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Institut für Neutronenphysik und Reaktortechnik
Projekt Schneller Brüter

Evaluations for the German Nuclear Data Library KEDAK-3
Part 2: Fissile and Fertile Materials

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Abstract

In this report evaluations for the fissile and fertile isotopes performed at this laboratory during the years 1973 to 1976 are presented. In particular the evaluations of the data for ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu are described. Results of a preliminary check of the evaluated data for a variety of critical assemblies are also given in this report.

Auswertungen für die Deutsche Kerndaten-Bibliothek KEDAK-3

Teil 2: Spalt- und Brutmaterialien

Zusammenfassung

In diesem Bericht werden die zwischen 1973 und 1976 hier durchgeführten Auswertungen für Spalt- und Brutmaterialien beschrieben. Im einzelnen wird über die Auswertungen für ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu und ^{241}Pu berichtet. Der Bericht enthält auch die Ergebnisse einer vorläufigen Prüfung neu ausgewerteter Daten für verschiedene kritische Anordnungen.

Contents

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1. Introduction

Recently the German nuclear data library KEDAK has been revised and its third version has been issued. The status of KEDAK-3 is summarized in reference /1/. In the following report the evaluations performed between 1973 and 1976 for the isotopes of uranium and plutonium are described, which have caused modifications of the previously recommended data on KEDAK.

The uranium isotopes stored on KEDAK-3 are ^{235}U and ^{238}U, for plutonium, the 5 isotopes ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu are included in the KEDAK-3 library. The major evaluation effort was devoted towards the evaluation of the data for ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu, whereas the evaluation for ^{238}Pu and ^{242}Pu was performed by the Israel group in support of the work at Karlsruhe (reference /2/ and /3/). No further work for these two isotopes of plutonium was done at Karlsruhe except that certain KEDAK conventions were checked and modified, where necessary. In the resolved resonance region point cross sections were calculated and stored on KEDAK. The evaluation for ^{235}U has already been published /4/, so that for this isotope in the present report only modifications with respect to reference 4 are described. For reasons which will become evident in description of the evaluations for ^{239}Pu and ^{238}U the fission-cross section and total cross section for ^{235}U were revised above 1 MeV.

In the following chapter the need for nuclear data evaluations for fast reactors is briefly discussed. The evaluations for ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{238}U and ^{235}U are described in the subsequent chapters. Some concluding remarks follow in the last chapter. In this chapter some results of a preliminary test of the recommended data in reactor physics calculations are also presented. Some special aspects of the inelastic scattering of ^{238}U are given in the appendix.

2. Needs for Nuclear Data Evaluation

For the design and optimization of reactors a precise knowledge of microscopic neutron data is needed. Uncertainties in the nuclear data require significant allowances to be made in the design and operating conditions of reactor cores and fuel processing systems. Fast breeder reactors are the most sensitive power reactors to uncertainties in the nuclear data. Many studies have been published which investigate the influence of the nuclear data uncertainties on reactor physics parameters (see for example reference /5,6,7/). One of the most instructive studies was presented by Greebler, Hutchins and Cowan /8/ at the 1970 Conference on nuclear data for reactors in Helsinki. They have studied the influence of nuclear data uncertainties on the fuel cost of a plutonium-fuelled fast reactor. On the basis of their study they set goals for the achievement of accuracy for different nuclear data. In table 1 and 2 some of their results for the isotopes relevant to this report are reproduced.

Table 1: Effects of data uncertainties in fission (n,f), capture (n,γ), inelastic scattering (n,n'), $\bar{\nu}_p$ and $\bar{\nu}$ on breeding ratio and fissile plutonium inventory for a proposed 1000 MW(e)

Data	Incident neutron energy	Data uncertainty range (± %)	Uncertainty in breeding ratio (±)	Uncertainty in fissile Pu inventory (± %)
^{238}U(n,γ)	1-100 keV	10	0.060	2.5
	>100 keV	10	0.015	0.6
^{238}U(n,n')	0.1-1.0 MeV	15	0.005	0.3
	>1.0 MeV	20	0.015	1.0
^{238}U(n,f)	>1.0 MeV	6	0.010	0.7
^{238}U-$\bar{\nu}_p$	>1.0 MeV	3	0.005	0.5
^{239}Pu(n,f)	0.1-20 keV	10	0.003	1.5
	20-300 keV	10	0.015	5.5
	>300 keV	6	0.004	1.5
^{239}Pu(n,γ)	0.2-20 keV	20	0.020	1.0
	20-80 keV	20	0.015	0.8
	>80 keV	20	0.002	0.1
^{239}Pu-$\bar{\nu}_p$	>0.1 keV	2	0.040	3.0
^{239}Pu(n,n')	>10 keV	40	0.005	0.3
^{240}Pu(n,γ)	0.1-100 keV	30	0.005	0.3
	>100 keV	40	0.001	0.1
^{240}Pu(n,f)	1-300 keV	30	0.003	0.2
	>300 keV	15	0.003	0.2
^{241}Pu(n,f)	>0.1 keV	25	0.003	1.0
^{241}Pu(n,γ)	>0.1 keV	40	0.002	0.1

Table 2: Goals set by Greebler et al. in 1970 for the nuclear data uncertainties to be achieved by 1975

Data	Incident neutron energy	Data uncertainty (± %) 1970	Goal 1975
$^{238}U(n,\gamma)$	100 eV-1 MeV	10	2
$^{238}U(n,f)$	1-10 MeV	6	3
$^{238}U(n,n')$	100 keV-10 MeV	20	5
$^{239}Pu(n,\gamma)$	0.1-500 keV	20	3
$^{239}Pu(n,f)$	0.1-10 MeV	10	2
$^{239}Pu-\bar{\nu}_p$	>0.1 keV	2	0.5
$^{239}Pu-\bar{E}$	>0.1 keV	10	2
$^{240}Pu(n,f)$	>1.0 keV	20	10
$^{240}Pu(n,\gamma)$	0.1 keV-1 MeV	30	10
$^{241}Pu(n,f)$	>0.1 keV	25	10

It is seen that to attain these goals a particularly high precission of 3 % or better (for 90 % confidence limits) is required for the fission and capture cross sections of ^{238}U and ^{239}Pu. $\bar{\nu}_p$ for ^{239}Pu has to be known to about 0.5 % in the energy range above 100 eV.

This study has given incentive to many new measurements of the above mentioned cross sections and the knowledge of these cross sections has been considerably improved in the last few years. However, as will be seen later, nuclear data measurements have not yet converged to a unique cross section basis. Thus the evaluators are required to revise their nuclear data libraries from time to time.

3. Evaluation of the Data for ^{239}Pu

For the isotope ^{239}Pu the following data have been revised after 1970:

- Resonance parameters
- point cross sections in the resolved resonance region
- fission cross section above the resolved resonance region to 30 keV and from 2 MeV to 15 MeV
- capture cross section and α above the resolved resonance region to 15 MeV
- total cross section from 100 keV to 15 MeV
- (n,2n) and (n,3n) cross sections from threshold to 15 MeV
- ν from 0.01 eV to 15 MeV

and all other data which are dependent on the data given above.

In the following a brief account of these modifications and the evaluation underlying these modifications is given.

3.1 Resolved Resonance Region

New resonance parameters on KEDAK were stored in 1971 and extend up to 660 eV. These parameters are taken from the evaluation of Ribon and Le Coq /9/. From 1 eV to 665 eV the point cross sections stored on KEDAK are based on the recent experimental data. In the energy interval from 1 eV to 300 eV the pointwise data correspond to the measurements of the capture and fission cross section by Gwin et al. /10/ and the total cross section measurements by Derrien et al. /11/. Between 300 eV and 665 eV the pointwise cross section data are derived from the resonance parameters stored on KEDAK.

3.2 Total Cross Section

In the energy region above 100 keV the new experimental data published after 1970 are those of Foster and Glasgow /12/, Cabé et al. /13/, Smith et al. /14/ and Schwartz et al./15/. There is also one unpublished work by Nadolny at RPI which is cited by Schwartz et al. The data of Nadolny are not available to us but they are reported to be in agreement with the data of Schwartz et al. Figure 1 shows the available experimental data together with the previously and presently recommended data on KEDAK. For the sake of clarity the experimental data shown are averaged over energy intervals of 0.2 MeV. It is seen that the agreement in the experimental data of Foster and Glasgow, Smith et al. and Schwartz et al.

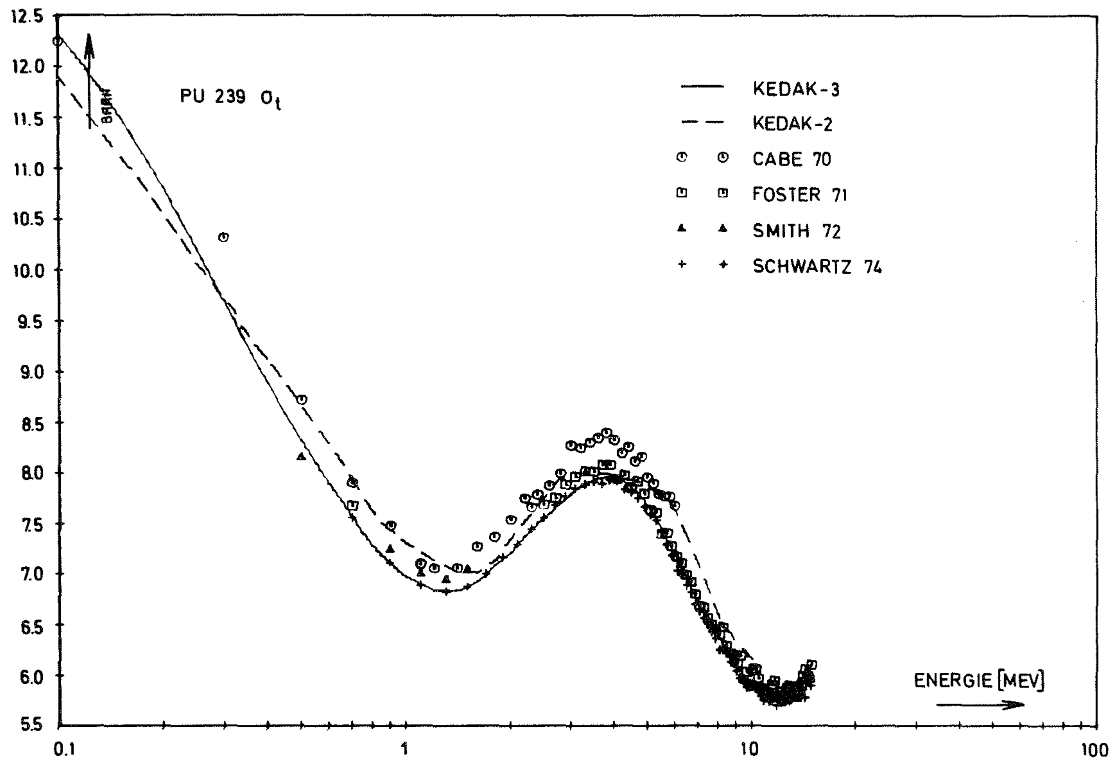


Fig. 1: Total neutron cross section for ^{239}Pu from 100 keV to 15 MeV

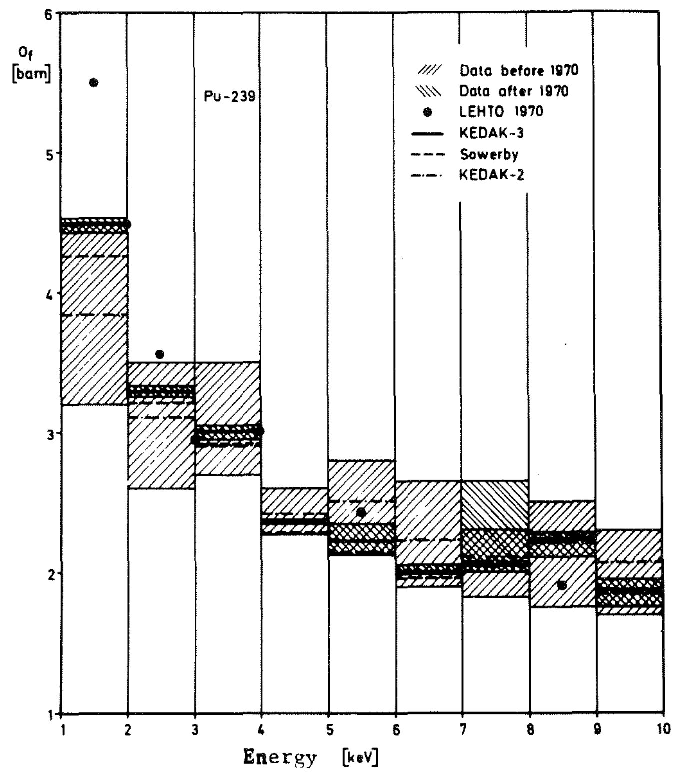
is good, whereas, the data of Cabé et al. are higher by 3 - 5 % throughout. (This trend is also observed in the case of ^{235}U and ^{238}U data of Cabé et al.) We assume, therefore, that there is a systematic error in the experiment of Cabé et al. and have reduced their data for our evaluation purpose by 3 %.

All the data mentioned above were measured with the time of flight technique and the uncertainties given by the authors vary from 2 to 5 %. Since, except the data of Cabé et al. all other data agree within 2 % throughout the energy range of the evaluation, we assume that in this energy region the total cross section for ^{239}Pu is well known and the uncertainty of this evaluation is less than 3 %.

As compared to ENDF/B-3 our recommended curve is about 1 - 2 % lower in the energy region above 2 MeV. The difference increases below 2 MeV and for energies below 1 MeV our recommended curve is about 5 % lower than the ENDF/B-3 data. The ENDF/B-4 data which have been made available after the completion of this evaluation show good agreement with the recommended data on KEDAK-3.

3.3 Fission Cross Section

With respect to KEDAK-2 the fission cross section for ^{239}Pu is revised below 30 keV and between 2 MeV and 15 MeV. The data in these energy intervals were revised formerly by Hinkelmann in 1970. In the lower energy region the experimental discrepancies are reduced considerably in the last few years. In Figure 2 fission cross section values averaged over 1 keV intervals are plotted for 9 intervals from 1 keV to 10 keV. The experimental data are divided in two groups, data published before 1970 (used by Hinkelmann for the KEDAK-2 evaluation) and those published after 1970 (Gwin et al. /16/, Weston and Todd /17/, Blons /18/ and Lehto /19/). With exception of Lehto, the agreement of the data, published after 1970, is good. For the KEDAK-3 evaluation, therefore, the data of Lehto are not included. The recommended curve is the weighted average of



Data before 1970:

Bollinger et al.	(1958)
Gilboy + Knoll	(1966)
Schunk et al.	(1966)
James + Patrick	(1968)

Data after 1970:

Weston + Todd	(1972)
Gwin et al.	(1973)
Blons	(1973)

Fig. 2: Spread of the fission cross section for ^{239}Pu between 1 keV and 10 keV

the data of Gwin et al., Weston and Todd and Blons. The difference between this evaluation and that of Sowerby et al. /20/, which is also shown in Fig. 2 may have two reasons; firstly Soverby has simultaneously evaluated σ_f for ^{235}U, ^{238}U, ^{239}Pu and σ_γ for ^{238}U and secondly (perhaps mainly) we have used revised data of Gwin et al. which were not available at the time of Soverby's evaluation. In Figure 3 the published experimental data for σ_f of ^{239}Pu are compared with the average of the data recommendend on KEDAK-3. The accuracy of the evaluation for the energy region 1 keV to 100 keV is estimated to be between 3.5 and 5.5 %. According to the WRENDA 1975 compilation, however, an accuracy better than 2 % is required for reactor physics calculations.

