KERNFORSCHUNGSZENTRUM

KARLSRUHE

Juli 1970

KFK 1186
EANDC(E) 128"U"

Institut für Neutronenphysik und Reaktortechnik
Projekt Schneller Brüter

Microscopic Neutron Nuclear Data and 5-Group Cross Sections for the Actinides ^{231}Pa, ^{232}U, ^{234}U, ^{236}U, ^{237}U, ^{237}Np, ^{238}Np, ^{236}Pu, ^{238}Pu, ^{241}Am, ^{242}Cm

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by

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Abstract

This report represents a first step in the framework of an accurate systematic evaluation for the following transactinium isotopes: ^{231}Pa, ^{232}U, ^{234}U, ^{236}U, ^{237}U, ^{237}Np, ^{238}Np, ^{236}Pu, ^{238}Pu, ^{241}Am, ^{242}Cm.

Microscopic neutron nuclear data have been evaluated and 5-group values derived for the radiative capture, the fission, the (n,2n) cross section and for the mean number of neutrons per fission. These data have been requested for safeguard studies and burnup calculations. In the case of lack of experimental data simple systematic methods have been applied for the determination of the cross sections.

Zusammenfassung

Diese Arbeit stellt einen ersten Schritt im Rahmen einer exakten systematischen Auswertung für die folgenden Transactiniumisotope dar: ^{231}Pa, ^{232}U, ^{234}U, ^{236}U, ^{237}U, ^{237}Np, ^{238}Np, ^{236}Pu, ^{238}Pu, ^{241}Am, ^{242}Cm.

Für den Einfangquerschnitt, den Spaltquerschnitt, den (n,2n)-Querschnitt und die mittlere Anzahl der Spaltneutronen sind mikroskopische Daten ausgewertet und 5-Gruppenkonstanten bestimmt worden. Diese Daten sind für Untersuchungen in der Spaltstoffflußkontrolle und für Abbrandrechnungen angefordert worden. Im Falle fehlender experimenteller Dateninformation wurden einfache systematische Methoden zur Bestimmung der Wirkungsquerschnitte angewandt.

Contents Page

I. Introduction

For the purpose of safeguard studies and burnup calculations for the analysis of the fuel-cycle the following types of microscopic neutron nuclear data have been evaluated and transformed into 5-group cross sections:

σ_γ - radiative caopture cross section
σ_f - fission cross section
σ_{2n} - cross section for the (n,2n)-process
$\bar{\nu}$ - mean number of secondary neutrons per fission

The investigations were carried out for the isotopes

$^{231}_{91}Pa$
$^{232}_{92}U$, $^{234}_{92}U$, $^{236}_{92}U$, $^{237}_{92}U$
$^{237}_{93}Np$, $^{238}_{93}Np$
$^{236}_{94}Pu$, $^{238}_{94}Pu$
$^{241}_{95}Am$
$^{242}_{96}Cm$

The whole energy range extending from 0 to 10 MeV has been subdivided in the following five groups:

Group	Energy range lower limit	Energy range upper limit	Characterization
1	800 keV	10 MeV	fast region
2	46.5 keV	800 keV	fast region
3	1 keV	46.5 keV	unresolved resonance region
4	0.465 eV	1 keV	(partly) resolved resonance region
5	0.025 eV		thermal group

As weighting spectra over the whole energy range the spectrum of a typical thermal reactor and that of a typical fast reactor have been used (Figures 1,2,3).

Zum Druck eingereicht am 8. Juli 1970

The thermal group comprises only the energy of 0.025 eV and the values indicated as thermal ones are in general unweighted neutron data at 0.025 eV.
This report represents the results of a first evaluation of the still very sparse experimental data information for the isotopes investigated. For a later time more thorough evaluations covering the full range of microscopic nuclear data types are envisaged. As far as reasonable and practicable use has been made of the existing literature. CINDA 68 /-61_7 has been taken as basic source of reference information. Highest priority has been given as far as considered suitable to the most recent references. Whenever possible already existing evaluations have been preferred. A comparison of the present results with later published evaluationswhich could no more be taken into account is given in chapter V.
The large gaps in the basic experimental data necessitated in man cases the use of nuclear systematics for the determination of the desired data. Here rather simple considerations and methods had to be applied because of the limited space of time which has been available from the side of the Karlsruhe safeguard project for the evaluation of the required data.

For each of the various energy ranges i.e. the thermal one, the (partly) resolved resonance region, the unresolved resonance region and the fast energy range the derivation of the desired neutron nuclear data is treated in a special chapter including each time all of the isotopes studied.

The tables 11 and 12 give a complete survey about the computed 5-group constant values for the two reactor types.
In performing the calculations reported in this paper use was made of the IBM 360/65 and partly of the IBM 7074, too.

II. Neutron cross sections at thermal energy (0.025 eV)

For the thermal values of the radiative capture and fission cross sections of the various isotopes published experimental or evaluated information was available with the exception of the capture cross sections of ^{238}Np and ^{236}Pu. These have been calculated according to the formula

$$\sigma_{\gamma therm} = \frac{\bar{\Gamma}_\gamma}{\bar{\Gamma}_f} \sigma_{\gamma therm} \qquad (II.1)$$

Here $\bar{\Gamma}_\gamma$ and $\bar{\Gamma}_f$ are averages of the partial widths for capture and fission for s-wave resonances.

The above formula is only strictly valid in the Breit-Wigner one-level approximation, where $\bar{\Gamma}_f$ and $\bar{\Gamma}_\gamma$ are the parameters belonging to the first resonance. Because of unknown resonance parameters for the two isotopes the average values from table III.1.1 in chapter III and the thermal fission cross section from table 1 have been used.

The thermal σ_f- and σ_γ-values for the isotopes considered are listed in table 1 together with the corresponding documentation. The preferred values are given in the tables 11 and 12.

Values for the mean number of neutrons generated by thermal fission $\bar{\nu}_{therm}$ are quoted in table 7. Their determination is described in chapter IV.5 which deals in general with the energy dependence of $\bar{\nu}$.

III. Neutron cross sections in the resonance region

The experimental information in this energy range consists of measured resonance integrals and resolved resonance measurements available for all isotopes except ^{237}U, ^{238}Np, ^{236}Pu and ^{242}Cm. The latter information is only for a few isotopes given up to some hundreds of eV. The resonance integrals offer the possibility to determine directly by means of average resonance parameters group averaged cross sections weighted with a 1/E spectrum.

Below 46.5 keV which is the upper limit of group 3 only s- and p-wave neutrons contribute to the radiative capture and fission cross sections. Consequently one has

$$\langle\sigma_x\rangle^i = \frac{\int_{\Delta E_i} \sigma_x(E)\ \phi(E)dE}{\int_{\Delta E_i} \phi(E)dE} = \langle\sigma_x^{\ell=0}\rangle^i + \langle\sigma_x^{\ell=1}\rangle^i \qquad \text{(III.1)}$$

where $x = \gamma$ or f

$i = 4$ or 3

For the isotopes studied it can be assumed to a good approximation that they are present in very strong dilution. If one uses the narrow-resonance approximation for the collision density, the cross sections of an isotope μ averaged over an energy group i are given in this case by the following relation [9]

$$\langle\sigma_x^\mu\rangle_\infty^i = \frac{\int_{\Delta E_i} \sigma_x^\mu(E)\ F(E)dE}{\int_{\Delta E_i} F(E)dE} \qquad \begin{array}{l} x = \gamma \text{ or } f \\ \text{with } i = 4 \text{ or } 3 \\ F(E) = \text{collision density} \\ \quad = \Sigma_t(E)\ \phi(E) \end{array} \qquad \text{(III.2)}$$

In addition to the above mentioned conditions this formula presupposes that the sum of the total cross sections of all other materials $\mu' \neq \mu$ is constant over ΔE_i. One has to be aware of the fact that this second condition is only then fulfilled, if the flux is not disturbed by resonances of the other materials $\mu' \neq \mu$, which is actually not the case.

The determination of the mean number of neutrons per fission in the resonance region is described in chapter III.5. The results are given in table 7. The values for σ_f, σ_γ and $\bar{\nu}\sigma_f$ averaged over the energy groups 4 and 3 are quoted in table 11 for a thermal reactor and in table 12 for a fast reactor spectrum.

III.1 Thermal reactor

For the collision density in the epithermal region the well-known 1/E-dependence was assumed which is expected to hold rather well in the whole region of a thermal reactor. This special energy dependence of the collision density enables us to determine the cross section averages over the energy group 4 (0.465 eV - 1 keV) by means of the measured infinite dilution resonance integral. More explicitly this would mean that the average cross sections over group 4 are obtained as difference between the measured infinite dilution resonance integral and the integral over the resonances above a cutoff energy E^* of 1 keV. The calculation of the latter one has been performed in principle by Dresner [10] and is outlined farther below

$$\langle\sigma_x\rangle_4 = \frac{1}{\int_{(4)} \frac{dE}{E}} \left[(RI_x^\infty)^{exp}_{E^*=E_{Cd}} - (RI_x)_{E^*=1keV} \right] \qquad \text{(III.1.1)}$$

where $x = \gamma$ or f

That procedure permits the application of average resonance parameters instead of resolved ones in an energy region where the latter ones should be used, but where in general they are known only in a small subrange. This is due to the fact that the resonance parameters have to be inserted only in the second term of equation (III.1.1), and that this term concerns the energy range above 1 keV, i.e. a range where the application of average resonance parameters is appropriate.

For the measured resonance integral $(RI_x^{\infty})^{exp}$ the cutoff energy E^* is equal to the cadmium cutoff energy. It has values between 0.4 and 0.6 eV depending upon the thickness of the Cd-layer covering the considered sample. We have assumed the cadmium cutoff for all measured resonance integrals as identical with the lower boundary of group 4. The resulting error is only then significant, if there is a resonance in the neighbourhood of 0.5 eV.
In the region above 1 keV, however, no resonances are known for any of the isotopes. The contributions of these resonances to the total resonance integral is only a small correction. Here the average resonance parameters will be sufficient and the cross sections averaged over the energy group 3 were obtained by computation of the resonance integrals as given by Dresner within the limits of 1 keV and 46.5 keV.

$$\langle\sigma_x\rangle_3 = \frac{1}{\int_{(3)} \frac{dE}{E}} (RI_x)_{1\ keV}^{46.5\ keV} \qquad \text{where } x = \gamma \text{ or } f \qquad \text{(III.1.2)}$$

The actual calculation of the resonance integrals proceeds as follows. The contribution of the resonances above some cutoff energy to the total resonance integral can be written in the following form

$$RI_x(E^*) = \sum_{J=|I-\frac{1}{2}|}^{I+\frac{1}{2}} g_J\, I_x^{\ell=0}(J) + \sum_{J=|I-\frac{3}{2}|}^{I+\frac{3}{2}} g_J\, I_x^{\ell=1}(J) \qquad \text{(III.1.3)}$$

where $x = \gamma$ or f

The first term of this equation represents the contribution of the s-wave resonances, the second that of the p-wave resonances.
The calculation of the resonance integrals has been carried out according to Dresner /‾10_7.
The quantities I_x are given by the expressions below.

$$I_x^{\ell=0}(J) = \frac{2\pi^2}{\bar{D}_J} \int_{E^*}^{\infty} \lambda^2(E) \left\langle \frac{\Gamma_n \Gamma_x}{\Gamma} \right\rangle_J \frac{dE}{E} \qquad x = \gamma \text{ or } f \qquad \text{(III.1.4)}$$

The bracket denotes an average with respect to the statistical distributions of the reaction widths.
The insertion of the reduced neutron width defined for s-wave resonances by

$$\Gamma_n^J = \Gamma_n^{(0)J} E^{+\frac{1}{2}} \qquad \text{(III.1.5)}$$

leads to

$$I_x^{\ell=0}(J) = \frac{2\pi^2}{\bar{D}_J} \int_{E^*}^{\infty} \lambda\!\!\!^{-2}(E)\, \sqrt{E} < \frac{\Gamma_n^{(0)J}\Gamma_x}{\Gamma^J} > \frac{dE}{E} \qquad \text{(III.1.6)}$$

First we assume that all the resonances in the energy range from E^* to infinity have the same partial widths namely $\bar{\Gamma}_n^{(0)}$, $\bar{\Gamma}_\gamma$, $\bar{\Gamma}_f$. Then one obtains

$$I_x^{\ell=0}(J) = \frac{2\pi^2\, \lambda\!\!\!^{-2}(E^*)}{\bar{D}_J} \bar{\Gamma}_x^J \int_{E^*}^{\infty} \frac{\bar{\Gamma}_n^{(0)J}\, dE}{(\frac{E}{E^*})(\bar{\Gamma}_n^{(0)J}\sqrt{E}+\bar{\Gamma}_\gamma^J+\bar{\Gamma}_f^J)\sqrt{E}} \qquad \text{(III.1.7)}$$

With transformation to the new variable $y^2 = \frac{E}{E^*}$ it follows

$$I_x^{\ell=0}(J) = \frac{4\pi^2\, \lambda\!\!\!^{-2}(E^*)}{\bar{D}_J} \bar{\Gamma}_x^J \int_1^{\infty} \frac{dy}{y^2(y+B)} =$$

$$= \frac{4\pi^2 \lambda\!\!\!^{-2}{}_0}{\bar{D}_J} \frac{\bar{\Gamma}_x^J}{E^*} \left(\frac{B-\ln\,(1+B)}{B^2}\right)_J \qquad \text{(III.1.8)}$$

$$\text{with } B(J) = \frac{\bar{\Gamma}_\gamma^J + \bar{\Gamma}_f^J}{\bar{\Gamma}_n^{(0)J}\sqrt{E^*}}$$

and $\qquad x = \gamma$ or f

For p-waves the energy dependence of the neutron width is approximately given by

$$\bar{\Gamma}_n^J \simeq \bar{\Gamma}_n^{(0)J} \, E^{\frac{3}{2}} \, \frac{R^2}{\lambda_0^2} \qquad \text{(III.1.9)}$$

Thus one obtains analogously as for the s-waves

$$I_x^{\ell=1}(J) = \frac{4\pi^2 \lambda^2(E^*)}{\bar{D}_J} \; \bar{\Gamma}_x^J \int_1^\infty \frac{dy}{y^3+B'} \qquad \text{(III.1.10)}$$

$$= \frac{4\pi^2 \lambda_0^2}{\bar{D}_J} \, \frac{\bar{\Gamma}_x}{E^*} \Big[\frac{1}{B'^{2/3}\sqrt{3}} \Big\{ \frac{\pi}{2} + \text{arc tan} \, \Big(\frac{B'^{1/3}-2}{B'^{1/3}\sqrt{3}} \Big) \Big\} - \frac{1}{6B'^{2/3}} \; \times$$

$$\times \ln \Big(\frac{(B'^{1/3}+1)^2}{B'^{2/3}-B'^{1/3}+1} \Big) \Big]$$

where $B'(J) = \dfrac{\bar{\Gamma}_\gamma^J + \bar{\Gamma}_f^J}{\bar{\Gamma}_n^{(0)J} E^{*3/2} \cdot C}$ with $C = \dfrac{R^2}{\lambda_0^2} = \dfrac{\sigma_{pot}}{4\pi\lambda_0^2} \approx 4.2 \cdot 10^{-6} \, [\text{eV}^{-1}]$

for the nuclei considered.

The used symbols have the following meaning:

R - effective radius of the nucleus

σ_{pot} - potential scattering cross section, assumed to be 11b

λ_0 - reduced neutron wave length

$\lambda_0 = 455 \cdot 18 \, \frac{A+1}{A} \sqrt{b} \, \sqrt{eV}$

with A = mass number of the target nucleus

Here we have taken $\lambda_0^2 = 2.09 \cdot 10^5 \, [b \cdot eV]$ for all the nuclei considered

$g_J = \dfrac{2J+1}{2(2I+1)}$ - statistical spin factor

with J - total angular momentum of the compound nucleus

I - spin of the target nucleus

$\bar{D}_J$ - average level spacing

Γ_x - partial width for fission (x=f) and capture (x=γ) respectively

Γ_n - neutron width

$\Gamma_n^{(0)}$ - reduced neutron width

Γ - total width = $\Gamma_n + \Gamma_\gamma (+ \Gamma_f)$

E^* - cutoff energy above which the contribution of the resonances to the resonance integral has been calculated

The effect of fluctuations in the neutron widths has been taken into account subsequently for nonfissile nuclei by applying according to Dresner a correction factor to the expression for $I_x^{\ell=0}$. These factors with values between 1.0 and 0.7 depending on the value of B have been taken from the curve of Kuhn and Dresner [10, pp. 98]. Γ_γ has been chosen as constant. Because of the many exit channels this is a good assumption for Γ_γ.
For fissile nuclei the statistical distribution of the fission widths has in a strict sense to be regarded addionally. Because of the large uncertainties in the fission widths, however, the rather extensive calculations were not considered worthwhile at present. This means that for fissile nuclei no correction factors at all have been applied. Doppler broadening of the resonances as well as interference effects between the resonances have not been considered.

