $<\sigma^0(n,\gamma)>$ = 658 ± 90b, averaged from the data in Refs [82, 84], agrees with the value $\sigma^0(n,\gamma)$ = 746b [84], calculated from the resonance parameters, and enables it to be stated that $\sigma^0(n,\gamma)$ is located in the cross-section interval 650-750b.

An approximate value of σ_γ(eff) can be derived from measurements on reactor spectra. According to the accuracy of the accumulation method, the values of σ_γ(eff) in Refs [26, 83] are taken with a 30% error, and the value of the normal mean $<\sigma_\gamma(\text{eff})> = 700 \pm 200$b in Refs [26, 83, 85] is also included in the above capture cross-section interval.

3. Apart from measurements in two different kinds of experimental conditions [2], which gave consistent values of RI_γ(th), there are no other publications on resonance capture integrals. To confirm the data for RI_γ(th) in Ref. [2], use is made of RI_{tot}^0 calculated from the resonance parameters obtained from measurements of the total cross-sections for neutron energies below 46 eV [82] and below 100 eV [84]. Taking into account the relationship $\sigma_f \ll \sigma_\gamma$ for ^{249}Bk, we can as a first approximation use RI_{tot}^0 for RI_γ^0 which agrees with RI_γ(th) [2].

For ^{249}Bk it is to be noted that the values of both $\sigma(n,\gamma)$ and RI_γ from the libraries [31, 58] coincide, and this is confirmed by the corresponding cross-sections recommended in the present work

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Table 1

Characteristics of Pa, Am and Bk isotopes

Isotope	E_n (eV)	$2gT_n$ (MeV)	E_f (MeV)
^{213}Pa	0,400 0,497	0,0740 0,0134	~0,4
^{241}Am	0,307 0,547	0,0560 0,923	
^{243}Am	0,416	0,00084	0,7-0,8
^{249}Bk	0,195	0,102	1,07

Note: E_n is the position of the level, T_n is the neutron width of the level, E_f is the fission threshold

Table 2

Capture cross-sections in protactinium isotopes

Reaction	σ_γ^0, barn	σ_γ(th), barn	σ_γ(eff), barn
^{231}Pa(n,γ)	200±5 [76] 260±13 [73]	200±5 [70] 218±14 [72] 201±22 [72] 201±6 [75] 186±13 [77]	175±30 [71] 219±6 [69] 299±60 [74] a)
weighted mean	208 19	201±13	218±13
^{232}Pa(n,γ)^{234}Pa		25±6 [64] b) 19±3 [65]	32±8 [64] b)
weighted mean		19±3 [65]	
^{233}Pa(n,γ)^{234m}Pa		43±11 [64] b) 20±4 [65]	75±19 [64] b)
weighted mean		20±4 [65]	
^{233}Pa(n,γ) $^{234(m+g)}$Pa		39±4 [65] 68±14 [64] b) 42±5 [67] 31,4±7,9[63]	37±14 [60] 55±14 [61] b) 107±27 [64] b) 128±20 [66] b)
weighted mean		39,0±3,5	37±14 [60]

Note:

(a) The data have been renormalized to the unified system of standards [31].

(b) The data have been excluded from consideration for the reasons stated in the survey of works or in the process of analysis.

(c) Owing to uncertainty in the value of E_{cd}, the data are used only as auxiliary values, particularly where information is lacking.

(d) In brackets under the calculated values for RI_γ and RI_f are shown the energy limits of integration given in the literature.

(e) No data are available on RI_f for $^{231, 233}$Pa.

(f) The weighted mean values are recommended as evaluated values for the particular type of cross-section (resonance integral).

(g) No data available on RI_f for ^{249}Bk.

Table 2 (contd.)