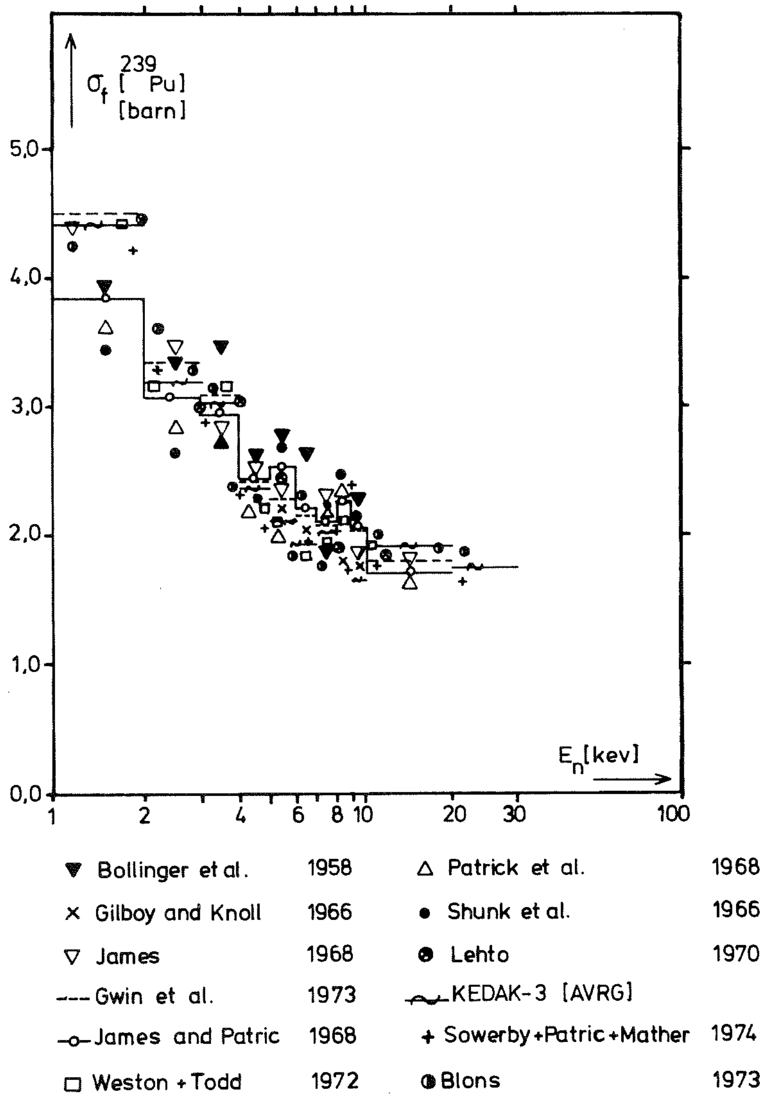


Fig. 3: Comparison of the average of the fission cross section for ^{239}Pu between 1 keV and 30 keV.

There are no measurements of the absolute fission cross section for ^{239}Pu in the MeV energy range. The evaluation in this energy range is, therefore, based on the ratio measurements of the fission cross section of ^{239}Pu to that of ^{235}U. The 1970 evaluation was based on the data of White and Warner /21/, Nesterov and Smirenkin /22/ and Hansen, McGuire and Smith /23/. Above 6 MeV the 1970 evaluation was solely based on the unpublished data of Hansen, McGuire and Smith. These authors have corrected the experimental data of Smith, Henkel and Nobles /24/ for inscattering effects. However, it seems that there are some inconsistencies in their data /25/. We have, therefore, revised the data on KEDAK in this energy range. The presently recommended KEDAK data follow the above mentioned evaluation of Sowerby et al. In figure 4 the presently recommended data are compared with the KEDAK-2 data and the experimental data derived from the ratio measurements. The accuracy of the evaluation in this energy region lies between 8.5 and 10 %.

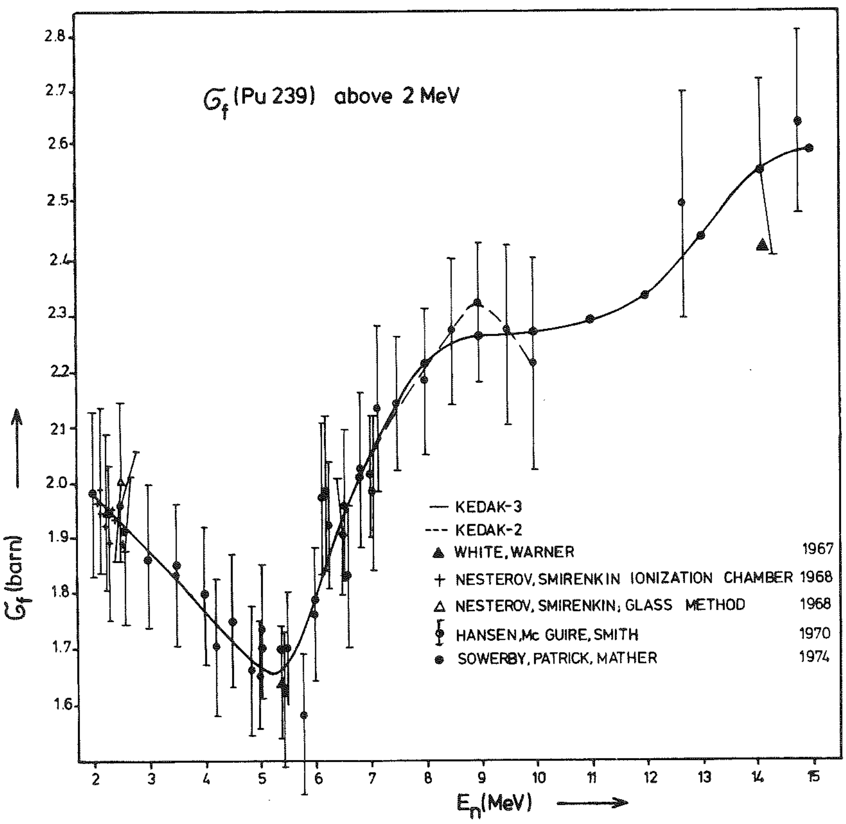


Fig. 4: Fission Cross section for ^{239}Pu above 2 MeV.

3.4 Alpha and Capture Cross Section

For the evaluation of the capture to fission ratio for ^{239}Pu, in the energy range below 30 keV the same scheme as used by Sowerby and Konshin /26/ in their 1972 evaluation was used,in addition the revised data of Gwin et al. /16/. and Weston and Todd /17/ were included in the present evaluation. In the energy range above 30 keV the data of de Saussure et al. /27/ and Bandl et al. /28/ were not renormalized. For the renormalization of these data Sowerby and Konshin averaged the data of de Saussure over an energy interval of 20 to 40 keV and took the mean of this value and the value of Hopkins and Diven /29/ at 30 ± 10 keV to obtain the normalization value. This would mean that in the experiment of Hopkins and Diven incident neutron flux is flat over the energy from 20 keV to 40 keV which is not certain. Moreover the shape of the alpha curve measured by them is not in agreement with that of other authors and in the meantime the published data of Kononov et al. /30/, as is shown in Figure 5, support the original normalization of de Saussure's data. For this evaluation

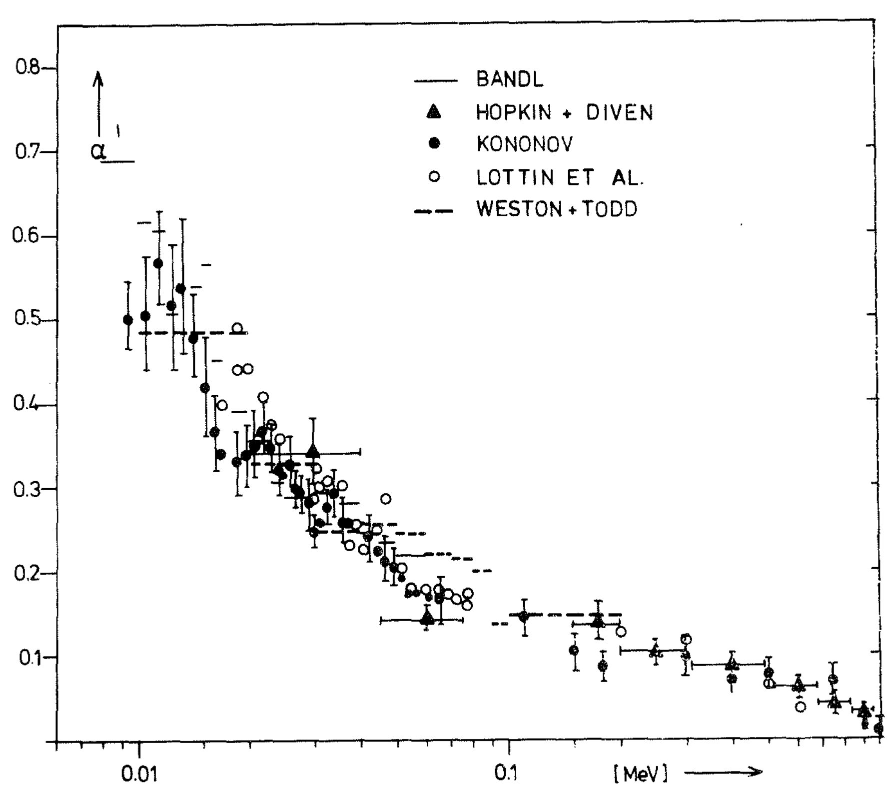


Fig. 5: Comparison of the experimental data for α of ^{239}Pu between 10 keV and 1 MeV.

weighted values of the data of Hopkins and Diven, de Saussure, Bandl and Kononov et al. are used. A smooth curve was drawn through these values using a cubic spline function. The result is shown in Figure 6. The uncertainty of the evaluation of α between 1 keV and 30 keV is estimated to be between 5 and 10 % and increases up to 25 % at 1 MeV.

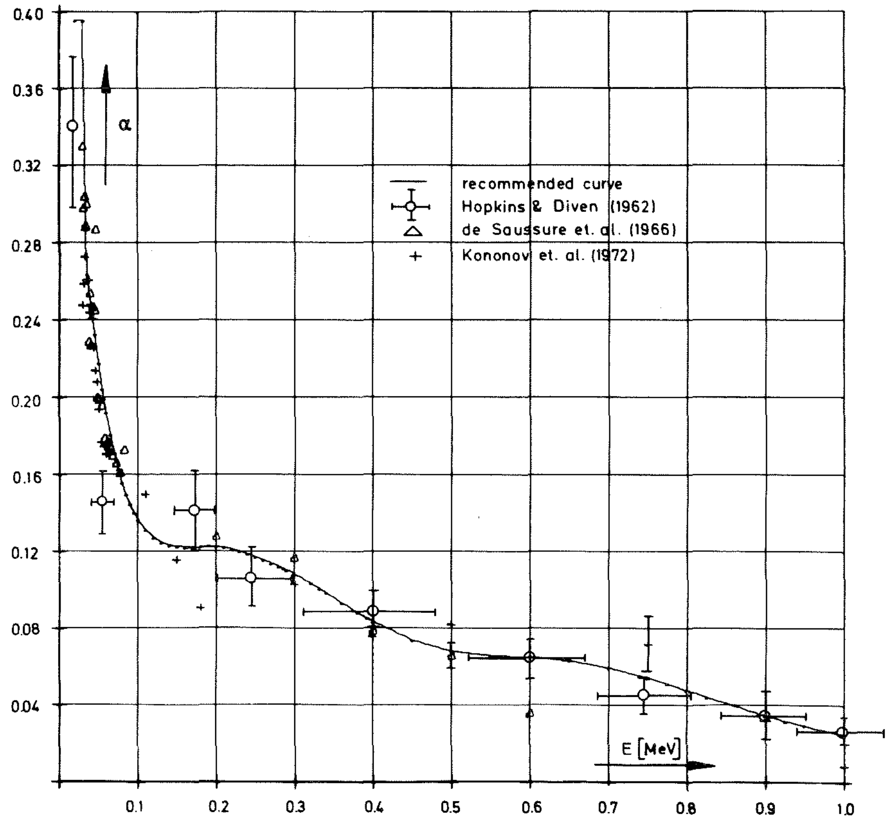


Fig. 6: Capture to fission ratio (Alpha) for ^{239}Pu between 30 keV and 15 MeV

Above 1 MeV there are no measurements either for alpha or for σ_γ. A E^{-n} dependance for σ_γ was assumed. Considering the systematics of the neighbouring nuclei n was choosen to be 1.65. In doing so, any contribution due to the direct reaction mechanism, is neglected which is expected to start at about 5 to 7 MeV (see for example ref. /31/). But due to the small absolute value of this cross section in the upper MeV range and its relative unimportance in reactor physics calculations at these energies this neglect is justified.

3.5 (n,2n) and (n,3n) Cross Sections

There is only one published experiment for these reactions, namely that of Mather et al. /32/. For their measurements Mather et al. have used a large loaded liquid scintillator as a 4π-detector. A property of these detectors is that neutrons have relatively long life time in the detector before they undergo a capture process. This allows the identification of an (n,2n) event by two separate pulses and of an (n,3n) event by three separate pulses and so on. The events giving 2,3,... separate pulses are counted. Corrections are to be applied for the background and for fission events which may give two or three neutrons. The measurement of (n,2n) and (n,3n) cross sections for ^{239}Pu is complicated by the heavy background activity of the sample and the spontaneous fission due to the ^{240}Pu content. The quoted errors for the (n,2n) cross section vary from 6 to 20 % and that for the only measured point for (n,3n) reaction at 13.1 MeV is about 50 %. The experimental data for the (n,2n)-reaction (Fig. 7) show a sharp rise in the excitation function within one MeV above the threshold, a flat broad summit and a sharp fall above the (n,3n) threshold. This behavior of the (n,2n) cross section is the same as predicted by Bertram /33/ using a statistical model similar to that used by Pearlstein /34/ but giving more attention to (n,3n) competition.