A. Resonance parameters

The average resonance parameters used in the calculations are summarized in the tables III.1.1 and III.1.2. Even and odd isotopes are listed separately. For the p-wave strength function the value $S_1 = 2.0 \cdot 10^{-4}$, independent of J, was assumed throughout for all isotopes.
Since even nuclei have the spin I=0, the quantum numbers J of the total angular momentum may take the values

$$J = \frac{1}{2} \quad \text{for } \ell=0$$
$$J_{1,2} = \frac{1}{2}, \frac{3}{2} \quad \text{for } \ell=0 \qquad \text{(III.1.11)}$$

Then it follows for the statistical spin factor of even nuclei for s-waves $g_{J=1/2} = 1$ and for p-waves $g_{J=1/2} = 1$ and $g_{J=3/2} = 2$. The resonance integral consists therefore of one s-wave resonance series and two p-wave resonance series. For odd nuclei the possible J-values and the statistical factors g_J have been tabulated in table III.1.2.

In addition to the basic s-wave resonance parameters in the tables are also given the p-wave neutron widths and the average level spacings for all J-values possible for $\ell=0$ and $\ell=1$. Here the J-dependence of the average level spacing predicted by the Fermi gas model has been used.

$$\bar{D}_J = \frac{\text{const}}{2J+1} \, e^{J(J+1)2\sigma^2} \qquad \text{(III.1.12)}$$

For the spin cutoff parameter σ the value 4 has been assumed, recommended by Harvey [11].

Hence it follows

$$\frac{\bar{D}_{J_2}}{\bar{D}_{J_1}} = \frac{2J_1+1}{2J_2+1} \cdot \frac{e^{J_2(J_2+1)/2\sigma^2}}{e^{J_1(J_1+1)/2\sigma^2}} \qquad \text{(III.1.13)}$$

In order to obtain absolute values for the average level spacing $\bar{D}_J$ one can make use of the observed s-wave level density

$$\rho_{obs} = \frac{1}{\bar{D}_{obs}} = \frac{1}{\bar{D}_{\ell=0}} = \frac{1}{\bar{D}_{\ell=0,J=|I-\frac{1}{2}|}} + \frac{1}{\bar{D}_{\ell=0,J=|I+\frac{1}{2}|}} = \frac{1}{\bar{D}_{\ell=0,J_1}} + \frac{1}{\bar{D}_{\ell=0,J_2}}$$

(III.1.14)

This leads to

$$\bar{D}_{\ell=0,J_1} = \bar{D}_{obs} \, (1+ \frac{2J_2+1}{2J_1+1} \, \frac{e^{J_1(J_1+1)/2\sigma^2}}{e^{J_2(J_2+1)/2\sigma^2}} \qquad \text{(III.1.15)}$$

The parity dependence of $\bar{\bar{D}}_{\ell,J}$ has been shown by Ericson /‾62_7 to be very small and has been neglected.

Using the average level spacings calculated in the indicated manner the neutron widths have been obtained by

$$\Gamma_{n\ \ell=0,J'}^{(0)} = \bar{\bar{D}}_{J'} \cdot S_0 \quad \text{and} \quad \Gamma_{n\ \ell=1,J''}^{(0)} = \bar{\bar{D}}_{J''} \cdot S_1 \quad \text{respectively}$$

with

$$|I-\tfrac{1}{2}| \leq J' \leq I+\tfrac{1}{2} \qquad |I-\tfrac{3}{2}| \leq J'' \leq I+\tfrac{3}{2} \qquad \text{(III.1.16)}$$

Here S_0 and S_1 are the strength functions for s- and p-wave neutrons respectively.

Tabelle III.1.1: Average resonance parameters for the even nuclei investigated

Isotope	$\bar{\Gamma}_\gamma$ [meV]	Reference	$S_0 x10^{+4}$	Reference	$\bar{D}_{obs}$ [eV]	Reference	$\bar{\Gamma}_f$ [meV]	Reference	$\Gamma^{(0)J=\frac{1}{2}}_{n\ell=0}$ [meV]	$\bar{D}_{\ell=1,J=\frac{3}{2}}$ [eV]	$\Gamma^{(0)J=\frac{1}{2}}_{n\ell=1}$ [meV]	$\Gamma^{(0)J=\frac{3}{2}}_{n\ell=1}$ [meV]
^{232}U (h)	50	1	1.0	12 (i)	13.1	1	360	1 (d)	1.31	7.20	2.62	1.44
^{234}U (h)	25	1	1.2	13 (i)	19.1	1	-	negligible subthreshold fission	2.29	10.50	3.82	2.10
^{236}U (h)	23	14	1.3	13 (i)	17.3	1,14	-		2.25	9.50	3.46	1.90
^{238}Np(h)	40	mean value assumed for fissile nuclei	1.3	calc.(b)	6.76	taken from 15 (f)	2040	calc.from (a)	0.88	3.72	1.35	0.74
^{236}Pu(h)	40		1.0	assumed value from systematics of neighbouring nuclei	7.35	taken from 15 (f)	195	calc.from (a)	0.735	4.04	1.47	0.808
^{238}Pu(h)	38	16 (i)	1.1	16 (i)	13.5	16 (i)	10.4	with $<\Gamma_f/D> = 0.77 \cdot 10^{-3}$ given in [17]	1.49	7.41	2.70	1.48
^{242}Cm (h) (e)	40	18	0.76	18 (i)	8.8	taken from 15 (f)	1.8	calc.from (c)	0.669	4.83	1.76	0.966

Table III.1.2: Average resonance parameters for the odd nuclei investigated

Isotope	$\bar{\Gamma}_\gamma$ [meV]	Reference	$S_0 x 10^{+4}$	Reference	$\bar{D}_{obs}$ [eV]	Reference	$\bar{\Gamma}_f$ [meV]	Reference	I	Reference	J(ℓ=0)	J(ℓ=1)
^{231}Pa(h)	48	1	0.60	1	0.44	1	-		$\frac{3}{2}$	1	1;2	0;1;2;3
^{237}U (h)	24	average fromU234, U236,U238	1.0	assumed value from systematics of neigh-bouring nuclei	only $\bar{D}^J_{\ell=0}$ $\bar{D}^J_{\ell=1}$	taken from 15 (f)	-		$\frac{1}{2}$	19	0;1	0;1;2;
^{237}Np(h)	44	20 (i)	1.0	20 (i)	0.67	20 (i)	-		$\frac{5}{2}$	1	2;3	1;2;3;4
^{241}Am(h)	40	1	1.1	21	0.81	1	0.21	2	$\frac{5}{2}$	1	2;3	1;2;3;4

Isotope	$\bar{D}_{\ell=0}$ [eV]		$\bar{D}_{\ell=1}$ [eV]				$\Gamma^{(0)}_{n\ell=0}$ [meV]		$\Gamma^{(0)}_{n\ell=1}$ [meV]				$g_J^{\ell=0}$		$g_J^{\ell=1}$			
	J_1	J_2	J_1	J_2	J_3	J_4	J_1	J_2	J_1	J_2	J_3	J_4	J_1	J_2	J_1	J_2	J_3	J_4
^{231}Pa	1.09	0.74	3.07	1.09	0.74	0.65	0.0655	0.042	0.614	0.218	0.148	0.130	$\frac{3}{8}$	$\frac{5}{8}$	$\frac{1}{8}$	$\frac{3}{8}$	$\frac{5}{8}$	$\frac{7}{8}$
^{237}U	14	4.7	14	4.7	2.8	-	1.40	0.470	2.80	0.94	0.56	-	$\frac{1}{4}$	$\frac{3}{4}$	$\frac{1}{4}$	$\frac{3}{4}$	$\frac{5}{4}$	-
^{237}Np	1.45	1.25	2.13	1.45	1.25	1.25	0.145	0.125	0.426	0.29	0.25	0.25	$\frac{5}{12}$	$\frac{7}{12}$	$\frac{3}{12}$	$\frac{5}{12}$	$\frac{7}{12}$	$\frac{9}{12}$
^{241}Am	1.73	1.50	2.54	1.73	1.50	1.50	0.190	0.165	0.508	0.346	0.30	0.30	$\frac{5}{12}$	$\frac{7}{12}$	$\frac{3}{12}$	$\frac{5}{12}$	$\frac{7}{12}$	$\frac{9}{12}$

Comments to the tables III.1.1 and III.1.2

(a) Using the thermal fission cross section and the s-wave strength function the average fission widths has been calculated from the formula

$$\sigma_{ftherm} = \frac{\pi \lambda_0^2}{\sqrt{E_{therm}}} \; S_0 \frac{\bar{\Gamma}_f}{E^*} \qquad \text{(III.1.17)}$$

valid for even nuclei with $g_J = \frac{2J+1}{2(2I+1)} = 1$. The meaning of E^* is explained below.

The relation can be deduced by considering the fission resonances as isolated and describing them by the one-level formula. Then it is

$$\sigma_f(E) = \sum_r \pi \lambda_r^2 \sqrt{\frac{E_r}{E}} \; \frac{\Gamma_n^r \, \Gamma_f^r}{(E-E_r)^2 + \frac{\Gamma_r^2}{4}} \qquad \text{(III.1.18)}$$

where the index r runs over the various s-wave resonances. $\ell>0$ contributions are completely negligible because only the case $E \to 0$ is of interest here.

Under the condition that $E \ll E_r$ and $\Gamma_r \ll E_r$ it follows

$$\sigma_f(E) = \frac{\pi \lambda_0^2}{\sqrt{E}} \sum_r \frac{\Gamma_n^{(0)r} \, \Gamma_f^r}{E_r^2} \qquad \text{(III.1.19)}$$

The energy region above E^* is now subdivided into intervals i of the length ΔE_i. The resonances in such an interval are designated by r_i. Their number in the interval i is consequently given by $\frac{\Delta E_i}{\bar{D}_i}$, where $\bar{D}_i$ is the average value of the level spacings in the interval i. Thus yields

$$\sigma_f(E) = \frac{\pi \lambda_0^2}{\sqrt{E}} \sum_i \sum_{r_i} \frac{\Gamma_n^{(0)r_i} \, \Gamma_f^{r_i}}{E_{r_i}^2} = \frac{\pi \lambda_0^2}{\sqrt{E}} \sum_i \frac{\Delta E_i}{\bar{D}_i} < \frac{\Gamma_n^{(0)} \, \Gamma_f}{E_r^2} >_i \qquad \text{(III.1.20)}$$

Because no correlations between Γ_f, Γ_n and E_r exist, we can assume for all the resonances in the interval i to have the same partial widths namely the mean values of the partial widths in the interval i

$\bar{\Gamma}_{ni}^{(0)}$ and $\bar{\Gamma}_{fi}$. Then it follows

$$\sigma_f(E) = \frac{\pi \lambda_0^2}{\sqrt{E}} \sum_i \frac{\bar{\Gamma}_{ni}^{(0)} \bar{\Gamma}_{fi}}{E_i^2} \frac{\Delta E_i}{\bar{D}_i} \qquad \text{(III.1.21)}$$

In order to be allowed to introduce energy independent reaction widths one has to make the assumption that all the resonances above E^* have the same partial widths and the same level spacing. The mean values of the neutron and fission widths and the mean level spacing of all these resonances have been adopted as appropriate quantities. This yields

$$\sigma_f(E) = \frac{\pi \lambda_0^2}{\sqrt{E}} \frac{\bar{\Gamma}_n^{(0)} \bar{\Gamma}_f}{\bar{D}} \sum_i \frac{\Delta E_i}{E_i^2} \qquad \text{(III.1.22)}$$

In the limiting case $\Delta E_i \rightarrow dE_i$ this leads to

$$\sigma_f(E) = \frac{\pi \lambda_0^2}{\sqrt{E}} \frac{\bar{\Gamma}_n^{(0)} \bar{\Gamma}_f}{\bar{D}} \int_{E^*}^{\infty} \frac{1}{E_i^2} dE_i = \frac{\pi \lambda_0^2}{\sqrt{E}} S_0 \frac{\bar{\Gamma}_f}{E^*} \qquad \text{(III.1.23)}$$

for $E \ll E_r$

The specialization on thermal energies permits the determination of the ratio $\bar{\Gamma}_f/E^*$ from this formula. $\bar{\Gamma}_f$ thus depends on the position of the lowest resonance. The lowest energy at which resonances of fissionable nuclei are situated is mostly 0.3 eV. We have chosen rather arbitrarily an energy of 0.5 eV which coincides with the cutoff energy E^*.

(b) In these cases the s-wave strength function was obtained by making use of the infinite dilution fission resoance integral.
The contribution of the resonances of the s-wave series, assumed as isolated , to the resonance integral is given by

$$RI_{f\ell=0}^{\infty} = 2\pi^2 \lambda_0^2 \sum_r \frac{1}{E_r^2} \frac{\Gamma_n^r \Gamma_f^r}{\Gamma^r} \qquad \text{(III.1.24)}$$

where "r" runs over all s-wave resonances.

With $\Gamma_f^r >> \Gamma_\gamma^r$, Γ_n^r (which is the case for the isotope studied) it follows $\Gamma^r \cong \Gamma_f^r$. If one assumes the contributions of the p- and higher ℓ-wave neutrons to the total resonance integral to be small compared to that of the s-wave neutrons - a condition which is generally fulfilled for the heaviest nuclei - one has to a good approximation

$$RI_f^\infty \cong RI_{f\ell=0}^\infty = 2\pi^2 \lambda\!\!\!^-{}_0^2 \sum_r \frac{\Gamma_n^{(0)r}}{E_r^{3/2}} \qquad \text{(III.1.25)}$$

Analogously as under (a) the equation (III.1.25) is transformed into

$$RI_f^\infty \cong 2\pi\lambda\!\!\!^-{}_0^2 \frac{\bar{\Gamma}_n^{(0)}}{\bar{D}} \int_{E^*}^\infty \frac{dE}{E^{3/2}} = \frac{4\pi^2 \lambda\!\!\!^-{}_0^2}{\sqrt{E^*}} S_0 \qquad \text{(III.1.26)}$$

Different from case (a), E^* has here the meaning of the cadmium cutoff energy.

If the fission resonance integral above E^* is known from experiment, this formula gives the possibility to determine the s-wave strength function S_0. This has been the case for ^{238}Np.

(c) The average fission width has been calculated from the approximate formula

$$\frac{RI_\gamma^\infty}{RI_f^\infty} \cong \frac{\bar{\Gamma}_\gamma}{\bar{\Gamma}_f} \qquad \text{(III.1.27)}$$

(d) The indicated value for $\bar{\Gamma}_f$ of U^{232} is the average of the Γ_f-values for the eight known resonances between 5.97 eV and 75.1 eV. It was checked whether this value can be taken as appropriate average also above 75 eV. For this purpose the resonance integral contributions of the known capture and fission resonances up to 75 eV have been calculated. Then the difference between the measured and these partial resonance integrals for capture and fission respectively gives the contributions of the resonances above 75 eV. The chosen $\bar{\Gamma}_\gamma$ and $\bar{\Gamma}_f$ values should fulfill the approximate relation:

$$\frac{RI_\gamma|_{75eV}^\infty}{RI_f|_{75eV}^\infty} \cong \frac{\bar{\Gamma}_\gamma}{\bar{\Gamma}_f} \qquad \text{(III.1.28)}$$

This was found to be actually the case.

(e) For lack of available data the average resonance parameters of ^{242}Cm have been assumed to be the same as for ^{244}Cm. This can be justified by their similar fission barriers and binding energies.

(f) The level density $\rho_J = 1/\bar{D}_J$ has been obtained from $\rho_J = \rho_0(2J+1)$ where J is the total angular momentum of the levels considered. In a report written by Moore and Simpson [15] ρ_0 is given for nuclei with even Z as a function of the neutron binding energy.

(h) If no contrary comment is reported the average resonance parameters have been obtained as arithmetic mean values of the resolved resonance parameters given in the quoted reference work.

(i) The values indicated have been calculated by the author of the cited reference himself from his own experimental data.

B. Resonance Integrals

In the following table measured and evaluated data of infinite dilution resonance integrals for capture and fission have been listed.