Fission cross-section in Pa isotopes

Reaction	σ_f^o, mbarn	σ_f(th), mbarn	σ_f(eff), mbarn
^{231}Pa(n,f)	14±25%[80]	19±4 [81]	10±5 [71]
weighted mean	14±4 [80]	19±4 [81]	10±5 [71]

Resonance capture integrals for Pa isotopes

Reaction	RI_γ^o, barn	RI_γ(th), barn	RI_γ(eff), barn
^{231}Pa(n,γ)	760±80 [78] (0.414 - ∞ eV)	775±70 [70] [a]	
		800±80 [73] [a]	
weighted mean	760±80 [78]	786±15	
^{233}Pa(n,γ)^{234g}Pa		454±100[65] [a]	436±67 [69]
			487±122[64] [ab]
weighted mean		454±100[65]	436±67 [69]
^{233}Pa(n,γ)^{234m}Pa		464±90 [65] [a]	722±180[64] [ab]
weighted mean		464±90 [65]	
^{233}Pa(n,γ)$^{234(m+g)}$Pa	901±45 [68] (0,4-10^4 eV)	918±100[65] [a]	1209±302[64] [ab]
		908±90[67] [a]	
		865±90[63] [a]	
weighted mean	901±45 [68]	897±23	

Table 2 (contd.)

Capture cross-sections in americium isotopes

Reaction	σ_γ^o, barn	σ_γ(th), barn	σ_γ(eff), barn
$^{241}Am(n,\gamma)^{242g}Am$		670±60 [1]	775±80 [4]
		780±78 [2]	635±67 [7] a)
		748±20 [3]	
weighted mean		745±24	693±69
$^{241}Am(n,\gamma)^{242m}Am$		70±5 [1]	95±26 [4]
		73±14 [2]	
		83,8±2,6[3]	
weighted mean		80±3	95±26 [4]
$^{241}Am(n,\gamma)^{242(m+g)}Am$		853±64 [2]	820±82 [6]
		740±65 [1]	
		831±23 [3]	
weighted mean		824±20	820±32 [6]
$^{242g}Am(n,\gamma)$			5100±1550[60] a)
$^{242m}Am(n,\gamma)$			1650±330[4]
$^{243}Am(n,\gamma)$		73±6 [1]	78±6 [23]
		83±6 [2]	77±2 [9]
		72±2 [24] a)	70±15 [35] b)
		83±10 [26]	
weighted mean		73±2	77±3

Table 2 (contd.)

Fission cross-sections in americium isotopes

Reaction	σ_f^o, barn	σ_f(th), barn	σ_f(eff), barn
^{241}Am(n,f)	3,13±0,19[10]	2,80±0,25[2]	2,8±0,3[13] [a]
		3,20±0,15[11]	4,0±0,8[4]
		3,15±0,10[1]	
		2,91±0,14[12] [a]	
		3,8±0,2 [15]	
weighted mean	3,13±0,19[10] [a]	3,15±0,13	3,0±0,3
^{242g}Am(n,f)		2950±800[21]	2100±420[4]
		2100±200[1]	2500±750[13]
weighted mean		2150±200	2195±170
^{242m}Am(n,f)	6328±320[16]	6080±500[11]	6800±1360[4]
	6950±250[19]	7372±310[20] [a]	
		5910±460[12] [a]	
weighted mean	6713±302	6748±488	6800±1360[4]
^{243}Am(n,f)		0,20±0,11[2]	
		≤0,067 [12] [a]	
		0,074±,004[33]	
		~0,0 [11]	
		.1983±,0042[34]	
weighted mean		0,074±0,010	

Table 2 (contd.)

Resonance capture integrals in americium isotopes

Reaction	RI_γ^0, barn	RI_γ(th), barn	RI_γ(eff), barn
$^{241}Am(n,\gamma)^{242g}Am$		2100±200[1]c)	1406±124[3]a)
		1570±10 [2]c)	
weighted mean		1576±30c)	1406±124[3]
$^{241}Am(n,\gamma)^{242m}Am$		300±30 [1]c)	220±19 [3]a)
		230±80 [2]c)	
weighted mean		291±23c)	220±19 [3]
$^{241}Am(n,\gamma)$ $^{242(m\,g)}Am$		2400±200[1] c)	1100±100[5] c)
		1800±100[2]c)	1469±147[8]a)
		1626±143[3]a)	
weighted mean		1626±143[3]	1469±147[8]
$^{242g}Am(n,\gamma)$	no experimental data		
$^{242m}Am(n,\gamma)$	no experimental data		
$^{243}Am(n,\gamma)$	1825±80 [25] (Ek=250 eV)	2300±200[1]c)	2290±50 [22]
		2210±150[2]c)	2250±50 [23]
			2249±50 [24]a)
			1930±190[9]
weighted mean	1825±80 [25]	2257±46c)	2250±20

Table 2 (contd.)