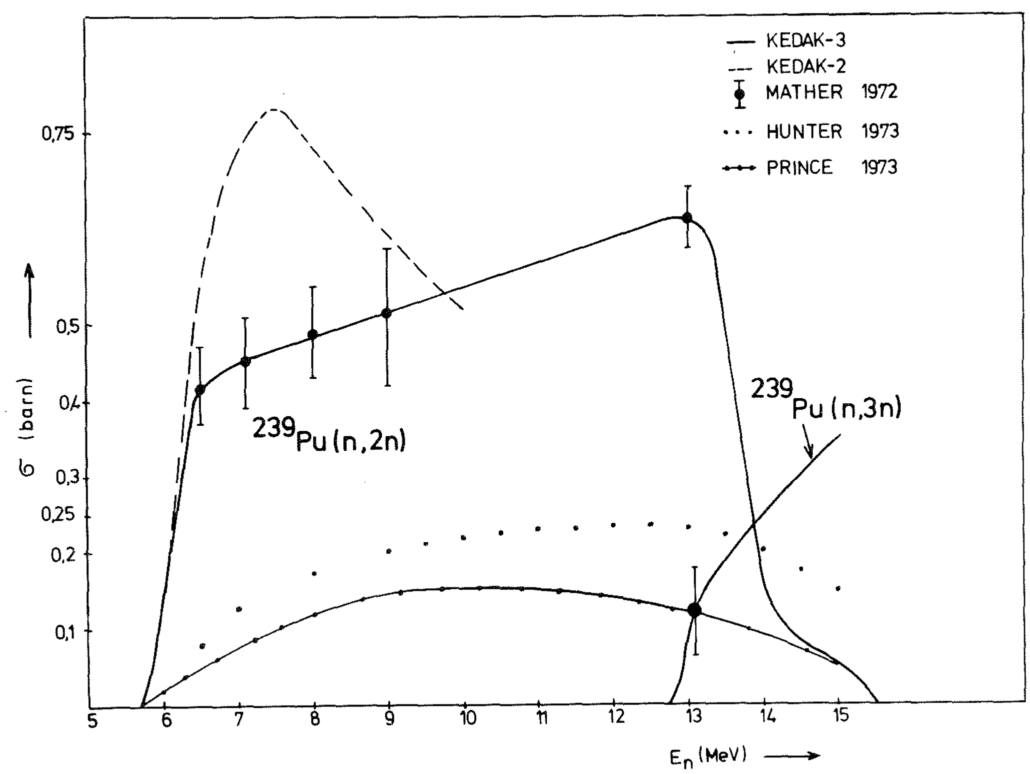


Fig. 7: ^{239}Pu(n,2n) and ^{239}Pu(n,3n) cross sections from threshold to 15 MeV

Recently Kawai /35/ has estimated the $^{239}Pu(n,2n)$ cross section using the Pearlstein's method. His results agree well with the data of Mather et al. /32/. Other evaluations (e.g. ref. /36/ and /31/ also shown in Fig. 7) based on theoretical considerations give much lower values for the (n,2n) cross section of ^{239}Pu.

The recommended KEDAK-3 data for the ^{239}Pu (n,2n) reaction is a smooth curve through the data of Mather et al. For the ^{239}Pu (n,3n) cross section a curve following the behavior of the ^{235}U (n,3n) reaction is drawn through the 13.1 MeV point of Mather et al.

The presently recommended data are compared with the previous data on KEDAK and other evaluations in Fig. 7.

3.6 Average Number of Neutrons per Fission ($\bar{\nu}$)

The published experimental data of $\bar{\nu}$ for ^{239}Pu prior to the 1970 evaluation amounted to about a few dozens of data points including some poor precision data around 14 MeV. However in 1970 high accuracy measurements were reported by Soleilhac et al. between 0.2 MeV and 1.4 MeV (ref. /37/) and between 1.3 MeV and 15 MeV (ref. /38/), by Nesterov et al. /39/ between 0.1 MeV and 1.6 MeV, by Mather et al. /40/ between 0.4 MeV and 1.2 MeV and by Savin et al. /41/ between 0.8 MeV and 5 MeV. Two more sets of experimental data are published after 1970 namely that of Walsh and Boldemann /42/ between 0.2 MeV and 2 MeV and that of Volodin et al. /43/ from thermal to 1.6 MeV.

For this evaluation the above mentioned data excluding those of Nesterov et al. /39/ but including the older data of Diven et al. /44/, Hopkins and Diven /45/ and Condé et al. /46/ are fitted to a set of straight lines. The reason for excluding the data of Nesterov et al. /39/ is that these data are systematically discrepant to all other data including those given in ref. /43/. Since the data of ref. /39/ and /43/ are from the same experimental group the older data of Nesterov et al. may be considered superseded by the data of Volodin et al. /43/. The recent data of Walsh and Boldemann /42/ are systematically lower than the recommended KEDAK data and the other experimental data by 2 to 3.5 %. Since most of the $\bar{\nu}$ measurements are made relative to some standard the data normalized to the valid standard values /47,48/ are used for the fitting purpose. The standard values used are:

$^{252}Cf \quad \nu_p^{sp} = 3.756$

$\nu_t^{sp} = 3.765$

$^{235}U \quad \nu_p^{th} = 2.407$

$\nu_t^{th} = 2.4229$

For the straight line fits nodes were used at 0.6, 1.5, 6 and 10.5 MeV. Whereas the change in the slope of the ν versus neutron energy curve at around 6 and 10.5 MeV is due to the onset of the (n,n'f) and (n,2n'f) channels, there is no profound explanation for the nodes at 0.6 and 1.5 MeV. However the fits obtained with these two nodes are far better than those obtained without these nodes. The straight line functions for the different energy intervals are:

0.001 eV to 0.5 MeV	$\nu(E) = 2.8846 + 0.119E$
0.6 MeV to 1.5 MeV	$\nu(E) = 2.8466 + 0.182E$
1.5 MeV to 6.0 MeV	$\nu(E) = 2.909 + 0.141E$
6.0 MeV to 10.5 MeV	$\nu(E) = 2.8136 + 0.1568E$
10.5 MeV to 15.0 MeV	$\nu(E) = 3.0867 + 0.1308E$

In Fig. 8 and 9 the experimental data are compared with the presently recommended data on KEDAK. The accuracy of the evaluated data is estimated to be better than 0.5 %. The evaluation of Manero and Konshin /49/ which is published in 1972 show results for ν of ^{239}Pu which agree with the KEDAK-3 data within the evaluation uncertainties.

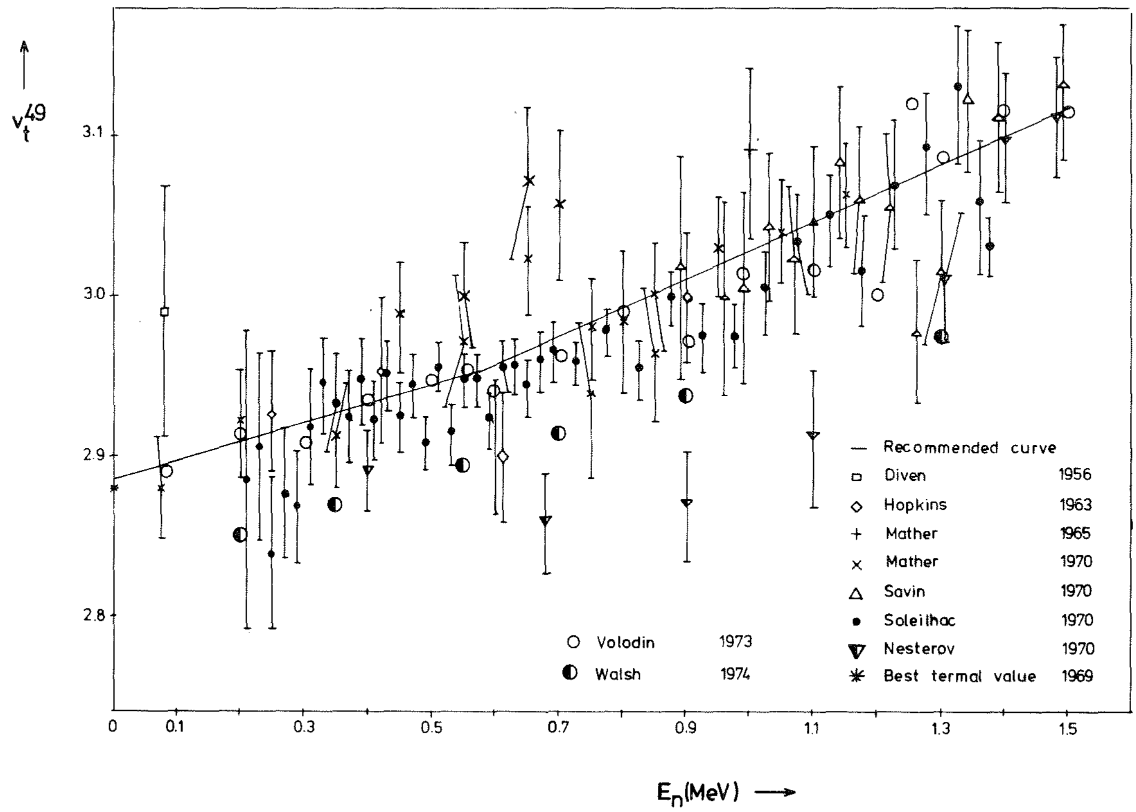


Fig. 8: $\bar{\nu}$ for ^{239}Pu between 0.001 eV and 1.5 MeV

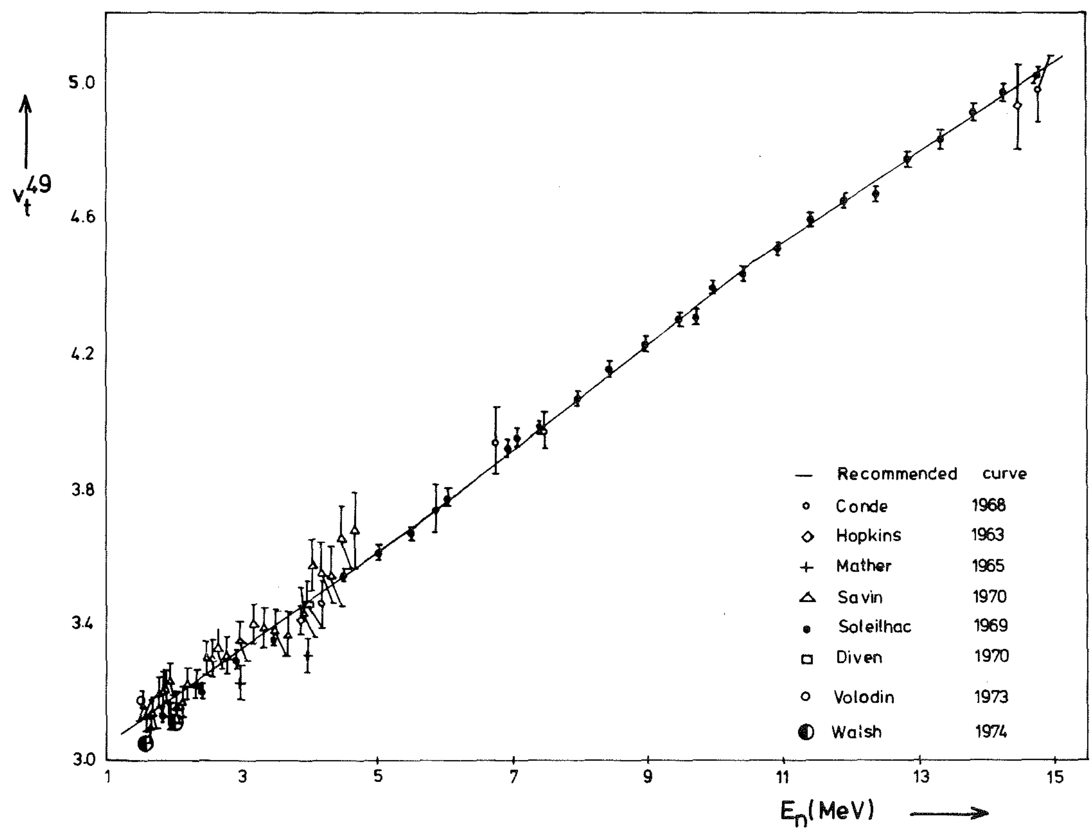


Fig. 9: $\bar{\nu}$ for ^{239}Pu between 1.5 MeV and 15 MeV

4. Evaluation of the Data for ^{240}Pu

The isotope ^{240}Pu is of particular interest in fast reactor physics. This isotope, even if it is not present in the fresh fuel, reaches an equilibrium concentration of about 10 % after several fuel cycles, a fuel cycle being a period between partial or complete refuellings of the reactor. This isotope does not only possess a higher $\bar{\nu}$-value of 3.18 neutrons per fission it also does have a significantly lower fission threshold than other fertile isotopes like ^{238}U and ^{232}Th. This means that in the case of ^{240}Pu a higher fraction of the neutron spectrum is contributing to the productions of fast neutrons. Moreover, the ^{240}Pu content is contributing to the production of the fissile isotope ^{241}Pu.

In a study mentioned in the introduction Greebler et al. /8/ had set a goal for the nuclear data community to achieve an accuracy of 10 % for fission cross sections above 1 keV and for the capture cross sections of this isotope for energies between 100 eV and 1 MeV. In the world request list for nuclear data WRENDA 1975, there are 4 priority 1 entries for ^{240}Pu(n,γ) above 100 eV requiring accuracy from 5 to 10 % and one request of 3 % accuracy for ^{240}Pu(n,γ) below 100 eV. The accuracy requirements for the ^{240}Pu (n,f) cross section are more stringent according to WRENDA 75 but priority assigned to these requests is 2.

In the following chapter the evaluation of the resonance parameters for ^{240}Pu and the capture cross section up to 1 MeV performed at this laboratory are described. All other data for ^{240}Pu are based on the evaluation of Caner and Yiftah /50/.