Table III.1.3: Infinite dilution resonance integrals for capture and fission

Isotope	RI_{γ}^{∞} [b]	Reference	Comments	RI_{f}^{∞} [b]	Reference	Comments
^{231}Pa	480	22	evaluation of measured resonance integrals	0		negligible subthreshold fission [1]
^{232}U	220	22	evaluation of measured resonance integrals; preferred value in [22]	320	22	evaluation of measured resonance integrals
^{234}U	700±70	23	preferred value in [23], calculated from resonance parameters			
	700	2	recommended in [2]	0	2	negligible subthreshold fission [1]
^{236}U	332±18	14	calculated from preliminary resolved resonance parameters up to 272.8 eV			
	400±40	1	recommended in [1]	0	2	negligible subthreshold fission [1]
	310	2	estimated from resonance parameters			
	400	2	recommended in [2]			
	417±25	24	measurement carried out in order to resolve the discrepancies in that value			

Table III.1.3 continued

Isotope	RI_{γ}^{∞} [b]	Reference	Comments	RI_{f}^{∞} [b]	Reference	Comments
	419±70	24	obtained by the U236 and gold cadmium ratios; relative to $\sigma_{therm}^{(U236)}=6\pm1b$			
	419±25	3	experimental value, determined relative to the value of 1550b for gold			
	Preferred value: 417		most recent and decision measurement			
^{237}U	290	3	calculated by a manner not indicated in detail in reference [3]	-		unknown value, assumed to be 0
^{237}Np	870±130	25	experimental value, 1/v part of the integral not included			
	943	2	adjusted from the non1/v-measurement of 870b of reference [25]			
	500	2	calculated from resolved resonance parameters, extrapolated to high energies			
	850	3	experimental value	0	3	
	946	22	the single measurement available of 870b [25] corrected in a manner not indicated in particular; probably for the lacking 1/v part of the measured integral	0		the integral over the resonances between 0.5eV and 1keV has been estimated to be 0.3b; against the capture integral it may be neglected
	Preferred value: 945		average of the two values for the resonance integral which include the 1/v-part of the integral			

Table III.1.3 continued

Isotope	RI_{γ}^{∞} [b]	Reference	Comments	RI_{f}^{∞} [b]	Reference	Comments
^{238}Np	29		calculated from (s)	1500±500	3	single measurement available
^{236}Pu	197		calculated from (t)	960		calculated from (s)
^{238}Pu	3260±280	26	completely outside explanation from resonance parameters			
	150	2	estimated from resonance parameters	25	2	measured value
	145.3	7,3	calculated from resonance parameters up to 100keV	23.7	7,3	calculated from resonance parameters up to 100keV
	Preferred value: 148		average value of the two calculated resonance integrals	Preferred value: 24		average value of the two available ones
^{241}Am	1600	2	calculated from resolved resonance parameters, extrapolated to high energies	8.5	2	calculated from resolved resonance parameters, extrapolated to high energies
^{242}Cm (u)	650	2	calculated from resolved resonance parameters; extrapolated to high energies			
	646	7	calculated from resonance parameters up to 100 keV	18	7	calculated from resonance parameters up to 100keV
	670	8	from the measured absorption integral (700b) with Capt/Abs =0.96 (the lower limit value of that ratio as estimated in [8])	30	8	from the measured absorption integral (700b) with Capt/Abs=0.96
	Preferred value: 670		preferred because of the experimental basic data	Preferred value: 30		preferred because it is based on a measurement of the absorption integral

(s) The resonance integral has been calculated from the approximate formula

$$\frac{RI_{\gamma}^{\infty}}{RI_{f}^{\infty}} = \frac{\bar{\Gamma}_{\gamma}}{\bar{\Gamma}_{f}}$$

where the mean capture and fission widths of Table III.1.1 have been inserted.

(t) The capture resonance integral of ^{236}Pu has been obtained using the formulae of Dresner (III.1.3, III.1.8) with the average values of Γ_{γ}, Γ_{f} and $\Gamma_{n}^{(0)}$ as listed in table III.1.1. There only the contribution of the s-waves has been taken into account.

(u) For ^{242}Cm the same resonance parameters as for ^{244}Cm have been assumed. Then the value of the absorption resonance integral too, may be taken to be the same as for ^{244}Cm. All the references and data given concerning the resonance integrals of ^{242}Cm refer to ^{244}Cm.

III.2 Fast reactor

In the resonance region the weighting of the cross sections was performed by using the NAP-Core spectrum (Figure 2). For the resolved resonance region this has an important consequence because the NAP-spectrum gives the greatest weight to the upper part of the energy range of group 4. In that range, however, the resonances for the most part are unknown and the known resonances, above all the highest ones, from the first part of the energy group do not play a great part in the averagings because of that special form of the weighting spectrum. Therefore the cross sections for the resolved resonance region have been computed by using the statistical method of the NEARREX-Code [32]. Only in that case, where cross sections have been already calculated with resolved resonance parameters, these values have been adopted. This concerns the following isotopes:

Isotope	Calculations with resolved resonance parameters up to	Reference
^{231}Pa	100 eV	[29] Drake and Nichols
^{232}U	75 eV	
^{234}U	370 eV	[30] Drake and Nichols
^{236}U	384 eV	

The cross sections for the unresolved region have been throughout calculated with the NEARREX-Code.

The resulting cross sections have been checked at several energies for ^{232}U and the four odd nuclei investigated.

The averaging was carried out according to the formula (III.2).

IV. Neutron cross sections in the fast region

For this energy range energy-dependent cross sections could be extracted from the literature for a large part of the isotopes considered. For the isotopes for which no cross section data were available simple nuclear systematics have been applied to generate the desired data.

The averaging over the two fast energy groups has been carried out according to

$$\langle\sigma_x\rangle_i = \frac{\int_{(i)} \sigma_x\ \phi(E)dE}{\int_{(i)} \phi(E)dE}, \quad \text{where } x = \gamma,\ f,\ 2n \quad i = 2 \text{ or } 1 \qquad \text{(IV.1)}$$

by using a computer program of Mrs. Krieg /‾27_7. The tables 11 and 12 give lists of the mean values for capture, fission, (n,2n) reaction cross sections and for the mean number of neutrons per fission in the fast energy region.

IV.1. Weighting spectra

As for a thermal reactor the cross sections were weighted with the flux spectra displayed in figure 1 /‾63_7.

For the fast reactor the flux spectrum of a 1000 MWe NA1-type plotted in figure 3 was used /‾64_7. We got it in the form of group fluxes $\phi_i = \int_{\Delta E_i} \phi(E)dE$.

In order to obtain the group averaged flux densities these have to be divided by the corresponding energy intervals ΔE_i. The resulting step-function was approximated by a smooth curve.

IV.2. Radiative capture cross section

Measurements of the capture cross section in the fast energy range for the isotopes in regard here have till now only been performed for ^{237}Np and ^{236}U at several energy points. For some other nuclei studied here calculations had been carried out so that radiative capture cross section values for the isotopes ^{231}Pa, ^{232}U, ^{234}U, ^{236}U, ^{238}Pu have been available pointwise over the entire energy range from 46.5 keV up to 10 MeV and for the isotope ^{237}Np over a subrange from 0.15 MeV up to 1.5 MeV. The references are given in table IV.2.1.

Table IV.2.1: References for capture cross section data in the energy range from 46.5 keV up to 10 MeV

Isotope	References	Comments
^{231}Pa	29	calculated from unresolved resonance parameters without taking into account competing processes; above 0.2 MeV a 1/E-dependence was assumed for $\sigma_\gamma(E)$
^{232}U	29	
^{234}U	30	the results of calculations with unresolved resonance parameters have been extrapolated above 1 keV by assuming a similar shape as that measured for σ_γ of U236 because of the rather similar s-wave resonance parameters
^{236}U	30	1 keV - 0.3 MeV calculated from unresolved resonance parameters; 0.3 - 4 MeV smooth curve through experimental data points; above 4 MeV 1/E-dependence assumed
^{237}Np	31	measurements with the activation technique at 8 neutron energies between 0.15 and 1.5 MeV;
^{238}Pu	7	below 2 MeV calculated with statistical theory with the basic value $<\Gamma_\gamma/D>_o = 2.54\cdot 10^{-3}$; above 2 MeV the σ_γ-shape was obtained by comparison with U238

For the isotopes ^{237}U, ^{238}Np, ^{236}Pu, ^{241}Am and ^{242}Cm, for which $\sigma_\gamma(E)$-values have not been measured hitherto, the average values of the capture cross section were obtained by the approximately valid relation

$$<\sigma_\gamma^k>_i = \frac{\bar{\Gamma}_\gamma^k}{\bar{\Gamma}_\gamma^{U238}} <\sigma_\gamma^{U238}>_i \qquad \text{(IV.2.1.)}$$

with i = 2 and 1 respectively and k denoting the isotope studied

This formula presupposes a similarity in the resonance structure of ^{238}U and the isotope concerned.

In the formula $<\sigma_\gamma^{U238}>$ means $\sigma_\gamma(E)$ (^{238}U) averaged over the groups 2 and 1 respectively by use of the weighting spectra in these groups as displayed in the figures 1 and 3. Here use was made of the microscopic capture cross sections of ^{238}U as given on the KEDAK-file [65]. As average capture width for ^{238}U the value $\bar{\Gamma}_\gamma^{U238}$ = 23 meV was taken which is consistent with the most recent capture cross section measurements of Moxon [28].

For ^{237}Np σ_γ-values were available only in the energy range from 152 keV up to 1.5 MeV. An extension of the capture cross section curve beyond these energy limits by assuming the shape of σ_γ to be the same as that of similar isotopes did not seem reasonable because of the very few data points given. Therefore the average values over the partial groups 2' -with the energy limits of 152 keV and 800 keV- and 1' -with the energy limits of 800 keV and 1.5 MeV- of the groups 2 and 1 respectively have been determined for ^{238}U and ^{237}Np. The average capture cross sections over the entire groups 2 and 1 have then been calculated from

$$\frac{<\sigma_\gamma^{Np237}>_i}{<\sigma_\gamma^{U238}>_i} = \frac{<\sigma_\gamma^{Np237}>_{i'}}{<\sigma_\gamma^{U238}>_{i'}} \quad \text{with } i = 2 \text{ and } 1, \quad i' = 2' \text{ and } 1' \qquad (IV.2.2)$$

The averages are given in the table 11 for all isotopes.

IV.3. Fission cross section

For the isotopes ^{231}Pa, ^{234}U, ^{236}U, ^{237}Np, ^{238}Pu fission cross section data based on measurements in the energy range from 46.5 keV to 10 MeV have been given in the literature. The references are quoted in table IV.3.1. For the other isotopes no experimental information at all has been available.

Table IV.3.1: References for fission cross section data in the energy range from 46.5 keV up to 10 MeV

Isotope	References	Comments
^{231}Pa	29	up to 3 MeV smooth curve through measured data points; above 3 MeV the authors say that there they have assumed the σ_f-shape to be the same as that of similar isotopes
^{234}U	33	measured fission ratios of U234/U235 have been given, the revised values [33] have been taken.
^{236}U	33 34	Recently measurements of the fission cross section for U236 relative to U235 in the energy range from 1 to 5 MeV have been carried out very carefully by Stein et al. [34]. Therefore his experimental values are recommended here in that range whereas out of it the values selected by Davey [33] have been adopted. In figure 4 the preferred values of Davey* are plotted as well as the measured values of Stein after multiplication with the U235 fission cross section values recommended by Davey [33].
^{237}Np	33	The same as for U234; most recent experimental values of Stein et al. [34] are in good agreement with the revised data of Davey based in the range from 1.0 to 5.0 MeV on earlier measurements of Stein et al. Therefore a revision was not necessary.
^{238}Pu	7	Based on recent experiments of D. Barton not more specified.

For ^{232}U, Drake has also performed an evaluation [29]. But above 1 keV experimental values do not exist and thus crude estimates not described in detail have been made. We have therefore preferred to utilize also for ^{232}U the fission systematic applied to ^{237}U, ^{236}Pu, ^{242}Cm and ^{238}Np. It is based on the following considerations of Zamyatnin [35].

The fissile isotopes may be divided roughly into two groups: one for the isotopes being fissionable by thermal neutrons and the other for isotopes with a fission threshold above thermal energies.

* In the meantime Davey himself has revised the fission cross section values for U236 recommended in 1968. His now preferred values [70] are also based on the experimental data of Stein et al. in the energy range 1-5 MeV.

The compound nucleus theory of Bohr [66] describes the fission cross section above some threshold energy by

$$\sigma_{f_0} = \sigma_c \cdot \frac{\Gamma_f}{\Gamma} \qquad \text{(IV.3.1)}$$

Here σ_c is the cross section for the formation of the compound nucleus and $\frac{\Gamma_f}{\Gamma}$ the branching ratio of the probability for the decay of the compound nucleus by fission. This yields for the relative fission probability f_0 of the compound nucleus

$$f_0 = \frac{\sigma_{f_0}}{\sigma_c} \doteq \frac{\Gamma_f}{\Gamma} \qquad \text{(IV.3.2)}$$

At neutron energies of about 5 to 7 MeV a new rise of the fission cross section sets for both groups of fissionable isotopes, i.e. for the isotopes fissionable by thermal neutrons as well as for the isotopes with a fission threshold above thermal energies. The excitation energy becomes then high enough to permit evaporation of one neutron without reducing the excitation energy of the residual nucleus below its fission threshold. The system then gets a second chance to undergo fission [36]. The threshold energy for the (n,n'f) reaction is equal to the fission barrier $E_f(A)$ of the original target nucleus A. The fission cross section above this threshold shall be designated by σ_{f_1}. At neutron energies of about 12 MeV a third chance of undergoing fission appears due to the emission of a second neutron.

Below the threshold for the (n,n'f) process the fission cross section is equal to that for the compound nucleus of mass number A+1. Above this threshold and below the threshold for the (n,2n'f) reaction the fission of the compound nucleus as well as the fission of the excited target nucleus of mass number A contribute to the total fission cross section. The general form of the function $\sigma_f(E)$ is shown in the following figure for the two types of fissile isotopes.

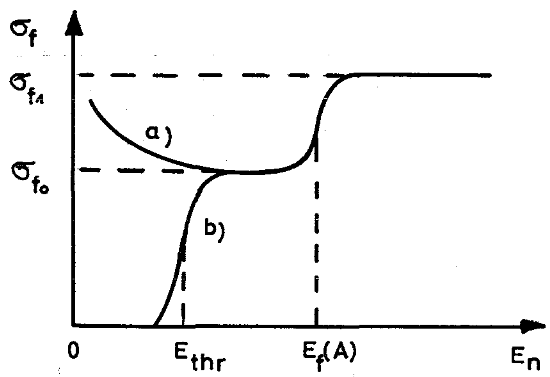

Figure IV.3.1 (from Zamyatnin [35])
a) isotopes fissionable by thermal neutrons
b) isotopes with a fission threshold above thermal

The threshold energy E_{thr} for the (n,f) process is given by $E_{thr}^{A} = E_f(A+1) - E_B(A+1)$, i.e. the difference between the fission barrier and the neutron binding energy of the compound nucleus of mass number A+1.

The fission probability after emission of one neutron is obtained by $(1-f_0^{A+1})f_0^A$, where f_0^A is the probability for fission of the compound nucleus with mass number A. This yields

$$\frac{\sigma_{f_1}}{\sigma_c} = f_0^{A+1} + (1-f_0^{A+1})f_0^A \qquad \text{(IV.3.3)}$$

and further

$$\frac{\sigma_{f_1}}{\sigma_{f_0}} = 1 + \frac{(1-f_0^{A+1})}{f_0^{A+1}} f_0^A \qquad \text{(IV.3.4)}$$

The values of the ratio $\sigma_{f_1}/\sigma_{f_0}$ calculated in such a way show according to Zamyatnin sufficiently good agreement with known experimental values of this ratio, so that one can estimate unknown fission cross sections in the region above 7 MeV, if the fission cross sections for these isotopes are known in the energy region of about 2 to 5 MeV.

If these latter values are unknown -as in the case of the isotopes in study here- there exists a possibility to predict them by using an empirical correlation proposed by Barschall and Henkel [37]. They plotted the fission cross section for fission induced by 3 MeV neutrons against the parameter $Z^{4/3}/A$ of the compound nucleus and found a linear relationship. The theoretical significance of the parameter $Z^{4/3}/A$ in this context is not yet know at present.

The systematic variation of σ_f (3 MeV) with Z and A is based on older measured σ_f-values. It has therefore been checked by plotting more recent values of known fission cross sections at 3 MeV against $Z^{4/3}/A$ (figure 5 and table 3).

The isotopes ^{232}U, ^{237}U, ^{236}Pu, ^{242}Cm, ^{238}Np, for which this fission systematic has been studied, belong to the first category of fissile nuclei in the above distinction, that is to those which are fissionable by thermal neutrons. As for ^{242}Cm and ^{237}U the magnitude of the thermal fission cross section, however, is very small.

The behaviour of $\sigma_f(E)$ has been assumed in the already indicated manner (figure IV.3.1a). The unknown σ_{f_0}-values for these isotopes were read from figure 5 with the calculated parameters $Z^{4/3}/A$ of the target nuclei.

In accordance with Zamyatnin we have assumed σ_c = 3b for all isotopes independent of the neutron energy. Then it was possible to calculate the fission cross section at the second plateau σ_{f_1}. The results are shown in table 4. The σ_{f_1}-value for ^{242}Cm σ_{f_1} = 2.99b can be compared with the cross section measuremed by Fomushkin [41] for fission induced by 14.5 MeV neutrons σ_f(14.5MeV) = 3.03b, although at energies of about 14 MeV the (n,2n'f) process contributes to the total fission cross section which is not the case at energies of the second plateau. Otherwise one could have emphasized the good agreement of the two values.

The fission cross section between the plateau values σ_{f_0} and σ_{f_1} was assumed to increase exponentially according to the Hill-Wheeler formula derived from channel-theory [42] .

$$\sigma_f(E) = \sigma_{f_0} + (\sigma_{f_1} - \sigma_{f_0}) \left(\frac{1}{1+e^{\frac{2\pi}{\hbar\omega}(E_f - E)}} \right) \qquad \text{(IV.3.5)}$$

E_f is the fission barrier energy of the compound nucleus. For the quantity $\hbar\omega$ the value $\hbar\omega$ = 500 keV [67], which refers to ^{239}Pu, has been taken. The functions $\sigma_f(E)$ for the isotopes considered are plotted in figure 6 and are listed in table 5. The average fission cross section over the energy group 2 can be inferred directly from the figures as the value of the first plateau.

In our investigation of fission cross sections it is only ^{241}Am which now still remains to be treated. For ^{241}Am a few measurements of the fission cross section are available. They are quoted in the following table.