Resonance fission integrals in americium isotopes

Reaction	RI_f^o, barn	RI_f(th), barn	RI_f(eff), barn
^{241}Am(n,f)	14,1±0,9[10] (f κ=1 MeV)	22,5±1,7[2] c)	22,2±2,1[8] a)
		21±2 [1] c)	
		27,7±1,6[11] c)	
weighted mean	14,1±0,9[10]	21,9±1,7	22,2±2,1[8]
^{242g}Am(n,f)	no experimental data		
^{242m}Am(n,f)	1553±78 [16] (Ek=20 MeV)	2260±200[11] c)	
	1570±110[17] (Ek=3.7MeV)	2027±100[14] c)	
	1800±65 [19] (Ek=20MeV)		
weighted mean	1677±85	2070±100	
^{243}Am(n,f)	8,45±0,45[27] Ek=2 MeV)	17,1±1,3[2] c)	
		9,0±1,0[11]	
weighted mean	8,45±0,45[27]	9,0±1,0[11]	

Table 2 (contd)

Capture cross-sections in curium isotopes

Reaction	σ_γ^o, barn	σ_γ(th), barn	σ_γ(eff), barn
^{242}Cm(n,γ)			20±5[4,57][a]
^{243}Cm(n,γ)		130,7±9,6[54]	137,4±9,6[54]
			200±100[4]
weighted mean		130,7±9,6[54]	137,4±9,6[54]
^{244}Cm (n,γ)		15,2±1,2[46]	25±10 [35]
			14±4 [42]
			8,4±4,2[23]
			14,5±4 [22]
weighted mean		15,2±1,2[46]	13,1±2,2
^{245}Cm(n,γ)	341±34 [41]		340±20[45]
			200±100[35]
			360±50[42]
			260±130[26]
weighted mean	341±34 [41]		336±16
^{246}Cm(n,γ)		1,14±0,30[46]	1,5±0,5[42]
		1,2±0,4 [45]	15±10 [35][b]
weighted mean		1,16±0,03	1,5±0,5[42]
^{247}Cm(n,γ)		60±20 [46]	60±30 [42]
			48 [22][b]
weighted mean		60±20 [46]	60±30 [42]
^{248}Cm(n,γ)	2,59±0,26[47]	10,7±1,5[46][b]	3±1 [42]
		2,63±0,26[50]	6,0±2,5[49]
weighted mean	2,59±0,26[47]	2,63±0,26[50]	3,4±1,0
^{249}Cm(n,γ)			1,6±0,8[56]
^{250}Cm(n,γ)			80±30 [55]

Table 2 (contd.)

Fission cross-sections in curium isotopes

Reaction	σ_f^o, barn	σ_f(th), barn	σ_f(eff), barn
^{242}Cm(n,f)			4,6 [4,13]a)
^{243}Cm(n,f)		579±31 [54]	633±27 [54]
		640±46 [12]a)	750±75 [4]
		672±60 [53]	
weighted mean		609±26	646±37
^{244}Cm(n,f)		1,0±0,2[11]	1,5±10[42]
		1,14±0,5[40]a)	
weighted mean		1,02±0,05	1,5±1,0[42]
^{245}Cm(n,f)	2143 58 [41]	1900±100[2]	1880±300 [23]
		2070±150[11]	2000±150 [35]
		1740±140[12]a)	1800±300 [36]
		1920±180[39]	2030±200 [42]
		2088±37[40]a)	2000±150 [26]
		2040±80[43]	
weighted mean	2143 58 [41]	2043±38	1980±32
^{246}Cm(n,f)		0,14±0,05[11]	
		0,176± 005[40]a)	
weighted mean		0,158±0,080	
^{247}Cm(n,f)	106±53 [87]	80±7 [11]	100±50 [42]
		85±5 [40]a)	
		108±5 [43]	
		120±12 [39]	
weighted mean	106±53 [87]	98,3±19,7	100±50 [42]
^{248}Cm(n,f)		0,35± 07[40]a)	
		0,39± 08[11]	
weighted mean		0,37±0,04	

Table 2 (contd.)