4.1 Resonance Parameters

After the publication of the evaluation of Caner and Yiftah and that of L'Hériteau and Ribon /51/ new experimantal data have been published which warrant a new evaluation of the resonance parameters for ^{240}Pu. There are three series of measurements for the resonance parameters of this isotope namely that from Harwell /52,53/, from Geel /54,55/ and from RPI /56/. The Harwell group has measured the total cross section σ_t, the capture cross section σ_γ and the elastic scattering cross section σ_n up to 1 keV. The Geel data contain the results of a measurement of σ_t up to 5.7 keV /57/ and σ_γ /58/, and for some resonances, also σ_n up to 820 eV /59/. In both series of data the capture cross sections were normalized to the capture rate at the 20 eV resonance. Although the data of these two laboratories agree reasonably well, they showed internal inconsistencies and systematic discrepancies and were strongly discrepant to the data of RPI until 1972. For the average capture width the Geel value was 23.2 meV, that of Harwell 21 meV and that of RPI 29.5 meV, while all of them claimed an accuracy of their parameters of about ± 2 %. A new measurement /53/ of the 20 eV resonance by the Harwell group showed that the parameters of the 20 eV resonance, adopted by the Harwell and the Geel group for their normalization, were wrong by 30 % for Γ_n and more than 50 % for Γ_γ. In its new measurement the Harwell group has normalized the capture data to the 1.056 eV resonance. Through this new normalization the agreement between all the three series i.e. Harwell, Geel and RPI was considerably improved. In the RPI data the resonance parameters up to 500 eV were obtained from the measurement of σ_γ and σ_t. The RPI-data for the capture cross section were normalized by comparison the measured capture area of the 92.5 eV resonance to the area calculated with the aid of resonance parameters as obtained from a simultaneous transmission measurement /55/.

In the common energy range up to 500 eV all the three series show good agreement in the values for the scattering widths, whereas for the capture width the Geel data are on an average about 8 % higher than the RPI and Harwell data.

Up to 500 eV the evaluated scattering and capture widths are the mean values of these three series. Between 500 and 665 eV our data are taken from the Geel measurements /55/. Above 665 eV the scattering widths are not changed if they correspond to the evaluation of Caner and Yiftah. The capture widths however have been changed from 23.5 meV to 30.5 meV, which is due to renormalization of the Geel and Harwell data. Similarly due to this renormalization the fission widths of the resonances at 20.46 eV and 38.32 eV which were based on the recommendation of L'Heriteau and Ribon /51/ and Pitterle /60/ are changed. These were derived from the measurement of Γ_γ/Γ_f and have to be changed due to the change of Γ_γ from 23.5 to 30.5 meV. For the next 3 resonances the Γ_f values of L'Heriteau and Ribon are taken for KEDAK. For the resonance parameters in the region of intermediate structure of fission (En > 740 eV) the data of Caner and Yiftah are kept unchanged. These data are in agreement with the values given by L'Heriteau and Ribon. For all other resonances the new average value

Γ_f = 0.2 meV (instead of Caner and Yiftah's value 0.0) is taken. From these resonance parameters the pointwise cross sections were calculated using the single level Breit-Wigner formalism and stored on KEDAK.

4.2 Capture Cross Section Between 4 keV and 1 MeV

The ^{240}Pu(n,γ) cross section is also revised in the energy region above the resolved resonances to 1 MeV. The new data in this region are based on the experimental data of RPI /56/, Weston and Todd /17/ and the statistical model calculations of Thomet /61/. In Figure 10 the newly recommended data for the capture cross section of ^{240}Pu is shown together with the data of other authors in the energy range from 5 keV to 1 MeV. As compared to the data of Caner and Yiftah the data have been increased throughout the energy range which is consistent with the increase of $<\Gamma_\gamma>$.

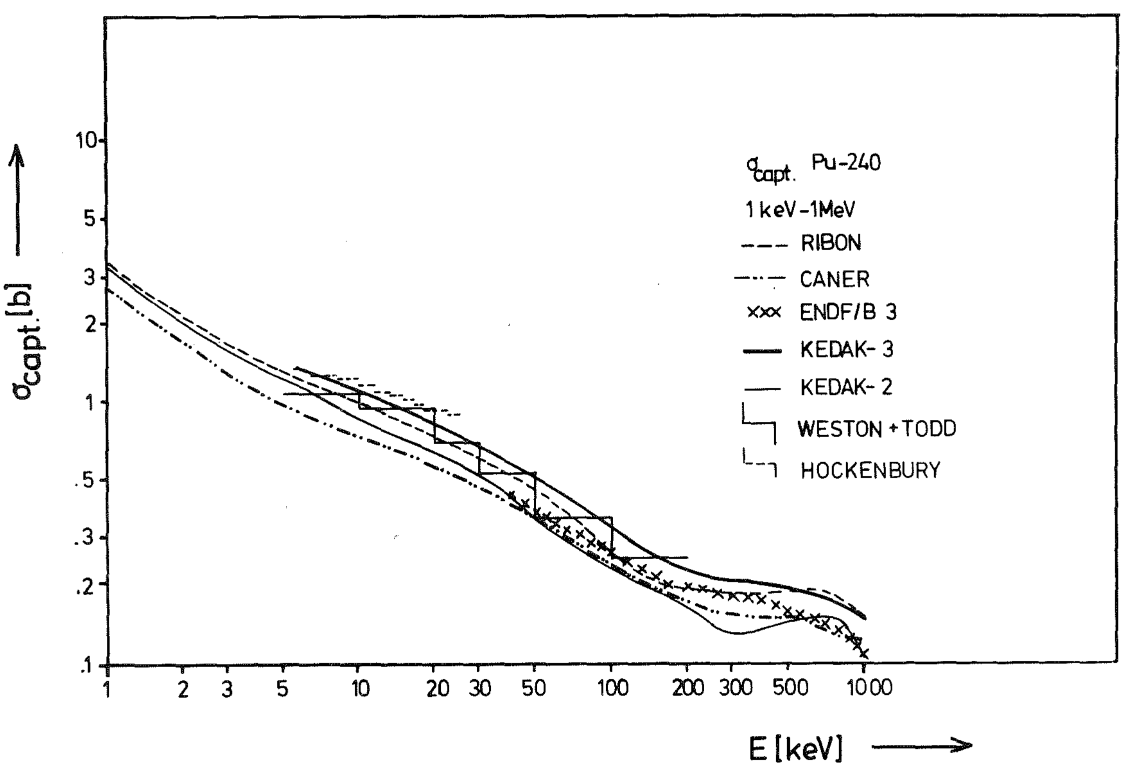


Fig. 10: Capture cross section for ^{240}Pu in keV region. Below 4 keV the data stored on KEDAK are based on resolved resonance parameters

The statistical resonance parameters for the energy range from 4 keV to 250 keV, given in Table 3, were determined by Fröhner /62/ using the computer codes STARA and FITCAS /63/. The parameters for $\ell = 0$ are maximum-likelihood estimates derived from the individual resonance parameters in the resolved resonance region with due account for missing levels. The p-wave strenght function was determined by a least-squares fit to total cross section data in the region of unresolved resonances using level-statistical theory. Other level-statistical parameters such as Γ_γ, Γ_f and the Dresner factors have also been revised so as to make them consistent with the recommended average cross sections.

Table 3: Average Resonance Parameters for ^{240}Pu

ℓ	J	$\bar{\Gamma}_\gamma$ (eV)	$\bar{D}$ (eV)	$\bar{\Gamma}_n$ (eV)	$\bar{\Gamma}_n/\bar{D}$	ν_f	ν_n
0	1/2	0.0306	12.5	$1.17\cdot10^{-3}$	$0.94\cdot10^{-4}$	1	1
1	1/2	0.0306	12.5	$2.38\cdot10^{-3}$	$1.9\cdot10^{-4}$	1	1
1.	3/2	0.0306	6.293	$1.196\cdot10^{-3}$	$1.9\cdot10^{-4}$	1	1
2	3/2	0.0306	6.293	$0.592\cdot10^{-3}$	$9.4\cdot10^{-4}$	1	1
2	5/2	0.0306	4.225	$0.397\cdot10^{-3}$	$9.4\cdot10^{-4}$	1	1

5. Evaluation of the Data for ^{241}Pu

According to Greebler et al. /8/ the fission cross section of ^{241}Pu should be known to better than ± 10 %. Recently in its conclusions, the IAEA-Advisory-Group meeting on transactinium nuclides /64/ confirmed the accuracy requirements for σ_f and σ_c of ^{241}Pu as given in WRENDA 1975 /65/.

In WRENDA 1975 there is a priority 2 request for 1 % accuracy from the Los Alamos Laboratory and a few priority 1 requests for 5-10 % accuracy for σ_f of ^{241}Pu and 3-10 % accuracy for σ_c or 10-20 % accuracy for α of ^{241}Pu.

The accurate knowledge of the ^{241}Pu cross sections is needed as this isotope contributes considerably to the reactivity and other core parameters such as reactor power. In fast reactors ^{241}Pu contributes up to about 8 % of the reactor power.

The previous data for ^{241}Pu on the nuclear data file KEDAK originates from an evaluation of Caner and Yiftah /66/. The evaluation was first performed in 1967 and was updated in 1973. The data for σ_f below 40 keV are based on nuclear theory and from 40 keV to 10 MeV they follow the 1968 evaluation of Davy /67/. Since 1968 a number of new measurements for σ_f of ^{241}Pu have been reported in the statistical resonance region. Therefore a new evaluation for σ_f of ^{241}Pu has been made. In this section an evaluation of σ_f and σ_c of ^{241}Pu is presented from 162 eV to 1 MeV. All the secondary data dependent on σ_f and σ_c have also been revised.

5.1 Fission Cross Section

The measurements of the fission cross section in the eV and low keV range are made predominantly with the time of flight technique using pulsed neutrons from a pulsed electron linear accelerator. The experimental data reported after 1968 are by James /68/ from Harwell, Migneco et al. /69/ from Geel, Weston and Todd /17/ from ORNL and Blons /18/ from Saclay. Blons has normalized his data at low energies (between 20 and 70 eV) to the data of James. Weston and Todd have normalized their data at thermal energies to the ENDF/B material No. 1106. Migneco et al. have normalized their data at energies between 4.65 eV and 10 eV to the evaluation of Hennies /70/. Thus it is expected that there is a normalization uncertainty in the different data. This uncertainty is of the order of 4 %.

The experimental errors given by Blons for his data are 3 % at low energies increasing up to 6 % at 30 keV. Weston and Todd give a total error of 3.5 % for their σ_f data. Migneco et al. presume a normalization uncertainty of 2 %. No other information about the statistical or systematical errors is given by them. The data of James have errors of 5 %.

In Table 4 and Figure 11 the data reported by different authors together with the result of the present evaluation are given for the average fission cross sections in different energy intervals between 0.1 keV to 30 keV. In this table data from the bomb shot experiment of Simpson et al./71/ are also included. It is seen that although quoted errors vary between 3.5 and 6 % the data spread is of the order of 20 %. The Saclay and Geel data seem to be systematically lower than the data of the other three laboratories. The recommended data are obtained by fitting the weighted average of the data given in Table 4 to a smooth curve as shown in Figure 11.

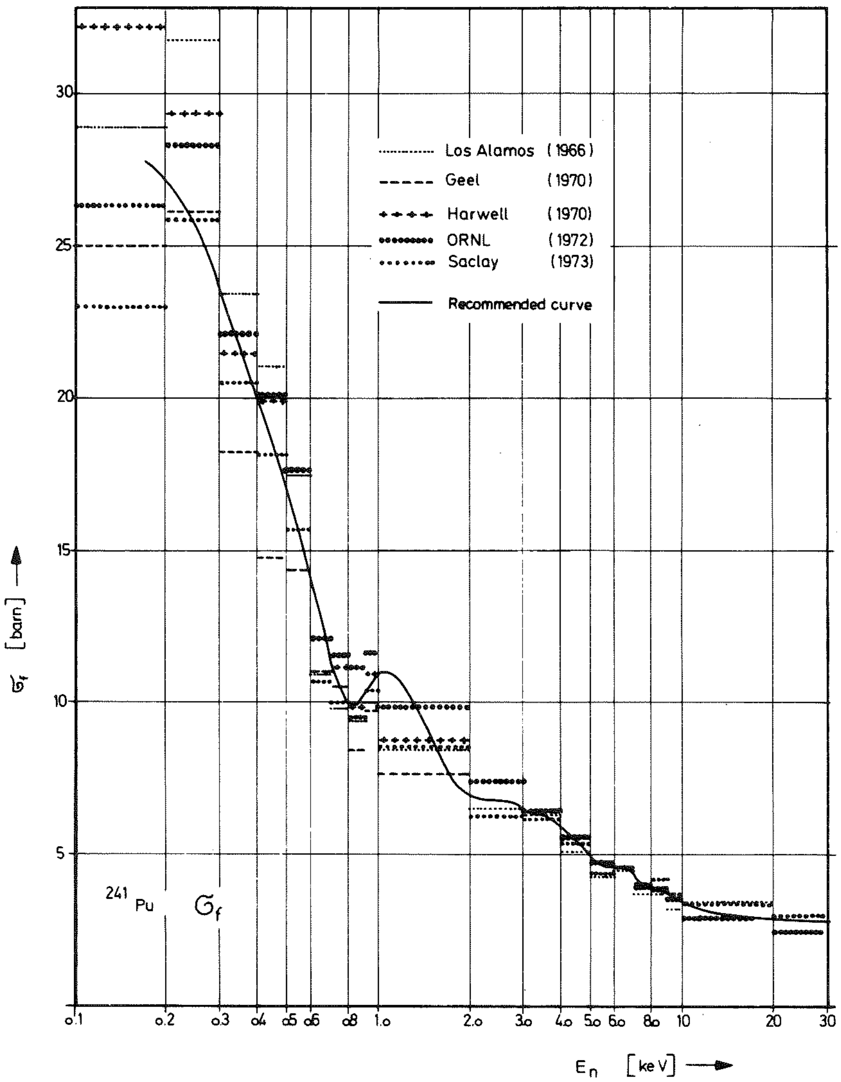


Fig. 11: Comparison of the fission cross section of ^{241}Pu from different authors in the energy range 100 eV to 30 keV.

Table 4 Comparison of Average Fission Cross Section for ^{241}Pu

$$\frac{1}{F_2 - F_1} \int_{F_1}^{F_2} \sigma_f(E)dE \quad \text{(barns)}$$

Neutron Energy Range (keV) E_1 – E_2	Los Alamos et al. 1966	Geel Migneco et al. 1970	Harwell James 1970	ORNL Weston and Todd 1972	Saclay Blons et al. 1973	Present evaluation
.1 - .2	28.91	24.98	32.11	26.32	22.98	23.74
.2 - .3	31.85	26.08	29.37	28.26	25.85	25.56
.3 - .4	23.43	18.20	21.46	22.13	20.5	21.68
.4 - .5	21.05	14.78	19.86	20.11	18.13	18.46
.5 - .6	17.47	14.36		17.66	15.70	15.61
.6 - .7	10.93	9.98		12.10	10.72	12.61
.7 - .8	9.79	9.55	11.13	11.54	10.0	10.6
.8 - .9	9.36	8.37	9.84	11.13	9.47	10.07
.9 - 1.0	9.98	9.71	10.95	11.57	10.41	10.62
1.0 - 2.0	8.43	7.64	8.79	9.85	8.55	8.95
2.0 - 3.0	6.52			7.39	6.26	6.78
3.0 - 4.0	6.31			6.45	6.13	6.28
4.0 - 5.0	5.08			5.53	5.37	5.43
5.0 - 6.0	4.30			4.72	4.34	4.63
6.0 - 7.0	4.50			4.57	4.58	4.52
7.0 - 8.0	3.72			3.93	4.01	4.02
8.0 - 9.0	3.75			3.79	4.17	3.90
9.0 - 10.0	3.20			3.54	3.71	3.62
10.0 - 20.0	3.36			2.89	3.33	3.01
20.0 - 30.0				2.41	2.95	2.8

The data used for σ_f of ^{241}Pu for this evaluation above 30 keV stem essentially from the $\sigma_f(^{241}Pu)/\sigma_f(^{235}U)$ ratio measurements of Käppeler /72/. His ratio values are multiplied with the $\sigma_f(^{235}U)$ values as stored on KEDAK-3 and fitted with a smooth curve. Data above 1 MeV are left unchanged, i.e. it still corresponds to the data of Smith /73/ and White /21/ renormalized to the U^{235} fission cross section values of Hansen /77/.