Table IV.3.2: Fission cross section measurements for ^{241}Am

Authors	Energy Range	σ_f-values [b]
Seeger, Hemmendinger, Diven [44]	20 eV- 1 MeV	listed data points and plots
Bowman et al. [43]	550keV- 6 MeV	preliminary curve
Protopopov et al. [45]	14.6 MeV	(2.35±0.15)
Kazarinova et al. [46]	2.5 MeV 14.6 MeV	1.95±0.2 2.95±0.15
Fomushkin et al. [41]	14.5 MeV	2.30±0.15 2.53±0.12

In the energy range from 30 keV up to 500 keV the average σ_f-values determined by Seeger et al. for selected intervals have been used.
From 600 keV up to 3 MeV the fission cross sections have been read from the curve of Bowman et al. In the range from 600 keV up to 1 MeV covered by both measurements, those of Bowman et al. and the Petrel measurements, the agreement between them is very good.
The experimental data points of Bowman above 3 MeV have not been adopted because they do not show the theoretically expected behaviour: The threshold energy for the (n,n'f) process on ^{241}Am is 6 MeV /-40_7, that means the σ_f-value corresponding to 6 MeV should be located on the rising branch of the σ_f(E)-curve of ^{241}Am. But the measurements of Bowman et al. do not show this behaviour.
Above 3 MeV the shape of the fission cross section has been adapted to that given in reference /-59_7 and adjusted to pass through a σ_f- value of 2.53b on the second plateau. This value has been selected among the four measurements at about 14.5 MeV.
The value of σ_f = 2.30b obtained by Fomushkin by detecting the fission fragments with ionization chambers shows a good agreement with the value of Protopopov, who has performed his measurements with a gas scintillation counter filled with Xenon. His other value of σ_f(14.5 MeV) = 2.53b has been determined by using glass-plate fragment detectors insensitive to α-radiation. This experimental method has to be preferred because of the high α-activity of ^{241}Am. In the case of ionization chambers the high background has to be taken into account and this will often be difficult. Thus one has only to come to a decision between the two values of 2.53b and 2.95b. From the formula of Zamyatnin (IV.3.4) one can infer the fission cross section of the first plateau by inserting the known value of the second plateau. The fission probability for ^{241}Am and ^{242}Am has been determined by using figure 5 and with σ_c = 3b. The resulting σ_{f_0}-values are σ_{f_0} = 1.8b following from the σ_{f_1}-value of Fomushkin and σ_{f_0} = 2.1b following from the σ_{f_1}-value of Kazarinova. The value of 1.8b is in good agreement with the plateau value measured by Bowman et al. and in moderate agreement with the value measured by Kazarinova. Therefore the value of σ_f(14.5 MeV) = 2.53b given by Fomushkin has been assumed to be appropriate for the second plateau. The preferred σ_f(E)-curve for ^{241}Am is shown in figure 7.

IV.4. (n,2n) cross section

The (n,2n) process competes with the other processes only in the energy group 1, because the threshold energy for this reaction is between about 6 and 7 MeV for the isotopes studied. Measurements are completely lacking for all isotopes in regard here except for ^{237}Np at a single energy point. Calculations of the (n,2n) cross section have already been performed for the isotopes ^{231}Pa, ^{232}U, ^{234}U, ^{236}U, ^{238}Pu. Authors and methods are given in the following table.

Table IV.4.1: References for (n,2n) cross section data

Isotope	Threshold	Author	Comment
^{231}Pa ^{232}U	6.64 MeV 7.32 MeV	Drake, Nichols [29]	statistical method, described by Pearlstein [36]
^{234}U ^{236}U	6.80 MeV 6.43 MeV	Drake, Nichols [30]	evaluation by Parker [37] based on cross sections for similar nuclides and optical model calculations
^{238}Pu	6.93 MeV	Dunford, Alter [7]	statistical method [36]; curves given

For the remaining isotopes ^{237}U, ^{237}Np, ^{238}Np, ^{236}Pu, ^{241}Am and ^{242}Cm (n,2n) cross section data have not been available and have been calculated with the method indicated by Pearlstein [47]. For ^{237}Np, contrary to the other isotopes mentioned, exists a single measurement of the (n,2n) cross section at 14.5 MeV which has served to fit the (n,2n) shape from Pearlstein.

Pearlstein uses the following relation for $\sigma_{n,2n}$

$$\sigma_{n,2n} = \sigma_{n,e} \cdot \frac{\sigma_{n,M}}{\sigma_{n,e}} \cdot \frac{\sigma_{n,2n}}{\sigma_{n,M}} \qquad \text{(IV.4.1)}$$

Here is $\sigma_{n,e}$ the total non-elastic cross section and $\sigma_{n,M}$ the sum of the cross sections of all the processes, in which the only nucleons released are neutrons

$$\sigma_{n,M} = \sigma_{n,n'} + \sigma_{n,2n} + \sigma_{n,3n} + \dots \qquad (IV.4.2)$$

The contribution of these reactions, in which more than one neutron is emitted (below 10 MeV this concerns only the (n,2n) reaction), to the total neutron-producing reactions is given by the ratio $\frac{\sigma_{n,2n}}{\sigma_{n,M}}$.

The ratio can be obtained as a function of the quantity $S = \frac{E_B}{E_n}$ (where E_B - binding energy per nucleon in the target nucleus, E_n - incident neutron energy) from a curve in dependence upon the parameter $p = 4aE_B$ (where a is the level density parameter). This parameter determines the increase of $\sigma_{n,2n}$ above the threshold.

The ration $\frac{\sigma_{n,M}}{\sigma_{n,e}}$ indicating the competition between neutron producing reactions and all other non-elastic processes can be read from the figure 3 in reference [47] using the neutron excess factor (N-Z)/A (N - number of neutrons, Z - number of protons, A - mass number). For heavy nuclei like those considered here the ratio of $\sigma_{n,M}$ to $\sigma_{n,e}$ is almost equal to unity, because the cross sections of the charged particle reactions are very small and the fast neutron capture cross section can also be neglected. Then it follows

$$\sigma_{n,e} = \sigma_{n,M} + \sigma_{n,f} \qquad (IV.4.3)$$

Thus above the fission threshold except $\sigma_{n,M}$ only the fission cross section contributes essentially to the non-elastic cross section. The non-elastic cross section $\sigma_{n,e}$ at 14 MeV is given by Pearlstein as a function of the mass number A. We have assumed for $\sigma_{n,e}$, analogously as for the calculation of unknown fission cross sections, a value of 3b. With the fission cross section from chapter IV.3 it then follows for $\sigma_{n,M}$

$$\sigma_{n,M} = \sigma_{n,e} - \sigma_{n,f}(E) \qquad (IV.4.4)$$

Now the (n,2n) cross sections could be determined from the ratio $\frac{\sigma_{n,2n}}{\sigma_{n,M}}$ obtained with the calculated parameters p and s from the curves of Pearlstein.

For ^{237}Np the (n,2n)-cross section values from threshold up to 10 MeV have first also been calculated like for the other isotopes regarded here according to the systematic given by Pearlstein with σ_c = 3b and taking into account $\sigma_f(E)$ in the manner described above. Then $\sigma_{n,2n}$ at 14.5 MeV was determined according to Pearlstein by taking into account the competition of the (n,3n) process, the threshold of which is at about 12.5 MeV. The measurement of the (n,2n) cross section at 14.5 MeV gives:
$\sigma_{n,2n}$ (14.5 MeV) = (0.39±0.07)b /̄49_7
For the adjustment to this value all the (n,2n) cross section values have been multiplied by the ratio

$$\frac{\sigma_{n,2n\ \text{exper.}}(14.5\ \text{MeV})}{\sigma_{n,2n\ \text{calc.}}(14.5\ \text{MeV})} = \frac{0.39}{0.264} = 1.477$$

The (n,2n) cross section values for the various isotopes are given in table 6 and displayed in figure 8a and 8b.

IV.5. Mean number of neutrons per fission

The averages of the mean number of neutrons per fission $\bar{\nu}$ over the five energy groups are here given as the average values of the quantity $\bar{\nu}\cdot\sigma_f$. At low energies up to the upper limit of group 3, $\bar{\nu}$ does not change with neutron energy. Thus yields

$$\langle\bar{\nu}\sigma_f\rangle_i = \bar{\nu}_i \langle\sigma_f\rangle_i, \quad \text{where } i=3,4,5 \tag{IV.5.1}$$

Over the energy range of group 2 $\bar{\nu}$ is still almost constant and the average has been determined as arithmetic mean value of the $\bar{\nu}$-values at the two energy limits of the group

$$\langle\bar{\nu}\sigma_f\rangle_2 = \frac{\bar{\nu}(E_2)+\bar{\nu}(E_3)}{2} \langle\sigma_f\rangle_2 \tag{IV.5.2}$$

The mean numbers of fission neutrons in the range of the energy groups 2,3,4 and 5 are given in table 7 for all the isotopes in regard. As for group 1 first of all the products $\bar{\nu}(E)\sigma_f(E)$ have been calculated and then the average values have been determined from equation (IV.1) setting $\sigma_x(E) = \bar{\nu}(E)\sigma_f(E)$.

The 5-group values of $\bar{\nu}\sigma_f$ are summarized in the tables 11 and 12.

With regard to the isotopes studied here the mean number of neutrons per fission $\bar{\nu}$ has hitherto been measured only for ^{234}U and ^{237}Np at single energy points.

For ^{231}Pa and ^{232}U Drake [29] has investigated the variation in $\bar{\nu}$ as a function of the neutron energy. The procedure, according to which $\bar{\nu}(E)$ has been determined, is not described in the report. As for ^{232}U the values have not been adopted for the same reason as indicated studying the fission cross section. For ^{231}Pa we have taken the values given by Drake as a basis for averaging.

Among the U-isotopes it was ^{234}U for which Fillmore [50] has given a review of available experimental data for $\bar{\nu}$, the mean number of prompt neutrons. The measured data points obtained by Mather et al. [51] covering the energy range up to about 4 MeV have been fitted in that evaluation by

$$\bar{\nu}_p(E) = 2.371 + 0.1353\ E\ (\mathrm{MeV}) \qquad (IV.5.3)$$

with normalization to the $\bar{\nu}_p$ for spontaneous fission of ^{252}Cf $\bar{\nu}_p(^{252}Cf) = 3.782$. This relationship for the dependence of $\bar{\nu}$ on the energy of the neutrons inducing fission was used for the determination of $\bar{\nu}(E)$ for ^{234}U in the whole energy range above the fission threshold.

To the other U-isotopes and the Pu-isotopes the systematics of Schuster and Howerton [52] were applied, as the calculated results of these authors for ^{235}U, ^{238}U and ^{233}U compare favourably with experimental data.

The variation in $\bar{\nu}$ as a function of the energy of the neutrons causing fission has been described by Leachman [53] in the following manner:

$$\bar{\nu}(E) = \nu_0 + \nu_1(E) \qquad (IV.5.4)$$

where ν_0 and ν_1 depend upon the fissioning isotope concerned. Schuster and Howerton have modified this equation by taking into account the various fission modes, that is the standard (n,f) process, the (n,n'f) fission above about 6MeV and the (n,2n'f) fission above about 12 MeV.

Instead of ν_0, the $\bar{\nu}$-value at thermal neutron energy, they have introduced ν_{thr}, the $\bar{\nu}$-value at the fission threshold energy. For ν_{thr} Schuster and Howerton have deduced the following systematic for U-isotopes.

$$\nu_{thr}(A) = \alpha + \beta\ (A-235) + \delta(-1)^A \qquad (IV.5.5)$$

where $\alpha = 2.39$, $\beta = 0.02$ and $\delta = 0.06$.
The constants have been obtained by fits to the ^{235}U-data. If one ignores the odd-even effect, then α is identical with the value of $\bar{\nu}$ for ^{235}U at threshold. The second term gives the change in ν_{thr} with mass number A of the uranium isotope. The third term takes account of the fact that a nucleus with an even number of neutrons tends to split into two fragments with also even numbers of neutrons.
For the determination of the slope ν_1 of the linear relation for $\bar{\nu}(E)$ a second systematic equation has been given by Schuster and Howerton for U-isotopes.

$$\nu_1(A) = \gamma + \lambda\ (A-235) \qquad (IV.5.6)$$

where $\gamma = 0.130$ and $\lambda = 0.006$.

λ takes into account that the slope ν_1 increases by 4.5% per additional nucleon in the U-isotope studied in comparison to ^{235}U, a fact which has been inferred by Schuster and Howerton from the measurements of $\bar{\nu}(E)$ for ^{238}U, ^{233}U and ^{235}U. According to Schuster and Howerton this behaviour has to be expected because ν_1 varies inversely with the neutron binding energy and this decreases by about 3% for each additional nucleon.
Above the threshold of the (n,n'f) and (n,2n'f) reaction the branching ratios between pure (n,f) and the other fission modes have to be estimated at each energy point. At energies up to 10 MeV only the (n,n'f) process competes with the standard fission mode. Then the general equation for $\bar{\nu}(A,E)$ deduced by Schuster and Howerton obtains the following form:

$$\bar{\nu}(A,E) = R(n,f)\left[\nu_{thr}(A)+\nu_1(A)\ (E-E_{thr}(n,f)\right] + R(n,n'f)\left[1+\nu_{thr}(A-1)+\nu_1(A-1)\ (E-E_{thr}(n,n'f)\right] \qquad (IV.5.7)$$

R(n,f) and R(n,n'f) give the contribution of the two fission modes, being considered here, to the total fission.
The calculations for the Pu-isotopes have been performed by using also the above formula with the only difference that the equations for ν_1 and ν_{thr} found by Schuster and Howerton are the following ones:

$$\nu_{thr}(A) = 2.77 + 0.02\,(A-239) + 0.06(-1)^A \qquad (IV.5.8)$$

$$\nu_1\;(A) = 0.124 + 0.006\,(A-239) \qquad (IV.5.9)$$

The magnitudesof R(n,f) and R(n,n'f)have been obtained except for ^{238}Pu from the q_f-plots in figures 4 and 6, where the dashed curves are the assumed extensions for the various fission modes. For ^{238}Pu these values have been taken from the corresponding plot in the evaluation of Dunford and Alter /‾32_7 with the assumption that the first plateau is fixed at 1 MeV. They are summarized in <u>table 9</u> for all the uranium and plutonium isotopes investigated.
The threshold energies for (n,f) and (n,n'f) fission according to chapter III.3 have the following meaning:

$$E_{thr(n,f)} = E_f(A+1) - E_B(A+1)$$

$$E_{thr(n,n'f)} = E_f(A)$$

where A is the mass number of the target nucleus.
The threshold energies for the two fission modes as well as the values ν_{thr} and ν_1 for the uranium and plutonium isotopes are given in <u>table 8</u>.
The change of $\bar{\nu}$ with neutron energy is shown for these isotopes in <u>table 10</u> and in <u>figure 9</u>.

For the Np-, Am- and Cm-isotopes it was impossible to derive similar systematics because ot the lack of data. Therefore the linear energy dependence of $\bar{\nu}$ given in equation (IV.5.4) has been assumed to be valid for ^{237}Np, ^{238}Np, ^{241}Am and ^{242}Cm. The constants ν_0 and ν_1 for the four isotopes have been determined as follows.
ν_0 is the average number of neutrons for thermal neutron-induced fission. A general correlation for these values is given by Gordeeva and Smirenkin /‾54_7 for the isotopes with $Z \geq 90$

$$\bar{\nu}_{thermal} = 0.1894Z + 0.007A - 16.60 + \delta_\nu \qquad (IV.5.10)$$

whre $\delta_\nu = 0.09\ \xi$ with $\xi = \begin{cases} +1 \text{ for odd-odd} \\ -1 \text{ for even-even} \\ 0 \text{ for odd-A} \end{cases}$ target nuclei

The formula may be applied only to those nuclei far removed from the range of closed shells and sub-shells. It is based on the representation of the number $\bar{\nu}$ of prompt neutrons emitted per fission by linear functions of Z and A, that is for a fixed neutron energy

$\bar{\nu}_p = C_1Z + C_2A + C_3$

C_3 takes account of the odd-even effect. The coefficients C_i have been determined by least-square fits to experimental data on thermal fission of the six target nuclei ^{229}Th, ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu, ^{241}Am. For the fit these experimental values have been renormalized by the authors to $\bar{\nu}_{thermal}(^{235}U) = 2.43$. The formula predicts the values of $\bar{\nu}_p$ for neutron-induced fission for nuclei with $Z \geq 90$ and $N > 152$ to within about 3%. The contribution of the delayed neutrons, however, to the total number of neutrons emitted is less than 1%. Therefore it has not been considered worthwhile to take their number into account here especially also because of the lack of information about it. The above formula (IV.5.10) yields the quantities ν_0 given in table IV.5.2 for the four isotopes being considered.

The quantity ν_1 in equation (IV.5.4) indicates the increase of $\bar{\nu}$ with increasing energy.

Almost all of the excitation of the fissioning nucleus, increasing with increasing incident neutron energy, appears as excitation of the fragments. This leads to

$$\frac{d\bar{\nu}}{dE} \approx 1/E_0 \qquad (IV.5.11)$$

where E is the incident neutron energy and E_0 the average energy required to release a neutron. Terrell has quoted a value of 6.7 MeV for E_0 and with that it follows $\nu_1 \approx 0.15\ MeV^{-1}$ [55]. This value has been adopted for the isotopes except for ^{237}Np, for which the existence of measurements has offered another way for the determination of ν_1.

For ^{237}Np the following experimental data information for $\bar{\nu}(E)$ has been available.