Resonance capture integrals for curium isotopes

Reaction	RI_γ^o, barn	RI_γ(th), barn	RI_γ(eff), barn
$^{242}Cm(n,\gamma)$	115±53 [38]		150±40 [5]
$^{243}Cm(n,\gamma)$			214,4±20,3[54]
$^{244}Cm(n,\gamma)$	643±53 [28]	626±53 [46]	650±50 [42]
			650±50 [23]
weighted mean	643±53 [28]	626±53 [46]	650±25
$^{245}Cm(n,\gamma)$	100 [41]		110±20 [42]
			101±8 [45]
weighted mean	100 [41]		102±3
$^{246}Cm(n,\gamma)$	101±11 [47] (Ek=5 keV)	118±15 [46]	135±25 [42]
		121±7 [45]	110±40 [29]
weighted mean	101±11 [47]	120±1	128±11
$^{247}Cm(n,\gamma)$		490±100[46]	800±400[42]
$^{248}Cm(n,\gamma)$	259±12 [47] (Ek=3keV)	250±24 [46]	275±75 [42]
		267±27 [50]	
weighted mean	259±12 [47]	275,5±8,5	275±75 [42]

Table 2 (contd.)

Resonance fission integrals for curium isotopes

Reaction	RI_f^o, barn	RI_f(th), barn	RI_f(eff), barn
^{242}Cm(n,f)	12,9±0,7[37] (Ek=50,9 keV)		
^{243}Cm(n,f)		1480±150[53]	1575±136[54]
			1860±400[42]
weighted mean		1480±150[53]	606±87
^{244}Cm(n,f)		13,4±1,5[11]	12,5±2,5[42]
		18,0±3,6[40]a)	
weighted mean		14,1±1,4	12,5±2,5[42]
^{245}Cm(n,f)	721±20%[41]	850±60[2]	750±50 [23]
		805±80[11]	
		1124±100[39]a)	
		789±40[40]a)	
weighted mean	721±20: [41]	835±53	750±50
^{246}Cm(n,f)		13,3±1,5[11]	
		10,2±0,4[40]a)	
weighted mean		10,4±0,8	
^{247}Cm(n,f)	890±53 [87] (0,1eV 80.keV)	730±70[11]	935±190[42]
		798±50[40]a)	
		1045±110[39]ab)	
weighted mean	890± 53 [87]	775±32	935±190[42]
^{248}Cm(n,f)		13,6±0,8[40]a)	
		13,1±1,5[11]	
weighted mean		13,6±0,1	

Table 2 (contd.)

Capture cross-sections in berkelium isotopes

Reaction	σ_γ^o, barn	σ_γ(th), barn	σ_γ(eff), barn
^{249}Bk(n,γ)	710±40 [84]	1800±10[2] [b]	1100±300[85]
	500±70 [82]		660±200[26]
			350±150[83]
weighted mean	658±90		700±200

Fission cross-sections in berkelium isotopes

Reaction	σ_f^o barn	σ_f(th) barn	σ_f(eff) barn
^{249}Bk(n,f)		<6 [86]	

Resonance capture integral in berkelium isotopes

Reaction	RI_γ^o, barn	RI_γ(th), barn	RIγ(eff), barn
^{249}Bk(n,γ)	870±120[82] (0,4÷46 eV)	1100±100[2]	
	1087±110[84] (0,625÷100 eV)	1300±300[2]	
weighted mean	988±108	1120±80[2]	

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