The Figure 12 showing the ratio of the fission cross section of ^{241}Pu to that of ^{235}U by the different authors (ref. /21/, /67/, /72-76/) is taken from Käppeler and Pfletschinger. The ratio values derived from the data stored on KEDAK-3 have been added to this figure. The KEDAK data are shown only above 30 keV as below 30 keV the ^{235}U fission cross section on KEDAK-3 are the high resolution data of Blons et al. whereas the data stored for ^{241}Pu give a smooth curve as mentioned above. Below 150 keV our data are lower than Davy's data.

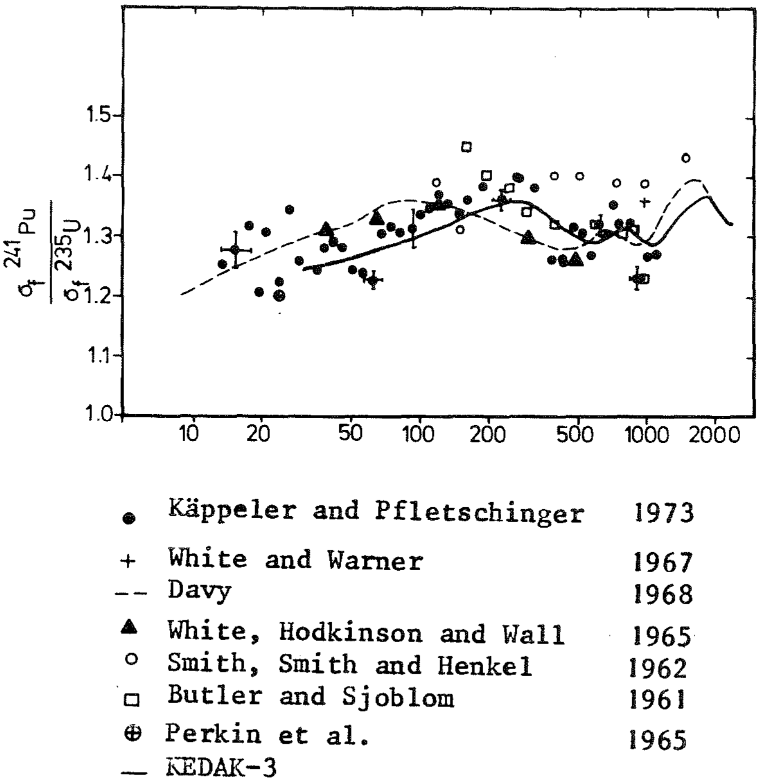


Fig. 12: Comparison of the ratio of the fission cross section of ^{241}Pu and ^{235}U from different authors.

The recently published data of Behrens and Carlson /78/ could not be included in this evaluation. However, in Figure 13 the data of Behrens and Carlson are compared with the data of Käppeler and Pfletschinger. It seems that the existance of some structure in the ratio value of $\sigma_f(^{241}Pu)/\sigma_f(^{235}U)$ is well established.

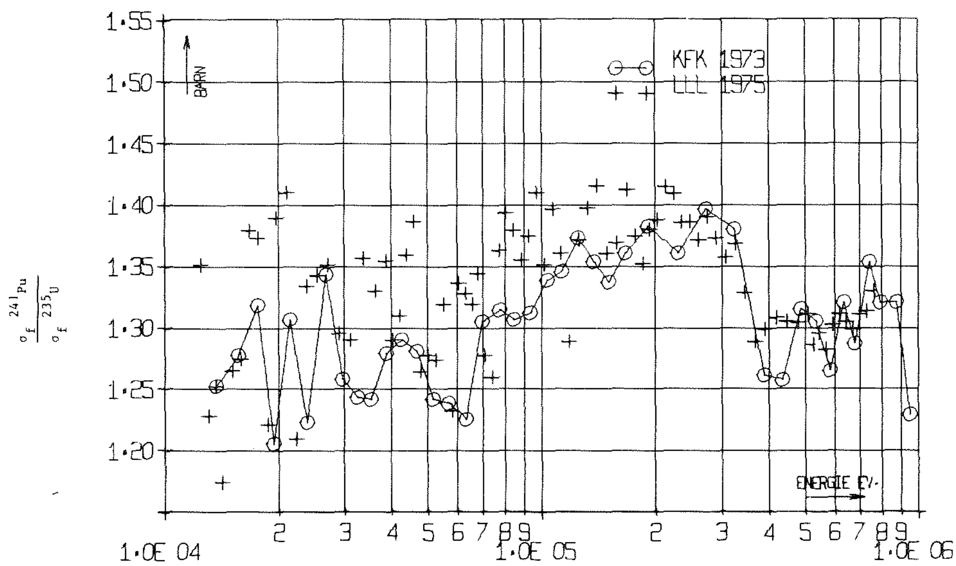


Fig. 13: Comparison of the ratio of fission cross section of ^{241}Pu and ^{235}U between the data of Käppeler and Pfletschinger (KFK 1973) and Behrens and Carlson (LLL 1975) in the energy range 10 keV to 1 MeV.

In Figure 14 the presently evaluated data are compared with the data of Caner and Yiftah /66/ and the KFKINR set /79/ in the energy range 162 eV to 1 MeV. It is seen that the presently recommended data show a structure below 30 keV. This structure is also seen in the ENDF/B data.

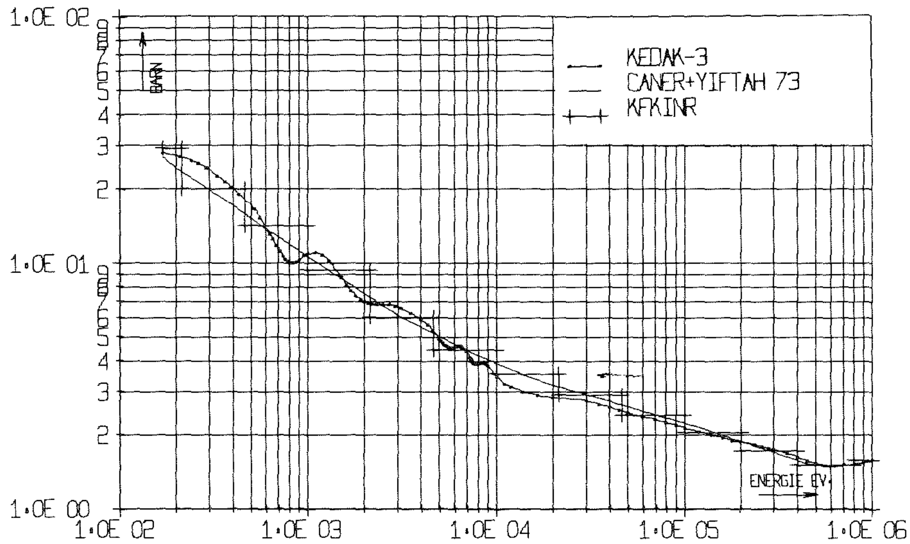


Fig. 14: The fission cross section for ^{241}Pu between 162 eV and 1 MeV.

The uncertainty in the evaluation of σ_f is estimated to be between 6 to 10 %. Hence the goal set by Greebler for 1975 is satisfied but the more stringent accuracy requirement for σ_f of 5 % and less is yet to be achieved.

5.2 Capture Cross Section

The only new measurement available for this cross section is that of Weston and Todd /17/. They have measured the capture-to-fission ratio from 10 eV up to 250 keV. For the recommended KEDAK-3 data of σ_c the alpha values of Weston and Todd are multiplied with their fission cross section values. A smooth curve is drawn through the resulting σ_c values. Weston and Todd give an uncertainty of 20 % below 20 keV and 10 % above 20 keV in their alpha values. This means that the uncertainties in the derived capture cross section and hence in our recommended data are about 25 % below 20 keV and 15 % above 20 keV.

The average of the Weston and Todd data for α and σ_c and of our data for σ_c are given in Table 5.

Table 5 Average Capture Cross Section for ^{241}Pu

$\frac{1}{E_2-E_1}\int_{E_1}^{E_2}\sigma_c(E)dE$ (barns)

Neutron Energy keV	σ_c/σ_f	σ_c Weston+Todd	σ_c Present evaluation
0.1 - 0.2	0.311	8.6	9.74
0.2 - 0.3	0.291	8.1	8.39
0.3 - 0.4	0.387	8.12	8.17
0.4 - 0.5	0.361	6.7	6.92
0.5 - 0.6	0.320	5.2	5.22
0.6 - 0.7	0.303	3.4	4.0
0.7 - 0.8	0.309	3.3	3.23
0.8 - 0.9	0.256	2.5	2.86
0.9 - 1.0	0.279	3.0	2.87
1.0 - 2.0	0.346	3.02	2.91
2.0 - 3.0	0.317	2.16	2.12
3.0 - 4.0	0.265	1.67	1.84
4.0 - 5.0	0.317	1.72	1.41
5.0 - 6.0	0.188	0.86	1.08
6.0 - 7.0	0.200	0.92	0.96
7.0 - 8.0	0.257	1.02	0.93
8.0 - 9.0	0.216	0.85	0.91
9.0 - 10.0	0.260	0.94	0.88
10 - 20	0.270	0.87	0.83
20 - 30	0.228	0.77	0.75
30 - 40	0.199	0.5	0.56
40 - 50	0.193	0.45	0.46
50 - 60	0.192	0.44	0.42
60 - 70	0.175	0.39	0.4
70 - 80	0.161	0.38	0.37
80 - 90	0.182	0.38	0.36
90 - 100	0.138	0.28	0.34
150 200	0.150	0.28	0.27
200 250	0.132	0.23	0.25

In Fig. 15 the newly recommended data are compared with those of Caner and Yiftah and with the KFKINR set. Between 0.3 and 300 keV the presently recommended data for σ_c are lower than the σ_c values given by Caner and Yiftah. Above 300 keV the data are left unchanged. Similar to the σ_f cross section a structure is seen below 30 keV.

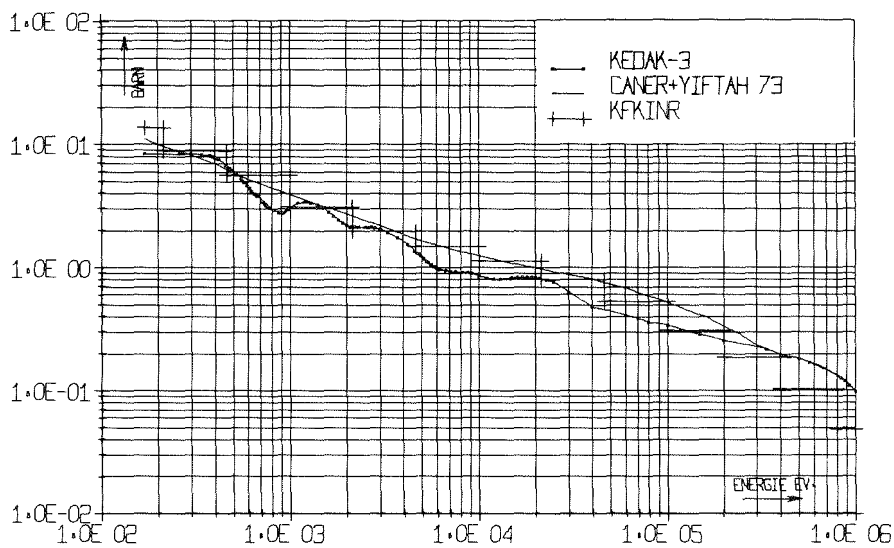


Fig. 15: The neutron capture cross section for ^{241}Pu between 162 eV and 1 MeV.

The WRENDA accuracy requirements of 3-10 % for σ_c or 10-20 % for alpha can not be considered as satisfied. Our data for σ_c are based on only one experiment, namely that of Weston and Todd. The details of the experiment are yet to be published.

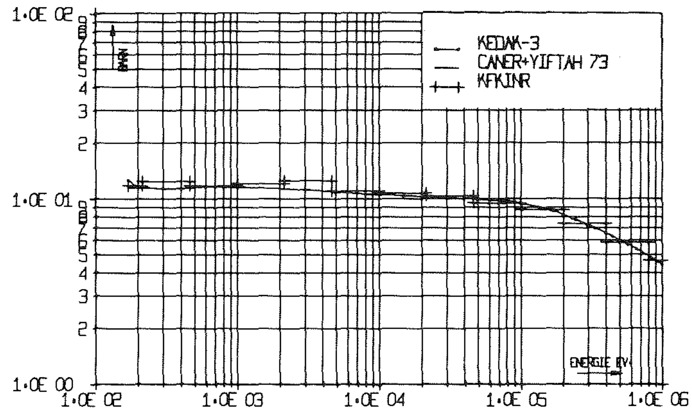
5.3 Other Cross Sections

In Figure 16 the other cross sections of ^{241}Pu stored on KEDAK are shown. It is seen that the elastic scattering cross section is the same as in the evaluation of Caner and Yiftah. The differences in σ_t, σ_{ab} , σ_{non} and in the transport cross section are due to the difference in σ_f and σ_c.

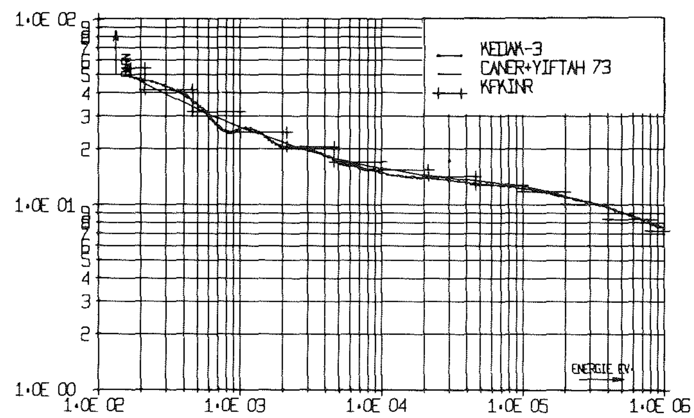
The average resonance parameters in the energy range 162 eV to 250 keV given in Table 6 were determined by Fröhner /62/ using the same scheme as for ^{240}Pu.