Table IV.5.1

Average neutron energy	$\bar{\nu}$	Reference	Comment	Renormalized value $\bar{\nu}$
1.40 MeV	2.81±0.09	[56]	indirect method on "Topsy" and "Jezebel" critical assemblies	
1.67 MeV	2.90±0.04	[56]	relative to U235, but standard value not given	
1.8 MeV	2.96±0.05	[57]	normalized to $\bar{\nu}(U235)_{thermal}$ =2.47	2.91 renormalized by us to $\bar{\nu}_{therm}(U235)=2.43$
2.5 MeV	2.72±0.15	[58]	prompt neutrons; normalized to $\bar{\nu}_{therm}(U235)$ =2.47	2.67 renormalized to $\bar{\nu}_{therm}(U235)$ = 2.43

The experimental value of Kuz'minov [58] has been excluded, because after renormalization it has become equal to the thermal value obtained by formula (III.5.10). The other three experimental data points and the calculated thermal value of $\bar{\nu}$ have proven as appropriate to a linear fit with slope $\nu_1 = 0.13$.

The following table gives a survey on the used values for ν_1 and ν_0.

Table IV.5.2: Straight-line functions $\bar{\nu}(E)$ for ^{237}Np, ^{238}Np, ^{241}Am, ^{242}Cm

Isotope	ν_0	ν_1	$\bar{\nu}(E)$
^{237}Np	2.67	0.13 MeV^{-1}	$\bar{\nu}(E)=2.67+0.13E$
^{238}Np	2.77	0.15 MeV^{-1}	$\bar{\nu}(E)=2.77+0.15E$
^{241}Am	3.08	0.15 MeV^{-1}	$\bar{\nu}(E)=3.08+0.15E$
^{242}Cm	3.19	0.15 MeV^{-1}	$\bar{\nu}(E)=3.19+0.25E$

The change in $\bar{\nu}$ with neutron energy is shown in the plots of <u>figure 10</u> for the above isotopes.

V. Final consideration

In the final phase of the investigations reported here an evaluation of cross section data for ^{237}Np carried out by the Idaho Nuclear Corporation has been published /¯60_7 which has not been regarded.
In the resolved and unresolved resonance region the computation of cross sections in this report is based completely on the resonance data of D. Paya. The Idaho evaluation uses a great part of the Paya data, but also older ones. They intend, however, to incorporate fully the Paya data in their next major re-evaluation of the ^{237}Np file. In the fast region for the capture cross section the measurements of Stupegia et al. /¯31_7 have been taken as a basis in the Idaho report as well as in this work.
As for the fission cross section of ^{237}Np the Idaho evaluation is based on the results of Perkin and White at low energies, and in the fast region the greatest weight is given to the data of White. The same basis have the recommended fission data of Davey used in this report. The (n,2n) cross section values have been determined in the two reports according to the procedure given by Pearlstein. In the Idaho evaluation, however, the shape of $\sigma_{n,2n}$ has not been fitted to the experimental value at 14.5 MeV /¯49_7. If the adjustment of the curve would be performed, one would obtain $\sigma_{n,2n}$ values larger by a factor of about 2.6 and these would be in better agreement with our results than the original values reported in the Idaho evaluation. Strictly the same values would yield only with identical $\sigma_{n,e}$- and $\frac{\sigma_{n,M}}{\sigma_{n,e}}$ - values (we have assumed $\sigma_{n,e}$ to be 3b in accordance with the value used in the fission systematics and $\frac{\sigma_{n,M}}{\sigma_{n,e}} = 1$, whereas the Idaho evaluation uses $\sigma_{n,e} = 2.85$b and $\frac{\sigma_{n,M}}{\sigma_{n,e}} = 0.98$, both values derived from the corresponding Pearlstein curves).
For the mean number of neutrons per fission of ^{237}Np the Idaho evaluation gives

$$\bar{\nu}(E) = 2.61 + 0.16E$$

This energy dependence has been determined by assuming a slope of 0.16 MeV^{-1} and passing through the average of the two measurements of Hansen /¯56_7.
In this report the two measurements of Hansen have been used together with

a Russian measurement to fix the slope of the straight-line function $\bar{\nu}(E)$, whilst the thermal $\bar{\nu}$-value has been taken from a systematic formula (see chapter IV.5.). The last procedure for the deduction of $\bar{\nu}(E)$ has to be preferred, because the slope for $\bar{\nu}(E)$ as assumed in the Idaho evaluation for ^{237}Np is not characteristical for this isotope (the assumed slope has been derived in /‾68_7 for a universal curve $\bar{\nu}(E)$ for neutron energies above 1.6 MeV for ^{232}U, ^{235}U, ^{239}Pu by adding a constant energy to the incident neutron energy for each nuclide). Both functions $\bar{\nu}(E)$ have been displayed in figure 10.

It would be just as well mentioned here that C.L. Dunford and H. Alter /‾7_7 have given for ^{238}Pu a straight-line function for $\bar{\nu}(E)$

$$\bar{\nu}(E) = 2.75 + 0.118E \text{ (MeV)}$$

which has not been adopted in this report. In this formula the multiplicities of fission modes have not been taken into account as postulated by Schuster and Howerton and carried out in this work. Both functions $\bar{\nu}(E)$, that of Dunford and Alter and that one derived here, are displayed in figure 9. The differences in $\bar{\nu}$ are of about 4% at maximum.

Concerning ^{236}U the average resonance parameters used in this report have been based on preliminary results of Carlson (referenced in CINDA 68) obtained from 17 positive resonances between 5.45 eV and 272.8eV. His finally published results /‾14, not referenced in CINDA 69_7 based on resonance measurements for a single negative resonance at -9.7 eV and 28 positive resonances up to an energy of 415 eV have not been taken into account. These results show that we have assumed too large values for S_0 and $\bar{D}_{obs}$ and too small values for $\bar{\Gamma}_\gamma$ and S_1. In a later re-evaluation this defect has to be corrected. A comparison of the parameters is given in table V.1 below.

Table V.1: Average resonance parameters for ^{236}U

Resonance parameter	Values preferred in this report	Values given by A.D. Carlson et al. (GA9057)	
$S_0 \times 10^{+4}$	1.3	1.35 ± 0.3	calculated from measured average capture cross sections
		$1.02^{+0.4}_{-0.2}$	calculated from resonance parameters
$S_1 \times 10^{+4}$	2.0	2.3 ± 0.6	
Γ_γ [meV]	23	23.9 ± 1	
$\bar{D}$ [eV]	17.3	$15.4^{+2.2}_{-1}$	
$\Gamma_n^{(0)}$ [meV]	2.25	$1.6^{+0.6}_{-0.3}$	

Certainly these resonance measurements of Carlson can give a decision concerning the thermal capture cross section determined by McCallum [69] by subtraction of a calculated scattering cross section value from a measured σ_{total}. This value differs by a large amount from the σ_γ-values resulting from activation measurements. It may be that this discrepancy is due to a wrong scattering cross section value which has been obtained by McCallum from parameters of the two lowest resonances at -8eV and +5.48 eV. Therefore it would be important to calculate again this value with the recent parameters of Carlson.

Acknowledgements

I wish to express my greatest appreciation to Dr. J.J. Schmidt for his close collaboration during the entire course of this work and for the critical readings of the manuscript.

Dr. A. Sauer and Dr. K.E. Schroeter deserve thanks for making available the thermal and fast reactor weighting spectra.

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List of the tables

Table 1: Thermal neutron cross sections at 0.025 eV

Isotope	σ_γ [b]	Reference	σ_f [b]	Reference	Comments
$^{231}_{91}Pa$	200±10	1	0	1(curve)	values at 0.025 eV; σ_γ recommended in [1
	200	29	0.0045	29	in [29] recommended values at 0.025 eV; σ_γ from available measurements (the same ones are considered as in [1]); σ_f calculated from resolved resonance parameters.
	preferred: 200		preferred: 0		The small subthreshold fission was neglected.
$^{232}_{92}U$	78±4	1	77±10	1	in [1] recommended values, σ_γ for thermal spectrum, σ_f for thermalized spectrum
	76.8	29	81.2	29	calculated from resolved resonance parameters
	preferred: 78		preferred: 77		the σ_f-value in [1] is based on two measurements: 1.81±15b Elson etal.Phys.Rev.89,320,1953 2.70±10b Seaborg etal.CS-3471,p.2,1946; with the value from [29] one obtains σ_f as arithmetic mean of the three values.
$^{234}_{92}U$	95±7	1	0	2	in [1 and 2 resp.] recommended values at 0.025eV; σ_γ based on measurements; σ_f is expected to be about 0.006b [2]
	95±10	23			value preferred in [23]
	preferred: 95		preferred: 0		
$^{236}_{92}U$	6.0±1	1	0	2	in [1,2 and 30 resp.] recommended values a 0.025eV; σ_γ based on several activation measurements
	6.1	30			
	5.6	3	0	3	in [3] recommended values at 0.025eV; σ_γ =6.0±0.4b obtained in resonance integral measurements
	5.6±0.7	14			obtained from preliminary σ_γ-measurements

Table 1: continued

Isotope	σ_γ [b]	Reference	σ_f [b]	Reference	Comments
	preferred: 5.6		preferred: 0		The first two σ_γ-values quoted here are averages over the same available measurements both taking into account the σ_γ-value of 8.1b [69] obtained from a measurement of σ_T. Without that value an unweighted average of 5.6b would follow from the basic measurements. Also most recent measurements [14] show the tendency to lower values.
$^{237}_{92}U$	480	3	2	3	values at 0.025eV, obtained from measurements of the corresponding effective cross sections
$^{237}_{93}Np$	170	6	0.019	6	experimental values at 0.025 eV
	169	3	0.02	3	in [3] preferred values at 0.025 eV, obtained from measurements
	preferred: 170		preferred: 0		the small subthreshold fission neglected
$^{238}_{93}Np$	43	calculated from (II.1)	2200±200	3	σ_f-value at 0.025 eV from measurement
$^{236}_{94}Pu$	33		162	5	σ_f measured in the thermal column of the MTR
$^{238}_{94}Pu$	500±100	1			in [1] recommended value at 0.025eV, based on measurements
	546.5	7	16.3	7	values at 0.025eV calculated from single-level resonance parameters
	546.7	3	16.3	3	preferred values at 0.025eV; σ_γ from σ_{Abs}= 563b
	preferred: 547		preferred: 16		
$^{241}_{95}Am$	582	1	3.13±0.15	4	values at 0.025eV; σ_γ from a measured σ_{Abs}-values with σ_f=3b;
	preferred: 582		preferred: 3		σ_f measured in the thermal column of the MTR relative to σ_f (Pu239)=806b ; renormalized to σ_f(Pu239)=740.6b [1] it follows σ_f(Am241)=2.88b

Table 1: continued

Isotope	σ_{γ} [b]	Reference	σ_f [b]	Reference	Comments
$^{242}_{96}Cm$	20±10	6	0.8	8	σ_{γ} measured for pile neutrons; σ_f calculated from $\sigma_{\gamma therm}$ under the assumption that the value estimated in [8] for the ratio $\sigma_{\gamma}/\sigma_{Abs}$=0.96 for Cm244 can be taken also for Cm242

Table 2: Preferred microscopic values of the fission cross section of ^{236}U

Neutron energy [MeV]	σ(n,f) [b]
0.550	0.0
0.608	0.0
0.672	0.017
0.743	0.048
0.821	0.142
0.907	0.290
1.00	0.331
1.25	0.567
1.50	0.649
2.00	0.782
2.25	0.837
2.50	0.840
2.75	0.806
3.00	0.790
3.25	0.797
3.50	0.810
3.75	0.816
4.00	0.806
4.25	0.802
4.50	0.807
4.75	0.786
5.00	0.779
5.49	0.80
6.07	0.93
6.70	1.27
7.41	1.55
8.19	1.72
9.05	1.73
10.00	1.64

Table 3: Variation of the fission cross section (see figure5) at 3 MeV with $Z^{4/3}/A$

(A mass number of the target nucleus)

Target nucleus	$Z^{4/3}/A$	σ_f(3MeV) [b]	Reference
$^{226}_{88}Ra$	1.732	0.	
$^{232}_{90}Th$	1.738	0.130	Davey [33]
$^{231}_{91}Pa$	1.772	1.30	Drake, Nichols [29]
$^{233}_{92}U$	1.782	1.71	Davey [33]
$^{234}_{92}U$	1.775	1.40	Davey [33]
$^{235}_{92}U$	1.767	1.18	Davey [33]
$^{236}_{92}U$	1.760	0.790	Stein et al. [34]
$^{238}_{92}U$	1.745	0.500	Davey [33]
$^{237}_{93}Np$	1.778	1.59	Davey [33]
$^{239}_{94}Pu$	1.788	1.82	Davey [33]
$^{240}_{94}Pu$	1.781	1.57	Davey [33]

Table 4: Plateau values of the fission cross section for the isotopes ^{232}U, ^{237}U, ^{238}Np, ^{236}Pu, ^{242}Cm

Target nucleus A	Fission barrier [40] E_f [MeV]	$E_B(A+1)$ [MeV]	first plateau σ_{f_o} [b]	f_o	second plateau σ_{f_1} [b]
^{232}U	5.49	5.93	1.86	0.62	2.67
^{231}U	experimental 4.966 (a)		2.13	0.71	
^{237}U	5.80 exp.	6.07	0.67	0.223	1.325
^{236}U	6.40 exp.		0.844	0.281	
^{238}Np	5.427 (a)	6.23	1.24	0.413	2.12
^{237}Np	6.04 exp.		1.50	0.500	
^{236}Pu	5.078 (a)	6.05	2.54	0.846	2.96
^{235}Pu	4.70 exp.		2.79	0.93	
^{242}Cm	4.847 (a)	5.69	2.70	0.90	2.99
^{241}Cm	4.40 exp.		2.96	0.986	

Among the fission barriers reported by Prince [40] those which have been determined by experiment or, if nonexistent, which have been calculated from (a), were selected.

(a) $E_f(\mathrm{MeV}) = (19.0-0.36\ Z^2/A+\varepsilon)$ $\varepsilon = \begin{cases} 0 & \text{even-even} \\ 0.4 & \text{odd} \\ 0.7 & \text{odd-odd} \end{cases}$

R.Vandenbosch, G.T. Seaborg, Phys. Rev. 110 (1958) 507

Table 5: Fission cross section data in the fast region for the isotopes ^{232}U, ^{237}U, ^{238}Np, ^{236}Pu, ^{242}Cm

(see also figure 6)

1. Average fission cross section values over group 2 from 46.5 keV to 800 keV

Isotopes	U232	U237	Np238	Pu236	Cm242
$\langle\sigma_f\rangle_2$ [b]	1.86	0.67	1.24	2.54	2.70

2. Fission cross section values in the energy range of group 1 from 800 keV up to 10 MeV

U232		U237		Np238		Pu236		Cm242	
E [MeV]	$\sigma_{n,f}$ [b]	E [MeV]	$\sigma_{n,f}$ [b]	E [MeV]	$\sigma_{n,f}$ [b]	E [MeV]	$\sigma_{n,f}$ [b]	E [MeV]	$\sigma_{n,f}$ [b]
0.80	1.86	0.80	0.67	0.80	1.24	0.80	2.54	0.80	2.70
4.5	1.86	5.9	0.67	5.5	1.24	4.2	2.54	3.9	2.70
4.75	1.90	6.15	0.69	5.75	1.28	4.45	2.56	4.15	2.71
4.9	2.04	6.3	0.81	5.9	1.44	4.6	2.63	4.3	2.76
5.0	2.27	6.4	1.0	6.0	1.68	4.7	2.75	4.4	2.85
5.1	2.50	6.5	1.18	6.1	1.92	4.8	2.87	4.5	2.93
5.25	2.64	6.65	1.30	6.25	2.08	4.95	2.94	4.65	2.98
5.50	2.67	6.9	1.325	6.5	2.12	5.20	2.96	4.9	2.99
10.0	2.67	10.0	1.325	10.0	2.12	10.0	2.96	10.0	2.99

Table 6: (n,2n) cross sections for the isotopes ^{237}U, ^{237}Np, ^{238}Np, ^{236}Pu, ^{241}Am, ^{242}Cm

(the underlined energies indicate the threshold of the (n,2n) process for the nucleus considered)

U237		Np237		Np238	
E [MeV]	σ(n,2n) [b]	E [MeV]	σ(n,2n) [b]	E [MeV]	σ(n,2n) [b]
0.80	0.	0.80	0.	0.80	0.
5.44	0.			5.39	0.
6.0	0.466			5.5	0.035
6.5	0.827			6.0	0.303
7.0	1.072	6.79	0.	6.5	0.423
7.5	1.273	7.0	0.0457	7.0	0.581
8.0	1.44	7.5	0.274	7.5	0.686
8.5	1.525	8.0	0.441	8.0	0.756
9.0	1.575	8.5	0.576	8.5	0.805
9.5	1.61	9.0	0.675	9.0	0.831
10.0	1.63	9.5	0.821	9.5	0.849
		10.0	0.973	10.0	0.863

Pu236		Am241		Cm242	
E [MeV]	σ(n,2n) [b]	E [MeV]	σ(n,2n) [b]	E [MeV]	σ(n,2n) [b]
0.80	0.	0.80	0.	0.80	0.
7.41	0.	5.82	0.	6.90	0.
7.8	0.0032	6.0	0.0289	7.0	0.
8.0	0.0062	6.5	0.174	7.5	0.0017
8.5	0.0148	7.0	0.282	8.0	0.0039
9.0	0.0228	7.5	0.347	8.5	0.0059
9.5	0.0284	8.0	0.367	9.0	0.0072
10.0	0.0320	8.5	0.404	9.5	0.0081
		9.0	0.428	10.0	0.00875
		9.5	0.442		
		10.0	0.452		

Table 7: Average values of the mean number of neutrons per fission for the energy groups:

5: 0.025 eV
4: 0.5 eV - 1 keV
3: 1 keV - 46.5 keV
2: 46.5 keV - 800 keV

Isotope	$\bar{\nu}_4=\bar{\nu}_5=\bar{\nu}_3$	$\bar{\nu}_2$
^{231}Pa	-	2.55
^{232}U	2.44	2.49
^{234}U	-	2.43
^{236}U	-	2.40
^{237}U	-	2.465
^{237}Np	-	2.73
^{238}Np	2.77	2.83
^{236}Pu	2.87	2.92
^{238}Pu	2.83	2.88
^{241}Am	3.09	3.15
^{242}Cm	3.19	3.25

Table 8: Mean number of neutrons per fission for the isotopes ^{232}U, ^{236}U, ^{237}U, ^{236}Pu, ^{238}Pu

Isotope	ν_{thr}	ν_1	Threshold [MeV] (n,f) process	(n,n'f)process
U232	2.39	0.112	-0.44	4.966
U236	2.47	0.136	+0.96	5.80
U237	2.37	0.142	-0.27	6.40
Pu236	2.77	0.106	-0.97	4.70
Pu238	2.81	0.118	-0.16	4.90
Pu235	2.63	0.100		
Pu237	2.67	0.112		
U231	2.25	0.106		
U235	2.33	0.130		

^{232}U

$$\bar{\nu}(E) = R_{n,f}(2.39+0.112(E+0.44))+R_{n,n'f}(1+2.25+0.106(E-4.966))$$

^{236}U

$$\bar{\nu}(E) = R_{n,f}(2.47+0.136(E-0.96))+R_{n,n'f}(1+2.33+0.130(E-5.80))$$

^{237}U

$$\bar{\nu}(E) = R_{n,f}(2.37+0.142(E+0.27))+R_{n,n'f}(1+2.47+0.136(E-6.40))$$

^{236}Pu

$$\bar{\nu}(E) = R_{n,f}(2.77+0.106(E+0.97))+R_{n,n'f}(1+2.63+0.100(E-4.70))$$

^{238}Pu

$$\bar{\nu}(E) = R_{n,f}(2.81+0.118(E+0.16))+R_{n,n'f}(1+2.67+0.112(E-4.90))$$

Table 9: Branching ratios for $\bar{\nu}$

U232			U236			U237			Pu236			Pu238		
E [MeV]	$R_{n,f}$	$R_{n,n'f}$	E [MeV]	$R_{n,f}$	$R_{n,n'f}$	E [MeV]	$R_{n,f}$	$R_{n,n'f}$	E [MeV]	$R_{n,f}$	$R_{n,n'f}$	E [MeV]	$R_{n,f}$	$R_{n,n'f}$
0.8	1.0	0.	0.8	1.0	0.	0.8	1.0	0.	0.8	1.0	0.	0.8	1.0	0.
4.5	1.0	0.	5.7	1.0	0.	5.9	1.0	0.	4.2	1.0	0.	1.0	1.0	0.
4.75	0.978	0.022	6.07	0.86	0.14	6.15	0.97	0.03	4.45	0.992	0.008	1.2	0.95	0.05
5.0	0.82	0.18	6.70	0.63	0.37	6.3	0.83	0.17	4.6	0.965	0.035	1.5	0.91	0.09
5.1	0.74	0.26	7.41	0.515	0.485	6.4	0.67	0.33	4.7	0.92	0.08	2.0	0.91	0.09
5.25	0.705	0.295	8.19	0.465	0.535	6.5	0.568	0.432	4.8	0.88	0.12	3.0	0.80	0.20
5.50	0.696	0.304	9.05	0.46	0.54	6.65	0.515	0.485	4.95	0.86	0.14	4.0	0.75	0.25
10.	0.696	0.304	10.	0.49	0.51	6.90	0.505	0.495	6.0	0.86	0.14	6.0	0.74	0.26
						10.	0.505	0.495	10.	0.86	0.14	8.0	0.77	0.23
												10.	0.77	0.23

Table 10: $\bar{\nu}$-values as a function of the neutron energy für several U- and Pu-isotopes

U232		U236		U237		Pu236		Pu238	
E [MeV]	$\bar{\nu}$	E [MeV]	$\bar{\nu}$	E [MeV]	$\bar{\nu}$	E [MeV]	$\bar{\nu}$	E [MeV]	$\bar{\nu}$
0.8	2.53	0.8	2.45	0.8	2.52	0.8	2.96	0.8	2.92
4.5	2.94	1.0	2.46	1.0	2.55	1.0	2.98	1.0	2.95
4.75	2.98	2.0	2.61	2.0	2.69	2.0	3.08	1.2	2.98
5.0	3.05	3.0	2.75	3.0	2.83	3.0	3.19	1.5	3.04
5.1	3.08	4.0	2.88	4.0	2.98	4.2	3.32	2.0	3.10
5.25	3.11	5.0	3.02	5.9	3.246	4.45	3.34	3.0	3.23
5.50	3.14	5.7	3.11	6.15	3.31	4.6	3.37	4.0	3.36
6.0	3.19	6.07	3.19	6.3	3.33	4.7	3.39	6.0	3.60
7.0	3.30	6.70	3.32	6.4	3.36	4.8	3.41	8.0	3.83
8.0	3.41	7.41	3.45	6.5	3.39	4.95	3.43	10.0	4.07
9.0	3.52	8.19	3.55	6.65	3.43	5.2	3.46		
10.0	3.63	9.05	3.67	6.9	3.46	6.0	3.55		
		10.0	3.79	8.0	3.62	7.0	3.64		
				9.0	3.75	8.0	3.75		
				10.0	3.89	9.0	3.86		
						10.0	3.96		

Table 11: 5-group averaged values of σ(n,f), σ(n,γ), σ(n,2n) and $\bar{\nu}\sigma(n,f)$ for the case of a thermal reactor spectrum (cross sections in barn)

Energy Group	5 thermal group			4 0.5eV - 1keV			3 1keV - 46.5keV			2 46.5keV - 800keV			1 800keV - 10 MeV			
Isotope	$\langle\sigma_\gamma\rangle$	$\langle\sigma_f\rangle$	$\langle\bar{\nu}\sigma_f\rangle$	$\langle\sigma_\gamma\rangle$	$\langle\sigma_f\rangle$	$\langle\bar{\nu}\sigma_f\rangle$	$\langle\sigma_\gamma\rangle$	$\langle\sigma_f\rangle$	$\langle\bar{\nu}\sigma_f\rangle$	$\langle\sigma_\gamma\rangle$	$\langle\sigma_f\rangle$	$\langle\bar{\nu}\sigma_f\rangle$	$\langle\sigma_\gamma\rangle$	$\langle\sigma_f\rangle$	$\langle\bar{\nu}\sigma_f\rangle$	$\langle\sigma_{2n}\rangle$
Pa231	200	0	-	61	0	-	3.5	0	-	0.43	0.18	0.46	0.05	1.2	4.2	$2.96\ 10^{-2}$
U232	78	77	188	20	39	95	0.7	5.0	12	0.16	1.9	4.6	0.06	1.9	7.3	1.49510^{-3}
U234	95	0	-	91	0	-	1.4	0	-	0.31	0.29	0.70	0.14	1.3	4.9	8.87510^{-4}
U236	5.6	0	-	54	0	-	1.4	0	-	0.31	0.004	0.01	0.14	0.69	3.5	$6.01\ 10^{-3}$
U237	480	2	4.8	37	0	-	2.2	0	-	0.18	0.67	1.7	0.07	0.68	3.1	$2.85\ 10^{-2}$
Np237	170	0	-	122	0	-	4.6	0	-	0.96	0.28	0.76	0.17	1.57	6.2	$4.79\ 10^{-3}$
Np238	43	2200	6094	3.7	191	528	0.16	8.1	22	0.30	1.2	3.5	0.12	1.3	6.0	$1.58\ 10^{-2}$
Pu236	33	162	465	25	123	353	1.0	4.8	14	0.30	2.5	7.4	0.12	2.6	9.7	$6.66\ 10^{-5}$
Pu238	547	16	45	18	2.8	7.9	2.4	0.64	1.8	0.14	1.1	3.0	0.03	2.3	9.0	$3.48\ 10^{-4}$
Am241	582	3	9.3	208	1.1	3.4	4.5	0.02	0.07	0.30	0.07	0.22	0.12	1.5	8.1	$5.81\ 10^{-3}$
Cm242	20	0.8	2.6	87	3.9	12.4	2.9	0.13	0.41	0.30	2.7	8.8	0.12	2.7	11.6	$3.21\ 10^{-4}$

Table 12: 5-group averaged values of $\sigma(n,f)$, $\sigma(n,\gamma)$, $\sigma(n,2n)$ and $\bar{\nu}\sigma(n,f)$ for the case of a fast reactor spectrum (cross sections in barn)

Energy Group	5 thermal group			4 0.465eV - 1keV			3 1keV - 46.5keV			2 46.5keV - 800keV			1 800keV - 10MeV			
Isotope	$\langle\sigma_\gamma\rangle$	$\langle\sigma_f\rangle$	$\langle\bar{\nu}\sigma_f\rangle$	$\langle\sigma_\gamma\rangle$	$\langle\sigma_f\rangle$	$\langle\bar{\nu}\sigma_f\rangle$	$\langle\sigma_\gamma\rangle$	$\langle\sigma_f\rangle$	$\langle\bar{\nu}\sigma_f\rangle$	$\langle\sigma_\gamma\rangle$	$\langle\sigma_f\rangle$	$\langle\bar{\nu}\sigma_f\rangle$	$\langle\sigma_\gamma\rangle$	$\langle\sigma_f\rangle$	$\langle\bar{\nu}\sigma_f\rangle$	$\langle\sigma_{2n}\rangle$
Pa231	200	0	-	10.6	0	-	3.0	0	-	0.53	0.11	0.28	0.07	1.1	4.2	$9.40\ 10^{-4}$
U232	78	77	188	3.7	10.3	25	0.8	2.2	5.3	0.18	1.9	4.7	0.07	1.9	7.3	$4.64\ 10^{-4}$
U234	95	0	-	5.8	0	-	0.9	0	-	0.33	0.19	0.46	0.18	1.3	4.9	$2.84\ 10^{-4}$
U236	5.6	0	-	4.9	0	-	0.9	0	-	0.33	0.0015	0.0036	0.18	0.62	3.5	$1.95\ 10^{-3}$
U237	480	2	4.8	16	0	-	3.9	0	-	0.07	0.67	1.7	0.18	0.68	3.1	$9.91\ 10^{-3}$
Np237	170	0	-	15.3	0	-	3.3	0	-	1.14	0.18	0.49	0.22	1.5	6.2	$1.54\ 10^{-3}$
Np238	43	2200	6094	2.1	18.3	51	0.54	7.8	22	0.12	1.2	3.4	0.30	1.3	6.0	$5.51\ 10^{-3}$
Pu236	33	162	465	4.7	8.8	25	1.0	2.0	5.8	0.12	2.5	7.3	0.30	2.6	9.7	$2.08\ 10^{-5}$
Pu238	547	16	45	6.9	1.6	4.5	1.2	0.28	0.78	0.16	0.88	2.5	0.03	2.2	9.0	$1.10\ 10^{-4}$
Am241	582	3	9.3	15.7	1.4	4.4	3.1	0.59	1.8	0.12	0.05	0.16	0.30	1.4	8.1	$1.97\ 10^{-3}$
Cm242	20	0.8	2.6	7.5	0.32	1.0	1.6	0.066	0.21	0.12	2.7	8.8	0.30	2.7	11.6	$1.02\ 10^{-5}$

Figure captions

Fig. 1 Flux spectrum of a thermal reactor

Fig. 2 NAP-core spectrum

Fig. 3 Flux spectrum of a fast reactor

Fig. 4 The fission cross section for ^{236}U

Fig. 5 Correlation of σ_f (3MeV) with $Z^{4/3}/A$

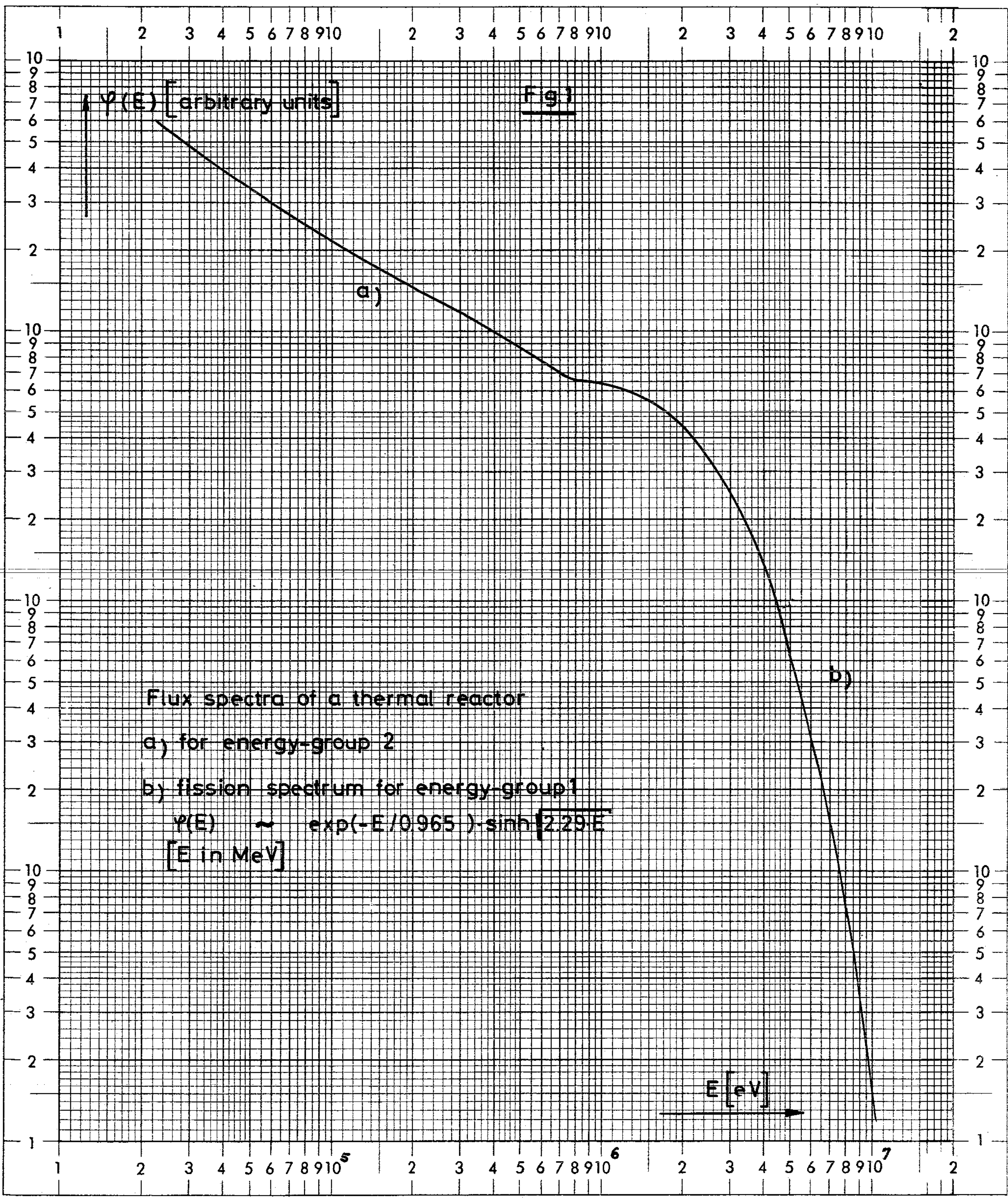
Fig. 6 The fission cross section in the fast region for ^{232}U, ^{237}U, ^{236}Pu, ^{238}Np, ^{242}Cm

Fig. 7 Preferred shape of $\sigma_f(E)$ for ^{241}Am

Fig. 8a The energy dependence of $\sigma(n,2n)$ for ^{237}U, ^{236}Pu, ^{241}Am,
Fig. 8b ^{238}Np, ^{237}Np, ^{242}Cm

Fig. 9 $\bar{\nu}$ as a function of the neutron energy for ^{232}U, ^{236}U, ^{237}U, ^{236}Pu, ^{238}Pu

Fig. 10 $\bar{\nu}$ as a function of the neutron energy for ^{237}Np, ^{238}Np, ^{241}Am, ^{242}Cm



φ(E) [arbitrary units]
Fig.1
a)
b)
Flux spectra of a thermal reactor
a) for energy-group 2
b) fission spectrum for energy-group 1
φ(E) ~ exp(-E/0.965)·sinh √2.29·E
[E in MeV]
E [eV]