ℓ	J	$\bar{\Gamma}_\gamma$ (eV)	$\bar{D}$ (eV)	$\bar{\Gamma}_n$ (eV)	$\bar{\Gamma}_n/D$	ν_f	ν_n
0	2	0.035	1.77	$1.823\cdot 10^{-4}$	$1.03\cdot 10^{-4}$	2	1
0	3	0.035	1.52	$1.566\cdot 10^{-4}$	$1.03\cdot 10^{-4}$	1	1
1	1	0.035	2.61	$5.74\cdot 10^{-4}$	$2.2\cdot 10^{-4}$	2	1
1	2	0.035	1.77	$3.89\cdot 10^{-4}$	$2.2\cdot 10^{-4}$	1	2
1	3	0.035	1.52	$3.34\cdot 10^{-4}$	$2.2\cdot 10^{-4}$	2	2
1	4	0.035	1.51	$3.32\cdot 10^{-4}$	$2.2\cdot 10^{-4}$	1	1

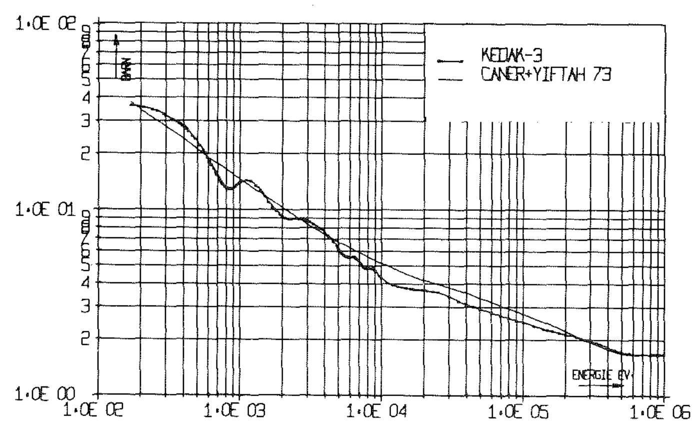
Table 6: Average Resonance parameters for ^{241}Pu



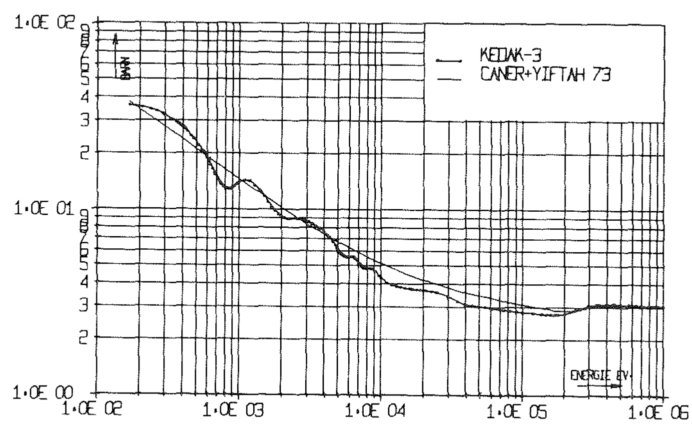
The neutron elastic scattering cross section for ^{241}Pu between 162 eV and 1 MeV.



The total neutron cross section for ^{241}Pu between 162 eV and 1 MeV.



The neutron absorption cross section for ^{241}Pu between 162 eV and 1 MeV.



The nonelastic scattering cross section for ^{241}Pu between 162 eV and 1 MeV.

Fig. 16: Elastic Scattering, total, absorption and nonelastic scattering cross sections for ^{241}Pu between 162 eV and 1 MeV.

6. Evaluation of the Data for ^{238}U

For the isotope ^{238}U the following data have been revised after 1970:

- Resonance parameters
- pointwise cross sections in the resolved resonance region
- total cross section from 5 keV to 15 MeV
- fission cross section from 500 keV to 15 MeV
- capture cross section from 5 keV to 15 MeV
- nonelastic, inelastic and elastic scattering cross sections
- (n,2n) and (n,3n) cross sections
- ν from 0.01 eV to 15 MeV

and all other data which are dependent on the data given above.

6.1 Resolved Resonance Region

The KEDAK-3 resonance parameters in the resolved resonance region from 4 eV to 4.6 keV are taken from the evaluation of Moxon /80/, the spin and angular momentum quantum numbers of the resonances are taken from BNL 325 /81/. The pointwise cross section data stored on KEDAK in the energy region up to 4 keV are derived from these resonance parameters.

The average resonance parameters shown in Table 7 were determined by Fröhner /62,63/ with the same method as for ^{240}Pu.

ℓ	J	$\bar{\Gamma}_\gamma$ (eV)	$\bar{D}$ (eV)	$\bar{\Gamma}_n$ (eV)	$\bar{\Gamma}_n/\bar{D}$	ν_f	ν_n
0	1/2	0.024	20.2	$1.879\ 10^{-3}$	$0.93\ 10^{-4}$	0	1
1	1/2	0.024	20.2	$3.64\ 10^{-3}$	$1.8\ 10^{-4}$	0	1
1	3/2	0.024	10.17	$1.879\ 10^{-3}$	$1.8\ 10^{-4}$	0	1
2	3/2	0.024	10.17	$0.946\ 10^{-3}$	$0.93\ 10^{-4}$	0	1
2	5/2	0.024	6.83	$0.635\ 10^{-3}$	$0.93\ 10^{-4}$	0	1

Table 7: Average Resonance Parameters for ^{238}U

6.2 Total Cross Section

The total cross section for ^{238}U in the energy region above the resolved resonances to 14 keV is taken from the work of Carraro and Kolar /82/. Above 14 keV the recommended curve is mainly based on the measurements of Uttley /83/ from 14 keV to 1 MeV, Schwarz et al. /15/ above 0.5 MeV. Kopsch et al. /84/ between 1 and 3 MeV, Smith et al. /14/ from 0.1 MeV to 5 MeV, Foster and Glasgow /85/ above 1.5 MeV. The experimental data were averaged over suitable intervals to smooth out the fluctuations in the measured cross sections. The data of Hibdon /86/ below 0.5 MeV and those of Henkel /87/ below 0.5 MeV and between 3 and 5 MeV were also included in this evaluation. The data of Cabé /13/ from 0.1 MeV to 6 MeV were used in the evaluation with reduced weight, since these data systematically appears to be higher than the other data by about 3 %.

The result of this evaluation is shown in Fig. 17 together with the previously recommended data on KEDAK and the experimental data. For the sake of clarity the latter are averaged over energy intervals of 0.2 MeV. The uncertainty of the present evaluation is estimated to be below 5 %.

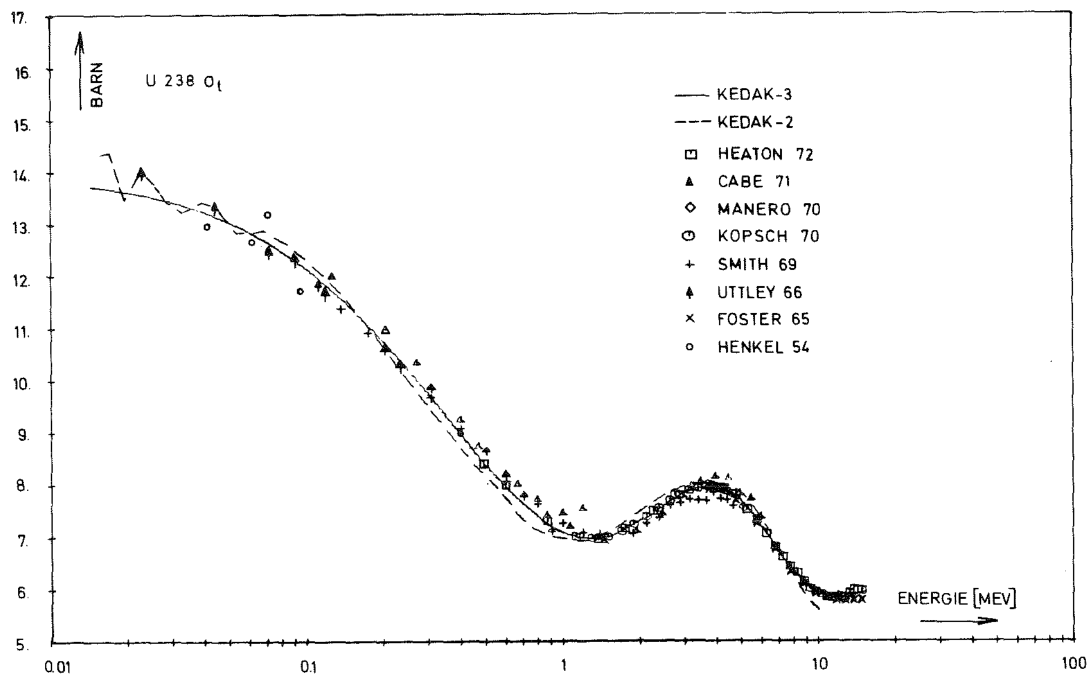


Fig. 17: Total neutron cross section for ^{238}U between 15 keV and 15 MeV.

6.3 Fission Cross Section

For the evaluation of the fission cross section of ^{238}U we have first evaluated the ratio measurements of σ_f ^{238}U to σ_f ^{235}U (the lowest curve in Fig. 18). The evaluation above 6 MeV is based mainly on the measurements of Cierjacks et al./88/, Hansen et al. /23/ and the corrected data of Smith, Henkel and Nobles /24/. Below 6 MeV the experiments considered are those of White and Warner /21/, Stein et al. /89/ and Meadows /90/. Following Davy /67/ and Sowerby /20/ we have reduced the original data of Lamphere /91/ by 6 % to match the more precise measurements of Stein et al..

The evaluated ratio value was then multiplied by the KEDAK-3 fission cross section of ^{235}U to obtain the fission cross section for ^{238}U (the continuous line). The evaluated ^{238}U fission cross section is compared with published experimental ^{238}U fission data in Fig. 18. The dashed curve shows the previously recommended data on KEDAK. The effect of the present evaluation is the reduction of σ_f for ^{238}U by 3-4 % in the energy region above 2 MeV.

In Fig. 19 the evaluated fission cross section is compared with the most recent experimental data measured by Leugers et al. /160/ which were measured some time after the evaluation was made. With the exception of the energy regions from 5-6 MeV and above 11 MeV the agreement is very good.

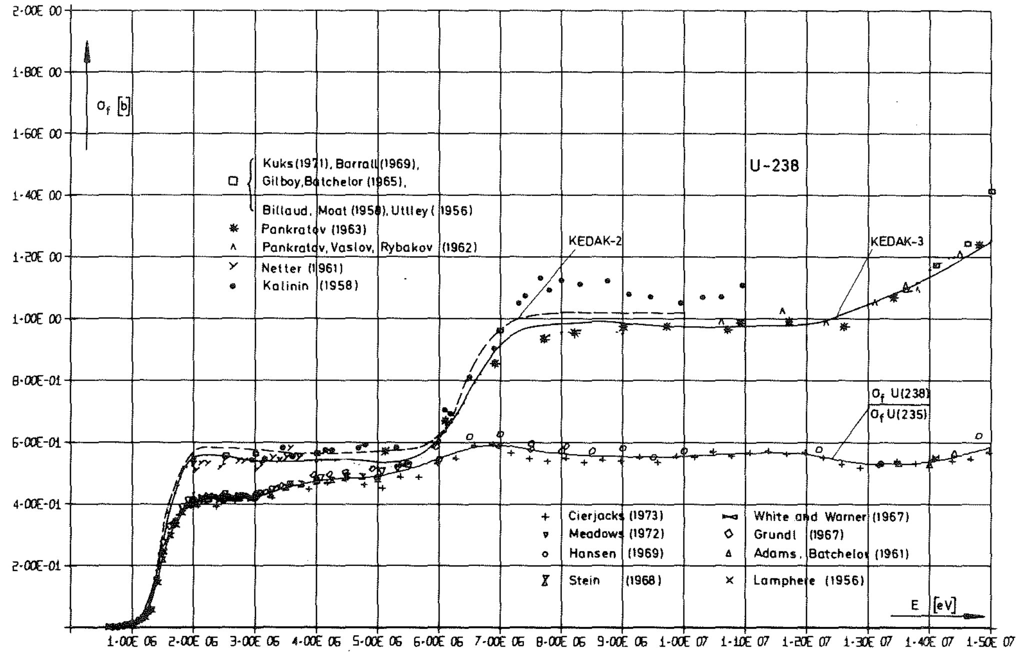


Fig. 18: Fission cross section for ^{238}U from threshold to 15 MeV.

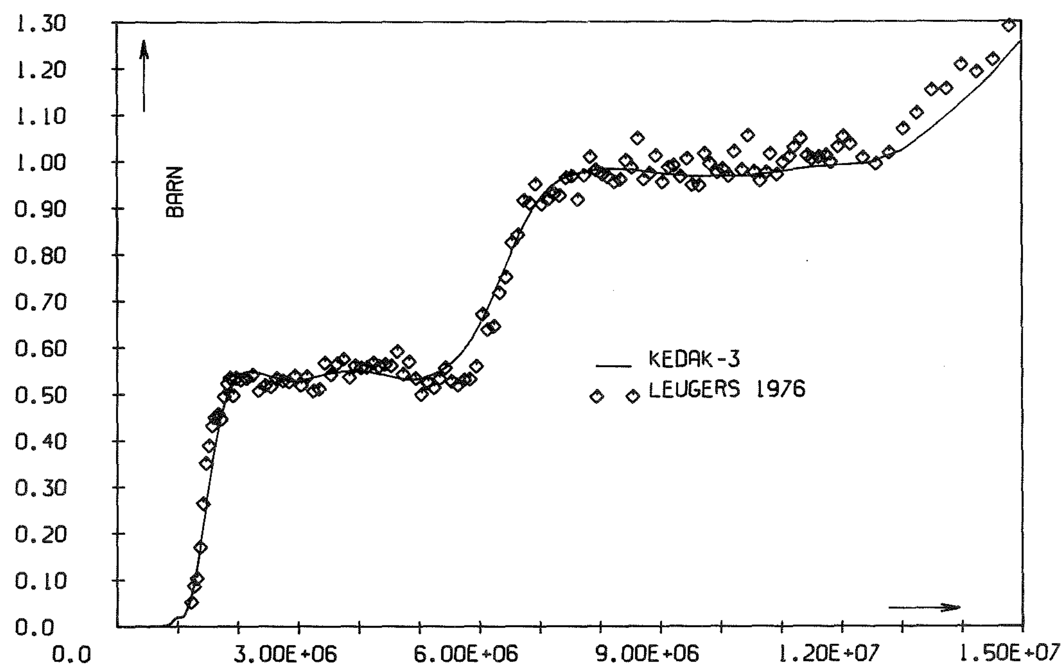


Fig. 19: Comparison of the fission cross section for ^{238}U between KEDAK-3 and Leugers et al. /160/.