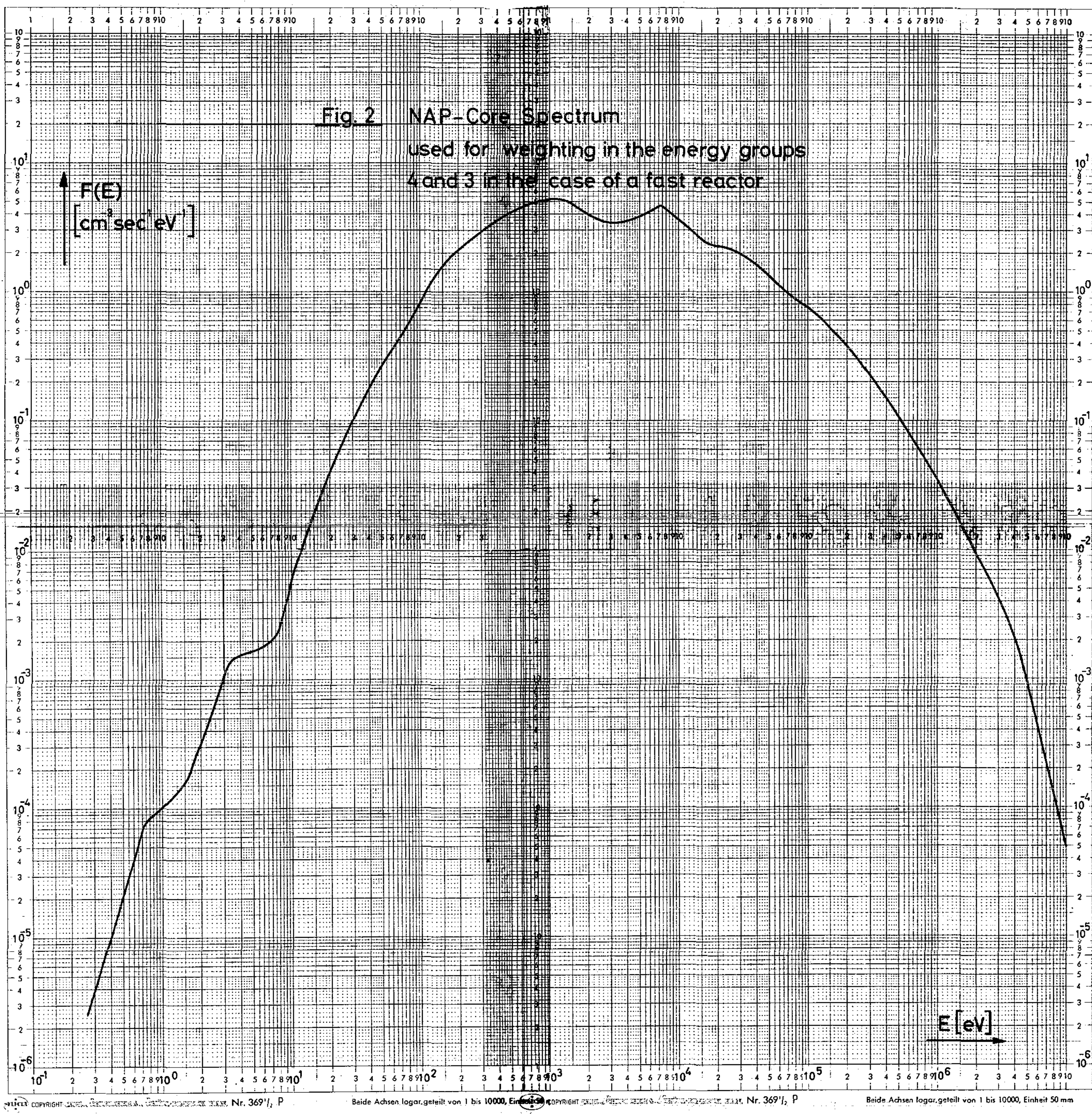


Fig. 2 NAP-Core Spectrum
used for weighting in the energy groups
4 and 3 in the case of a fast reactor
F(E)
[cm⁻²sec⁻¹eV⁻¹]
E [eV]

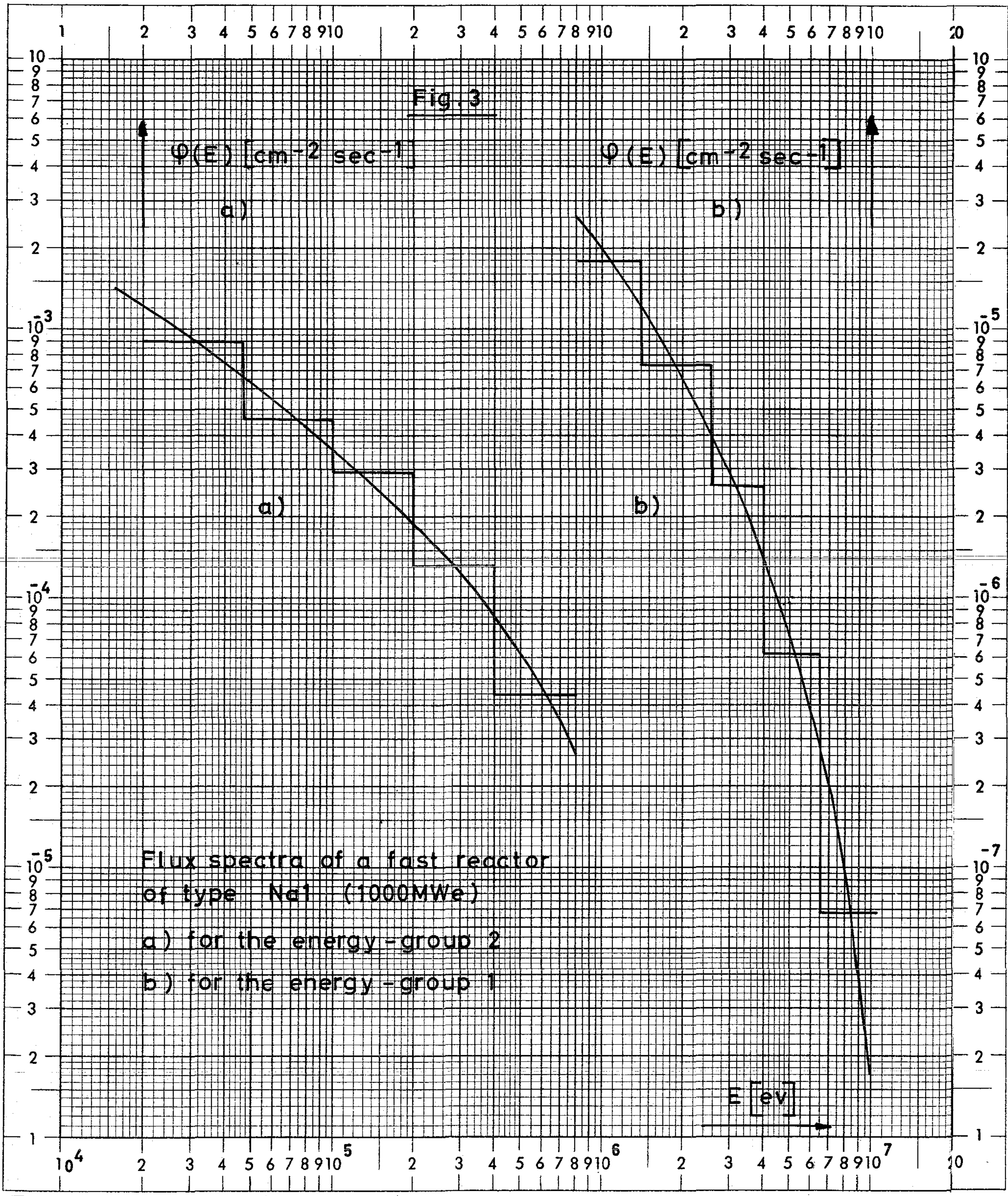


Fig. 3
φ(E) [cm-2 sec-1]
a)
φ (E) [cm-2 sec-1]
b)
a)
b)
Flux spectra of a fast reactor
of type Na1 (1000MWe)
a) for the energy - group 2
b) for the energy - group 1
E [ev]

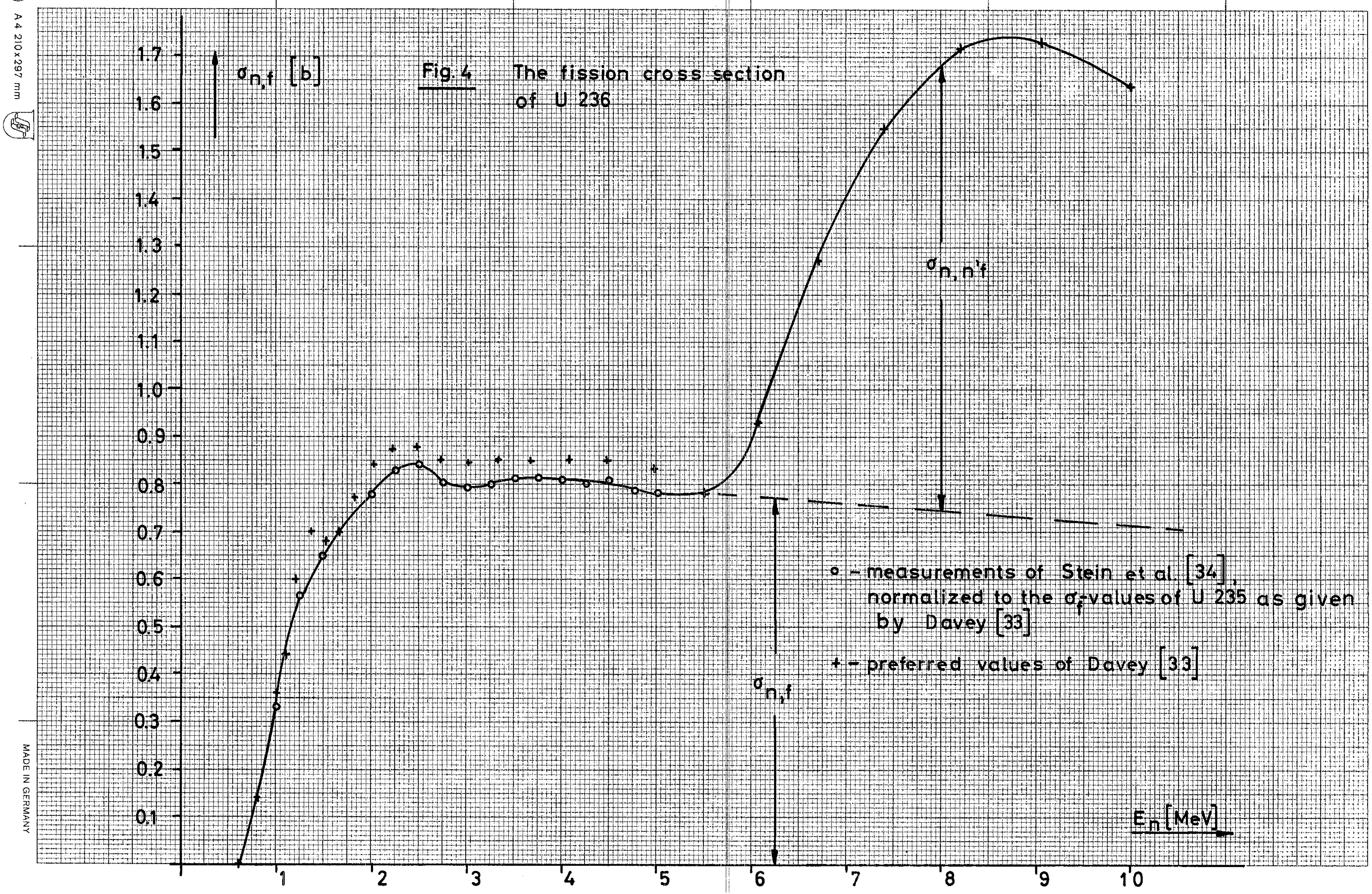


Fig. 4 The fission cross section of U 236

Fig. 5 Variation of the fission cross section for fission induced by 3 MeV neutrons with $Z^{4/3}/A$

(A – mass number of the target nucleus)

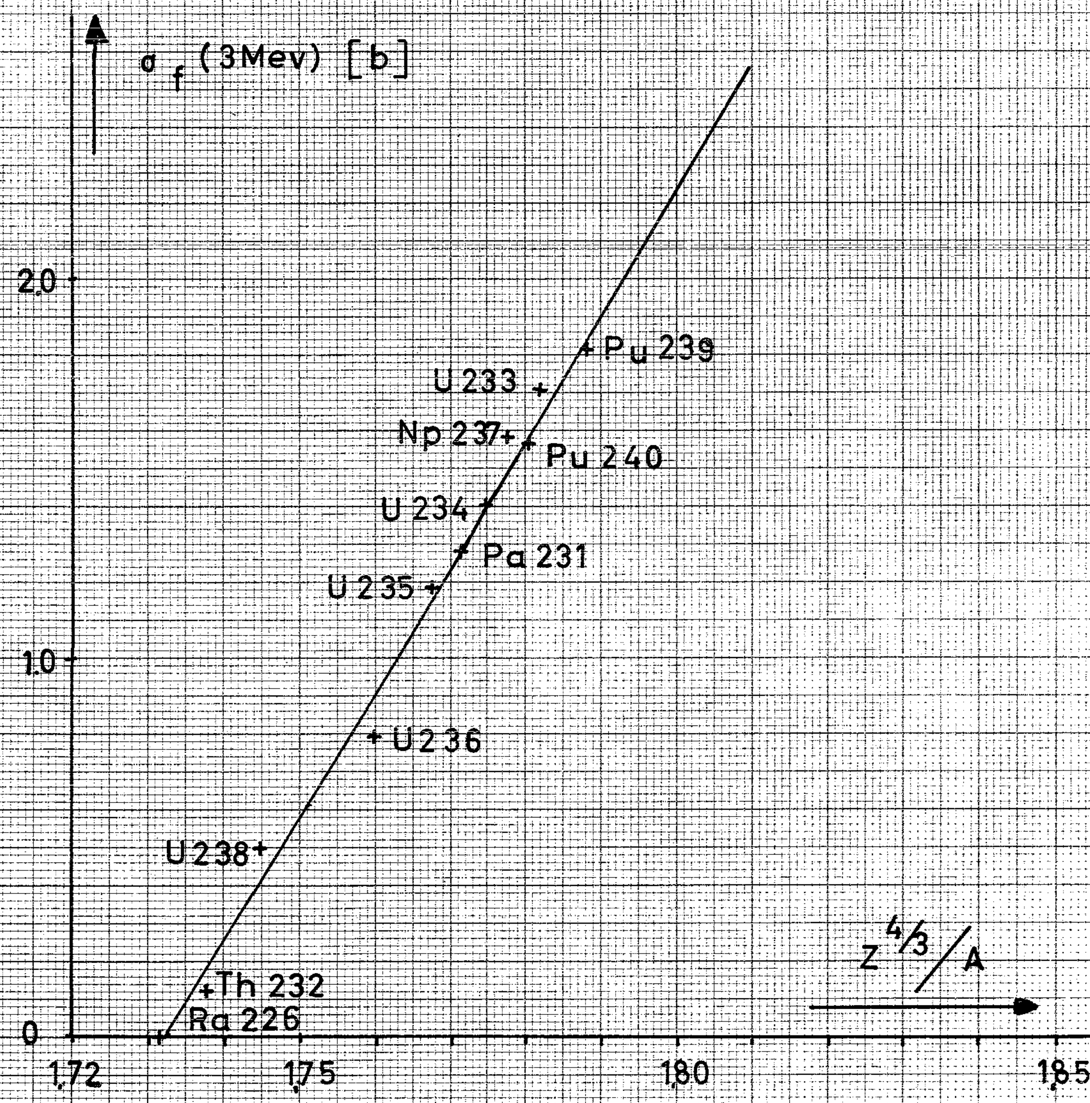
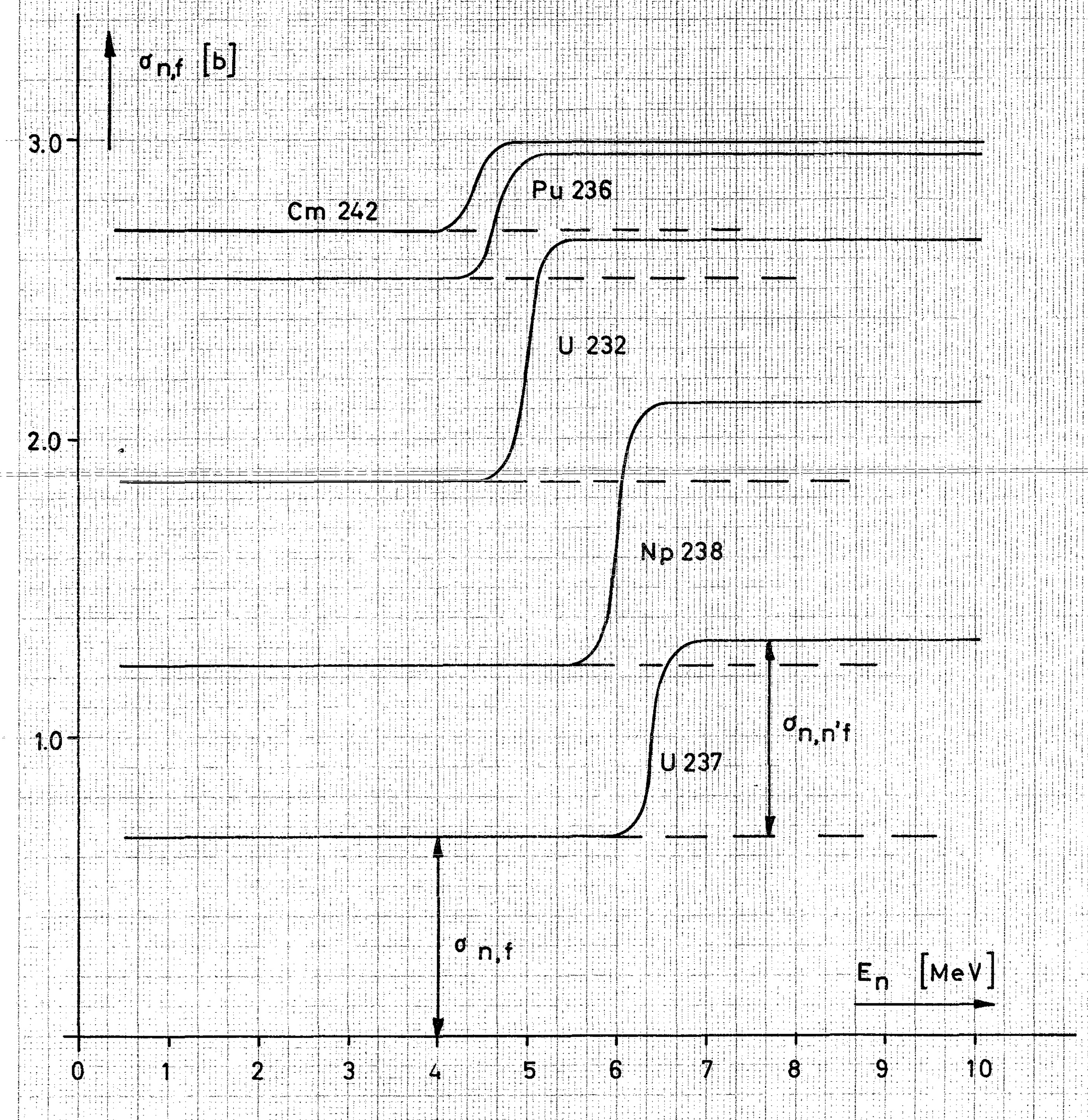


Fig. 6 Fission cross section in the fast region

(see also table 5)



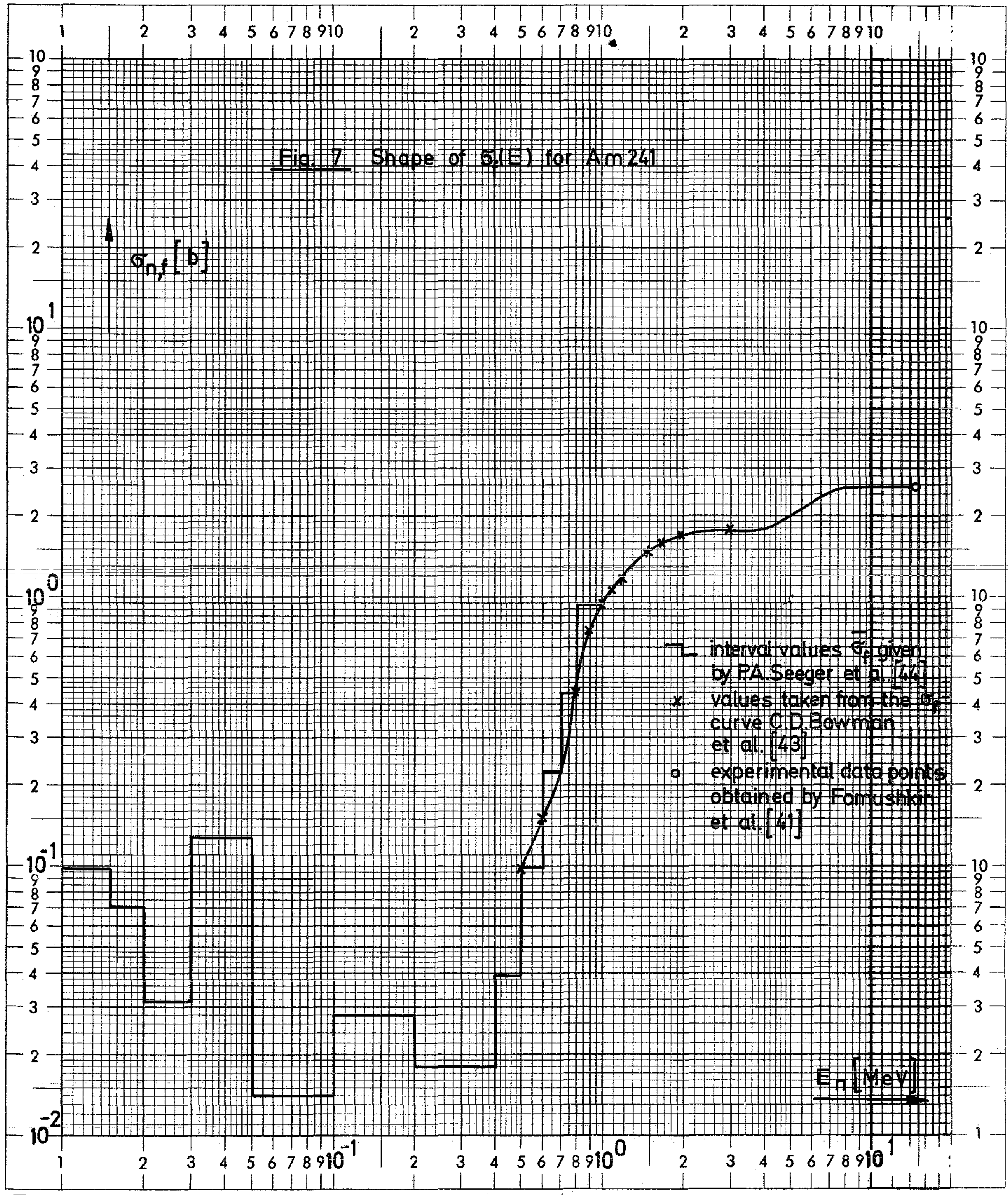


Fig. 7 Shape of $\sigma_f(E)$ for Am 241

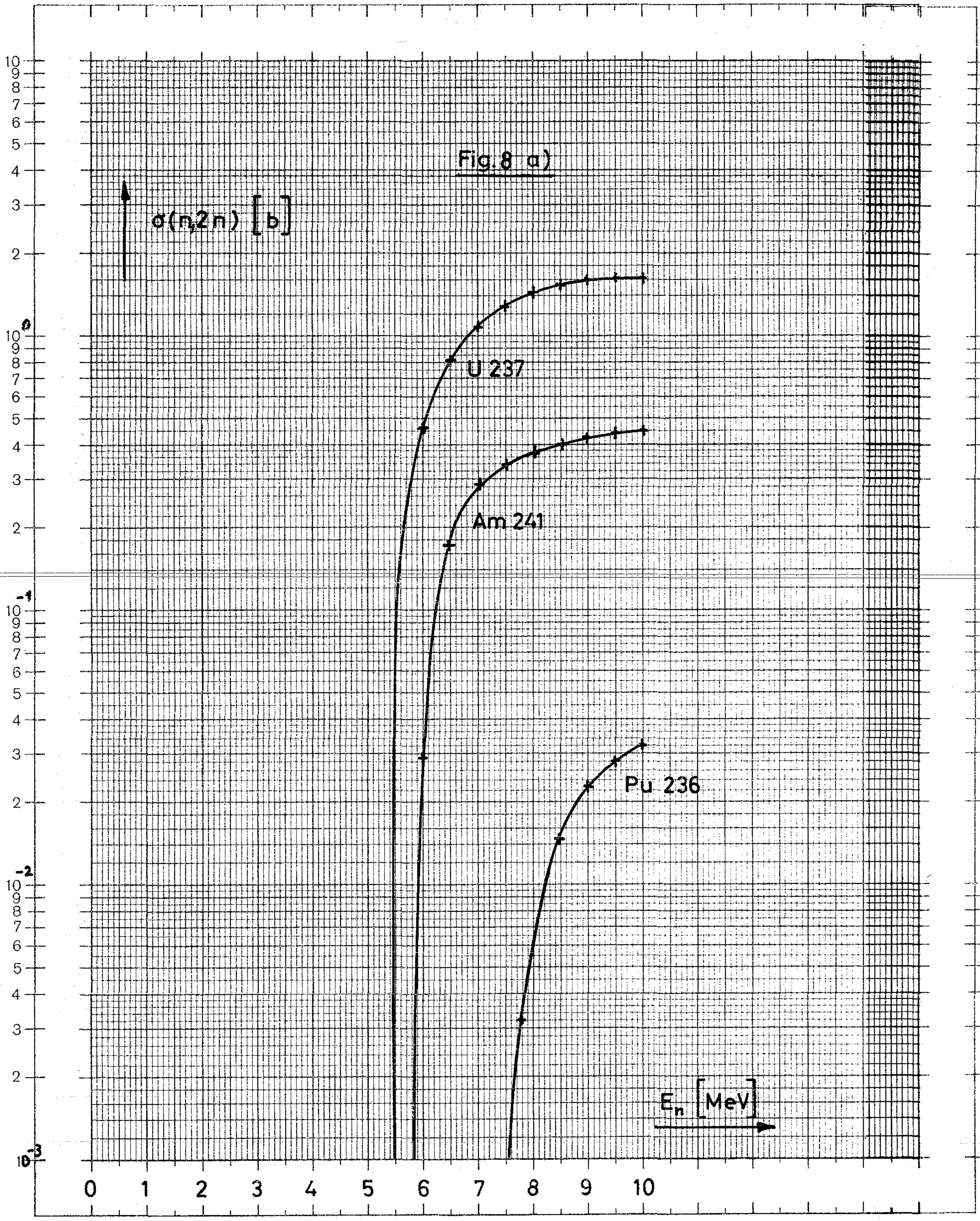


Fig. 8 a)
σ(n,2n) [b]
U 237
Am 241
Pu 236
E_n [MeV]
0 1 2 3 4 5 6 7 8 9 10

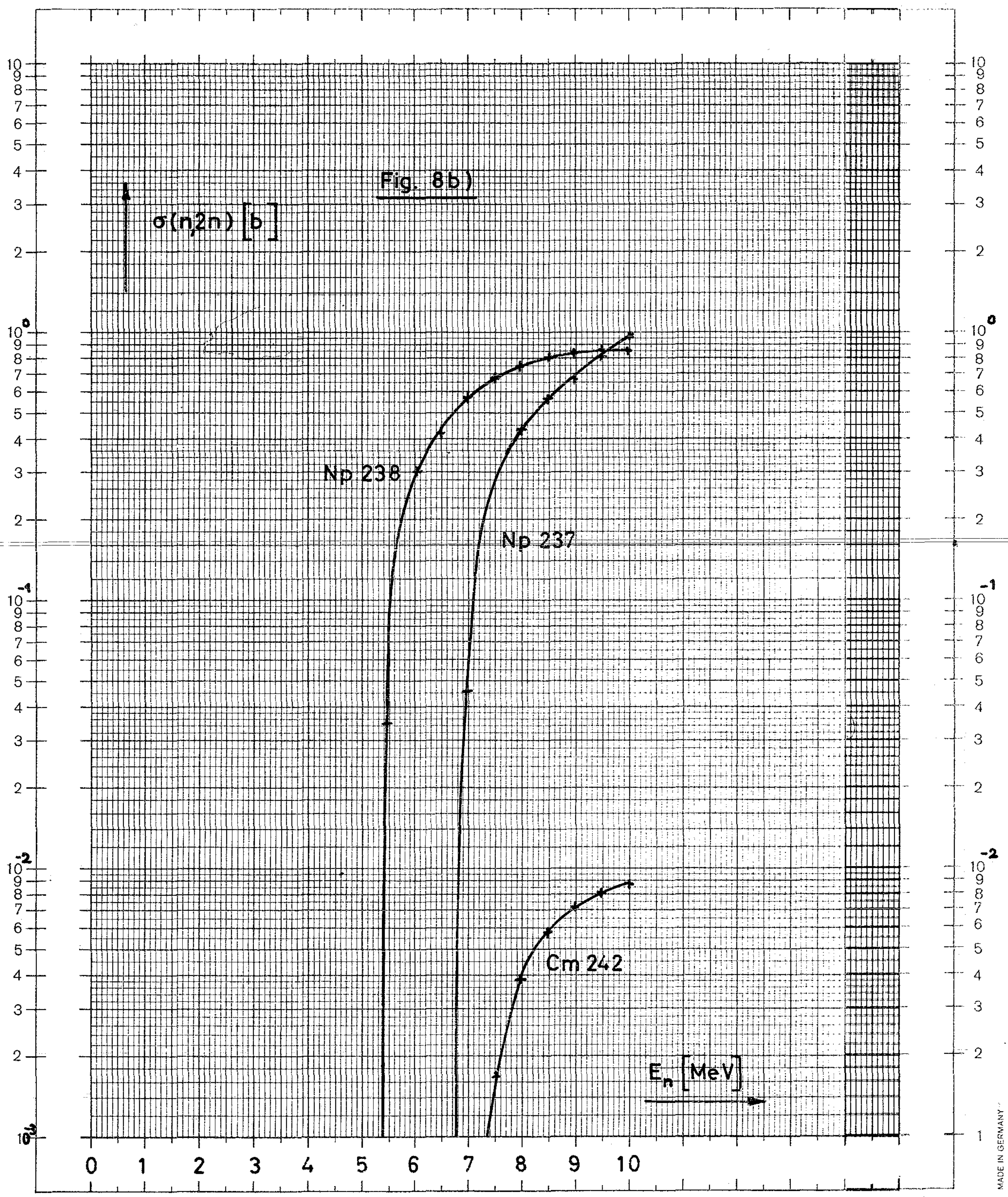


Fig. 8b)
σ(n,2n) [b]
Np 238
Np 237
Cm 242
E_n [MeV]
0 1 2 3 4 5 6 7 8 9 10

Fig. 9 $\bar{\nu}$ as a function of the neutron energy for the isotopes U 232, U 236, U 237, Pu 236, Pu 238.

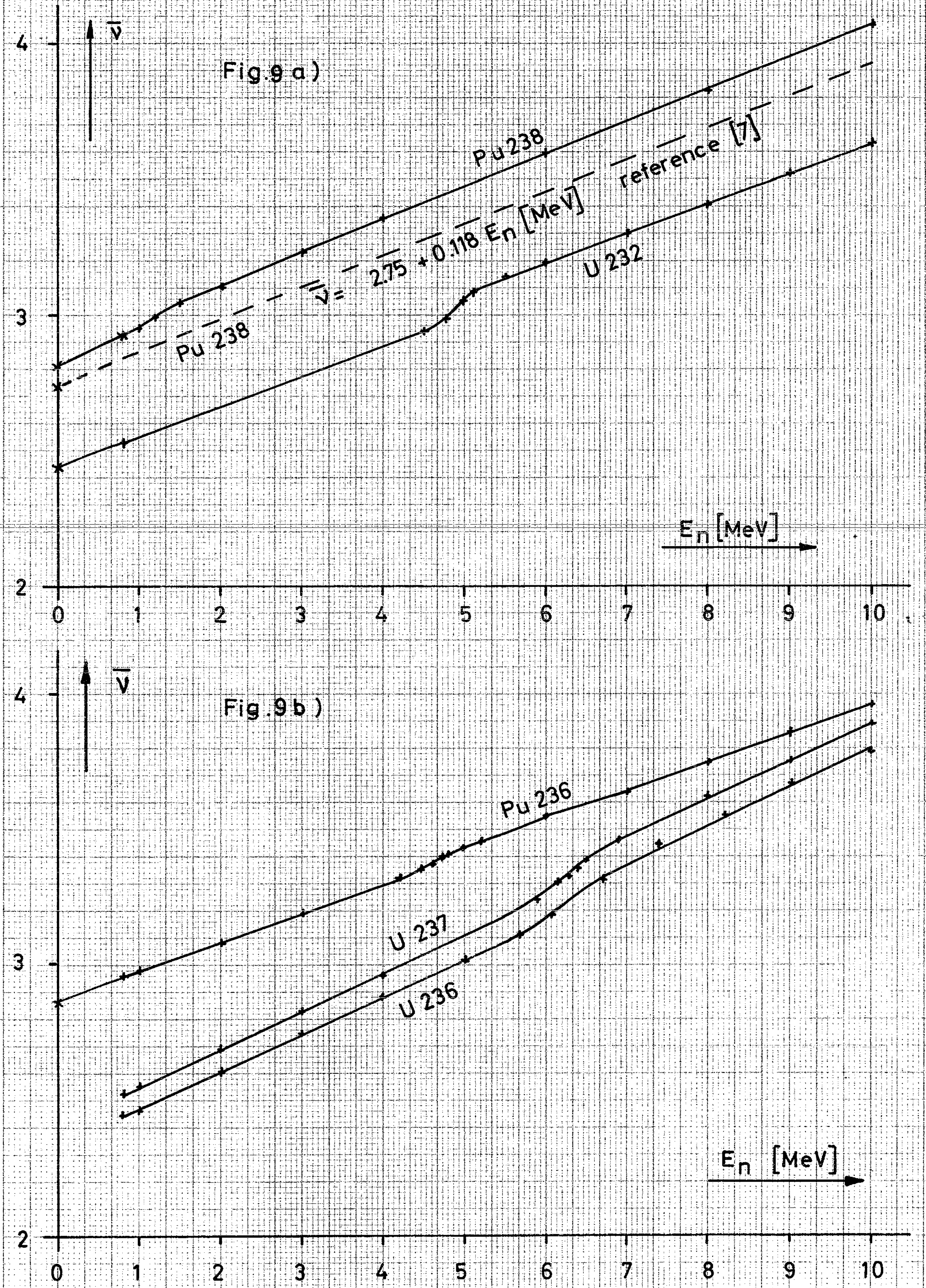


Fig. 10 $\bar{\nu}$ as a function of the neutron energy for the isotopes Np 237, Np 238, Am 241, Cm 242.