The average of the evaluated data over the ^{235}U neutron spectrum is 0.2963 which is about 2 % lower than the older experimental values of 0.304 ± 0.007 (ref. /92/), 0.312 ± 0.004 (ref. /93/) and 0.31 ± 0.01 (ref. /94/). The uncertainty of the evaluated data is estimated to be 5 % up to 10 MeV and 2.5 to 5 % between 10 and 15 MeV. The subthreshold fission in the case of ^{238}U which was discovered by Silbert and Berger /95/ and has recently been measured with good accuracy and good energy resolution by Block et al. /96/ has not been taken into account in this evaluation.

6.4 Capture Cross Section

Only data published after 1969 are considered for this evaluation. The older data as demonstrated in the lower part of the Figure 20 show large discrepancies in absolute values and in the shape of this cross section.

The data published after 1969 are:

Authors	Lab.	Year	given accuracy	Ref.
Moxon	Harwell	1969	4 - 8 %	/97/
Friesenhahn et al.	GA	1970	6 - 10 %	/98/
de Saussure et al.	ORNL	1973	5 - 10 %	/99/
Spencer + Käppeler	KFK	1975	11 %	/100/

The last measurement is primarily a shape measurement with shape uncertainty < 5 %.

In Figure 20 some experimental data and evaluations (ref. /97-107/) are compared with the KEDAK-3 data for σ_c of ^{238}U. On the ordinate the ratio of different data to the KEDAK-3 data is shown.

Although uncertainties in different experimental data vary between 4 and 11 %, the discrepancies among the different data sets are as large as 20 %. Not only the different data are discrepant in their absolute values, the shapes of σ_c measured by different authors also show large disagreements.

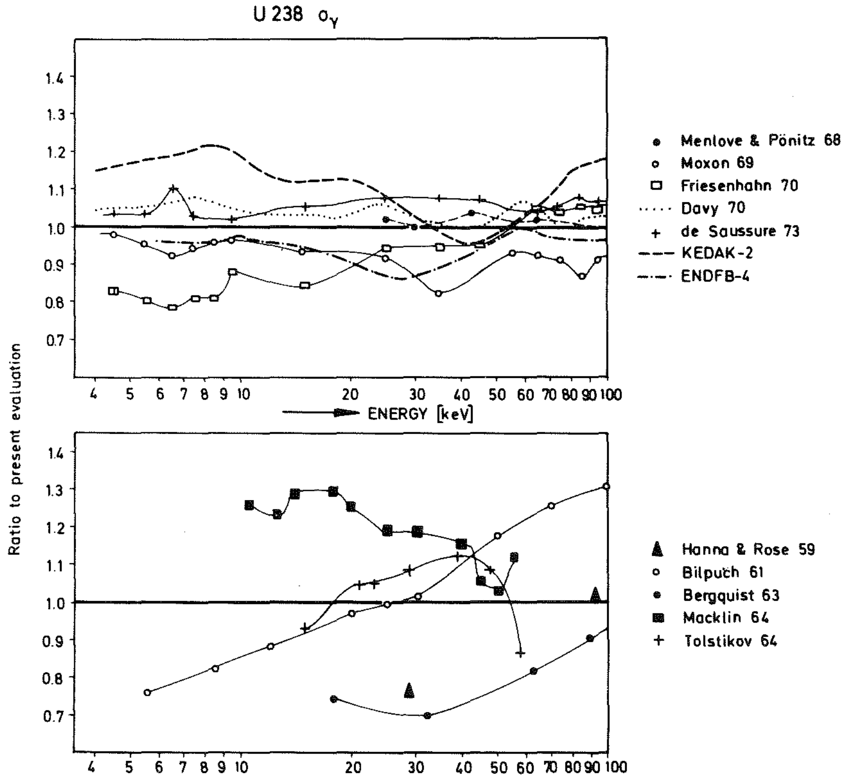


Fig. 20: Comparison of different experimental data and evaluations for $^{238}U(n,\gamma)$ with the KEDAK-3 data (ref. /97 to 107/).

The recent measurement of Spencer and Käppeler /100/, which is primarily a shape measurement, agree well in shape with that of the data of de Saussure (Fig. 21) and to a lesser extent with the data of Moxon. But the shape of the data of de Saussure and Friesenhahn show a strong disagreement although both these data are measured with essentially similar experimental technique. This may be due to the high gamma-detector bias of 3.5 and 4 MeV used by Friesenhahn as compared to 2.8 MeV used by de Saussure. The data of Friesenhahn below 20 keV have therefore been used with reduced weight.

A comparison of different evaluations shows a tendency of decreasing the σ_c data with time: KEDAK-2 (1966) is up to 20 % higher than the KEDAK-3 data and Davy's /102/ evaluation (1970) is about 3-5 % higher than the KEDAK-3 evaluation. The ENDF/B-IV evaluation gives the lowest σ_c values. It is apparently due to the heavy weight given to the data of Friesenhahn in the ENDF/B-IV evaluation.

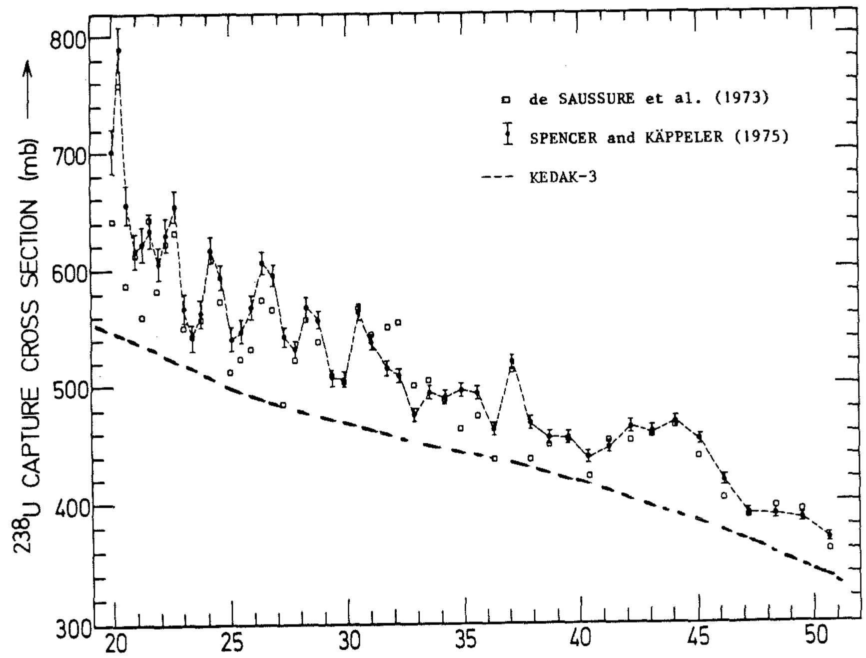


FIG. 21

Fig. 21: Comparison of the capture cross section for ^{238}U from ref. /99/ and /100/.

Above 100 keV the data evaluated by Sowerby et al. /20/ are used in KEDAK-3. In Fig. 22 the presently recommended data on KEDAK between 100 keV and 10 MeV are compared with the published experimental data and some other evaluations(ref. /101, 102, 107-116/). The uncertainty of the present evaluation is estimated to be 10-7 % in the energy region 4 keV to 100 keV. Above 100 keV Sowerby et al. gives an uncertainty of 7 % up to 1 MeV, increasing to 10 % at 3 MeV and 33 % at 7 MeV.

Fig. 23 shows the comparison of the presently recommended KEDAK data with the previously recommended curve. The new capture cross section is smaller almost over the whole energy range. The experimental data shown are averages over 10 keV intervals.

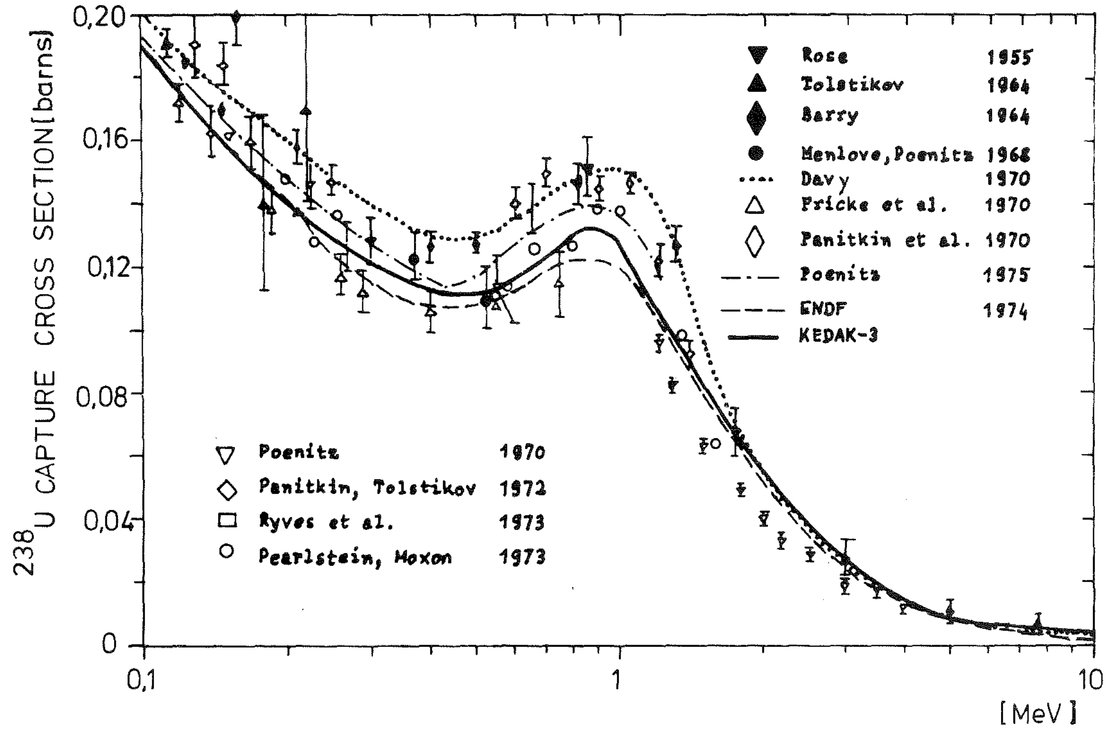


Fig. 22: Comparison of the data by different authors for $^{238}U(n,\gamma)$ between 100 keV and 10 MeV.

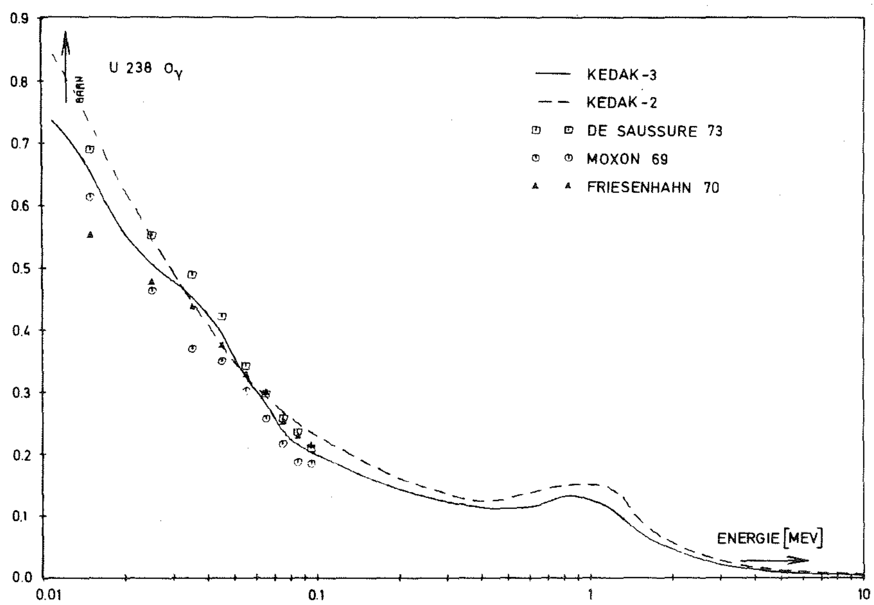


Fig. 23: Comparison of presently and previously recommended data for $^{238}U(n,\gamma)$

6.5 Scattering Cross Sections

A detailed study of these cross sections has been presented at the specialist meeting at Harwell /117/. A copy of this paper is attached in the appendix A2. In the following only a brief description of this evaluation is given.

A combined evaluation of the elastic, inelastic and nonelastic cross sections was performed using the relation

$$\sigma_t = \sigma_{el} + \sigma_a + \sigma_{in} = \sigma_{el} + \sigma_{nel}$$

In principle there are the following three different methods for the evaluation of the total inelastic scattering cross section

$$\sigma_{in} = \sum_k \sigma_{in}^{(k)} \qquad (1)$$

$$\sigma_{in} = \sigma_t - \sigma_{el} - \sigma_a \qquad (2)$$

$$\sigma_{in} = \sigma_{nel} - \sigma_a \qquad (3)$$

In the energy region below 1.8 MeV, where the discrete excited levels can be resolved, the partial inelastic scattering cross sections of these levels are measured and method (1) can be used. Thus, the error in the total inelastic scattering cross section derived in this way is determined by the error in the measurements of the individual levels or groups of levels. On the other hand if the inelastic cross section is inferred from methods (2) or (3), the uncertainties in the cross sections σ_t, σ_a, σ_{el} or σ_{nel} determine the uncertainty in the resulting total inelastic cross section. Therefore it has to be decided for each energy region which of the possible methods leads to the smallest uncertainties in the resulting cross section.

The method (3) is not possible below 2 MeV because the nonelastic cross section is measured only in the region above 2 MeV. As has been shown in an investigation of Smith /118/ the uncertainties of method (2) in the energy region below 0.8 MeV are rather large (∿ 25 %) and are estimated to be larger than those of method (1). Therefore up to 0.8 MeV method (1) was chosen for the evaluation of σ_{in}; the resulting cross section corresponds to the evaluation of Kanda /119/. Between

1 and 2 MeV error analysis does not allow a unique decision between the methods (1) and (2), because the uncertainties in both methods are estimated to be about 15-25 %. In this case we consider the results of the neutron spectrum measurements as an independent physical criteria. Although the neutron spectrum measurements cannot reproduce the exact shape of the inelastic cross section, they provide decisive information about its overall behavior. Thus method (2) was chosen because it leads to a cross section which is more similar to that inferred from neutron spectrum measurements /120/.

In the energy region between 2 and 5 MeV the method (2) was preferred because the uncertainties of the old nonelastic cross section measurements /121/ lead to uncertainties of the resulting cross section of the method (3) which are estimated to be larger or not smaller than those of method (2). The evaluation of the elastic scattering cross section in the energy range from 1 MeV to 5 MeV is based mainly on the new microscopic data of Smith /118/. In the energy range above 6 MeV the nonelastic cross section data were taken from the evaluation shown in Figure 24. This evaluation of the nonelastic cross section

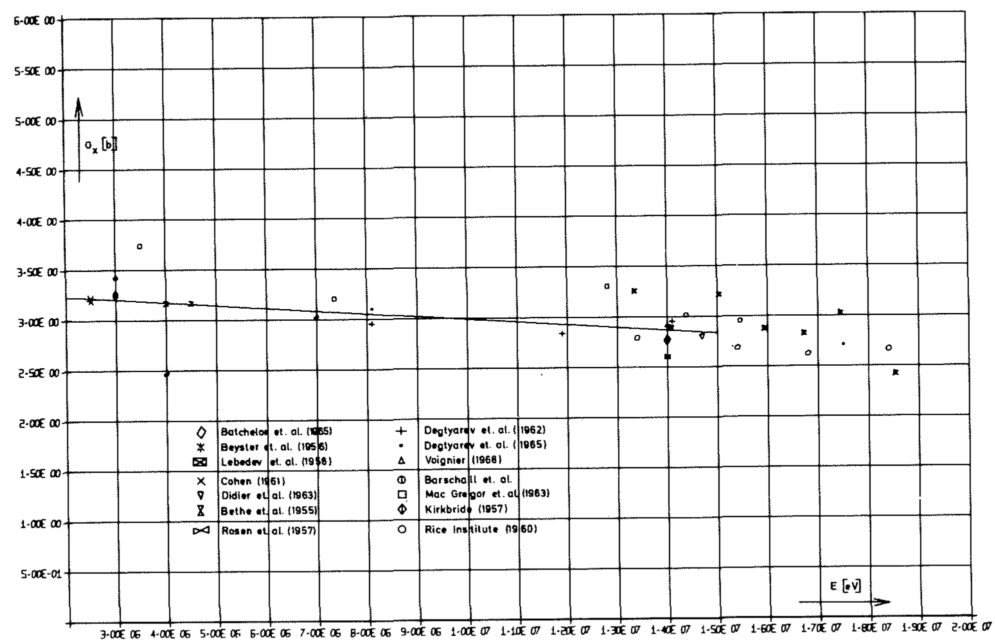


Fig. 24: Nonelastic cross section for ^{238}U between 2 MeV and 30 MeV.

is in good agreement with the evaluation of Schmidt /121/ with maximum deviation of about 3 %. In addition to the data sets (ref. /122-134/) used for the former KEDAK evaluation of the nonelastic cross section /121/, the only data published after 1966 (Voignier /135/) were included for KEDAK-3. The difference between the previous and the present KEDAK data for σ_{in} in this energy region is therefore mainly due to the different values of σ_a.

In Fig. 25 the results for the inelastic cross section are shown together with the previously recommended KEDAK data, the results of the neutron spectrum measurements of Bluhm /120/ and the KFKINR-set /79/. The present evaluation is characterized by a reduction of the previously recommended data in the energy region from 0.5 MeV to 5 MeV, amounting to 60 % about 1.5 MeV. The uncertainty of these recommended data is estimated to be less than 20 % below 5 MeV and of the order of 30-35 % above 6 MeV which is primarily due to the uncertainty in σ_a.

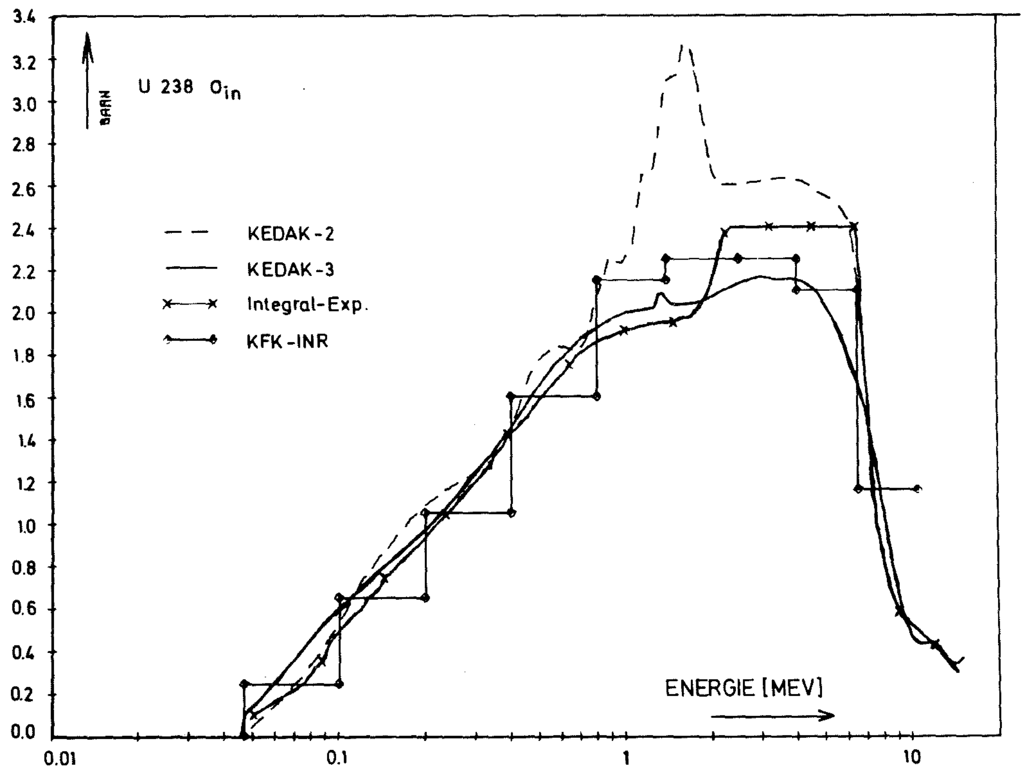


Fig. 25: $^{238}U(n,n')$-cross section from threshold to 15 MeV.

6.6 (n,2n) and (n,3n) Cross Sections

The evaluated and experimental data (ref. /122, 137-142/) for the $^{238}U(n,2n)$ cross section are shown in Figure 26. As is reported in Pitterle's paper /136/ the original measurements by Knight /137/ and Graves /138/ have been corrected by Barr /139/. These corrected data were divided by the ^{238}U fission cross sections of Smith, Henkel and Nobles /24/. These ratios were then combined with the present evaluation for the ^{238}U fission cross section. The original data of Knight and Graves have not been taken into account in the least squares fit.

The fission spectrum average of the evaluated (n,2n) cross section has the value 15.1 mb which is compatible with the value 17 ± 3 mb measured by Sherman /143/.

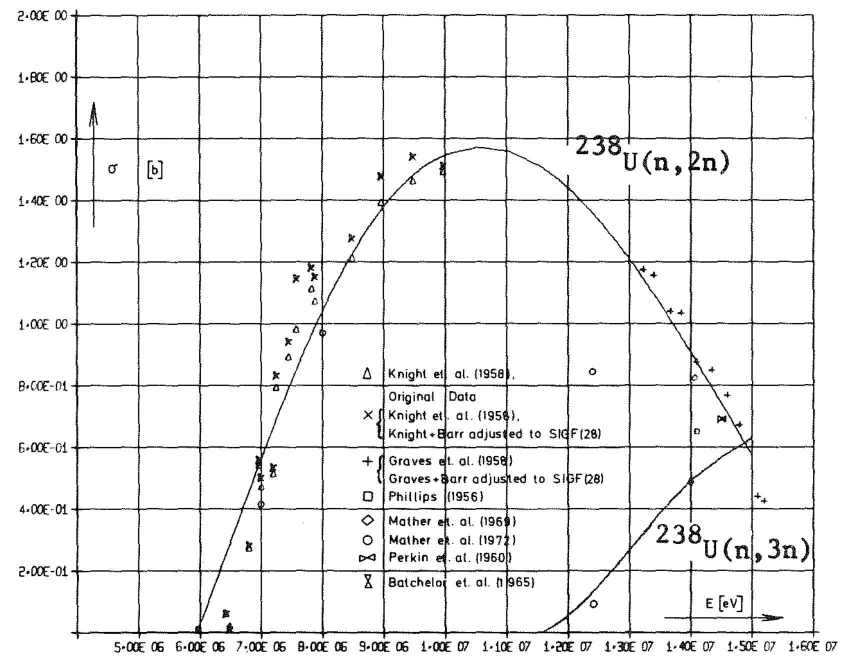


Fig. 26: ^{238}U(n,2n) and ^{238}U(n,3n) cross sections from threshold to 15 MeV

The present evaluation of the ^{238}U(n,3n) cross section is based on the measurements of Mather /142,144/ which are the only reported (n,3n) cross section measurements with significant accuracy. The evaluated and experimental data are also shown in Figure 26.

6.7 Average Number of Neutrons per Fission ($\bar{\nu}$)

The evaluation of the average number of neutrons per fission $\bar{\nu}$ has been performed by Isbasescu /145/. It is based on the measurements of Diven /146/, Blaise and Leroy /147/, Smirenkin /148/, Kuzminov /149/, Butler /150/, Moat /151/, Condé /152/, Asplund-Nilsson /153/, Mather /154/ and Soleilhac /155/. Since the results of these measurements have been renormalized to the value of 3.7567 for $\bar{\nu}_p$(^{252}Cf) from spontaneous fission /156/ by Mather /157/ and fitted by straight lines, the results of Mather's fit of these experimental data were accepted for the present evaluation.

In order to obtain $\bar{\nu}_{total}$ from the experimental $\bar{\nu}_p$-values of the $\bar{\nu}_p(E)$ curve recommended by Mather it is assumed that the delayed neutrons show the following energy dependence:

$\bar{\nu}_d = 0.049 \pm 0.005$	below 4.5 MeV
$\bar{\nu}_d = 0.086406 - 0.02488 * \ln E_n(\mathrm{MeV})$	between 4.5 MeV and 10 MeV
$\bar{\nu}_d = 0.0286 \pm 0.0025$	from 10 MeV to 15 MeV

The constant value of ν_d taken below 4.5 MeV corresponds to the value measured by Masters et al. /158/ at 3.1 MeV and confirmed by Krick and Evans /159/. Krick and Evans have also made measurements at many energy points in the region 4 MeV - 7 MeV in order to investigate the energy dependence of $\bar{\nu}_d$. From their experimental data $\bar{\nu}_d$ was obtained in the energy region 4.5 MeV - 10 MeV. Above 10 MeV the only experimental value for $\bar{\nu}_d$ was at 14.9 MeV, measured by Masters et al. /158/ which can not be extrapolated with energy dependence below 10 MeV. Therefore a constant value for $\bar{\nu}_d$ was assumed in the energy region 10 MeV - 15 MeV.

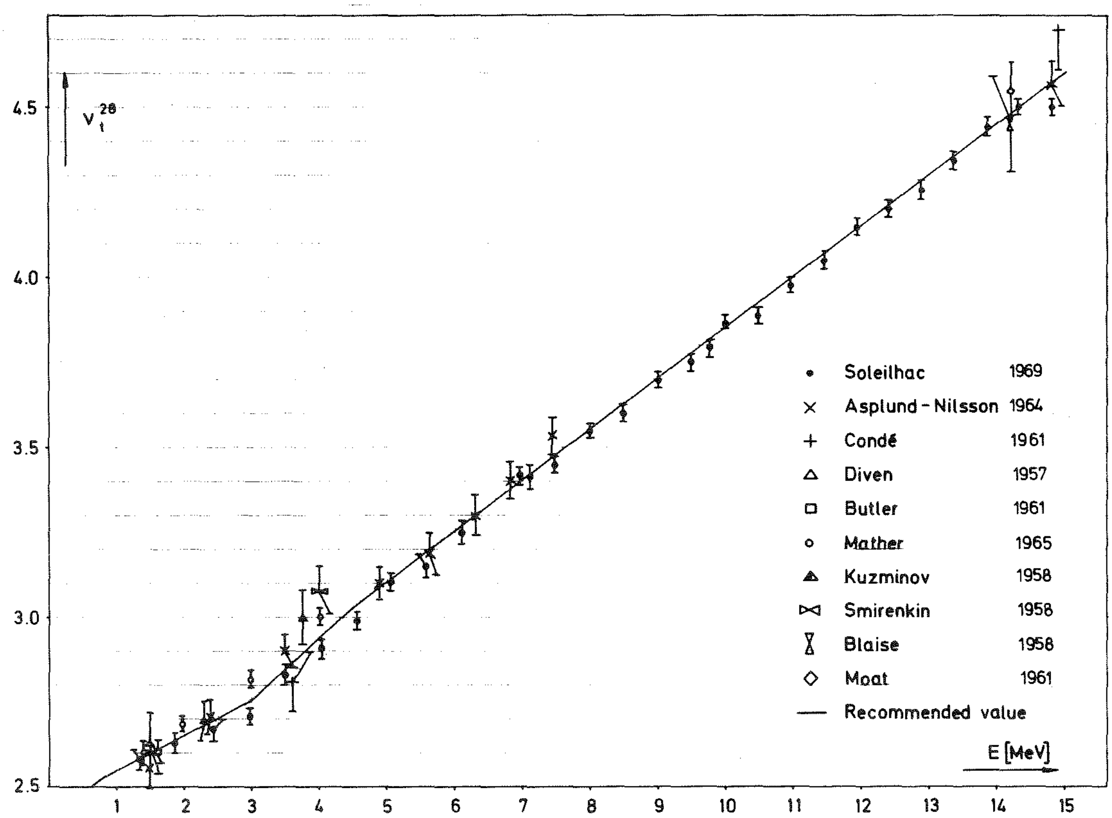


Fig. 27: $\bar{\nu}$ for ^{238}U

In Fig. 27 the experimental $\bar{\nu}$ values obtained with the above assumptions for $\bar{\nu}_d$ are given together with their errors. Furthermore the presently recommended $\bar{\nu}(E)$ curve resulting from Mather's fit to the ν_p measurements is shown, it can be approximately represented by

$$\bar{\nu} = 0{,}153\ E + 2{,}323.$$

The uncertainty of the recommended data is about 10 to 1 % from threshold to 1.5 MeV and 1-2 % from 1.5 MeV to 15 MeV. The high uncertainty below 1.5 MeV was assigned because of the complete lack of experimental data below 1.3 MeV.

7. Evaluation of the Data for ^{235}U

The evaluation of the neutron cross sections of ^{235}U has already been published /4/. In this section only the following two necessary modifications with respect to ref. 4 are described:

Total cross section from 1 MeV to 15 MeV
Fission cross section from 1 MeV to 15 MeV

7.1 Total Cross Section

The total cross section of ^{235}U was reevaluated above 1 MeV because the former evaluation /4/ was primarily based on the data of Cabé et al. /13/, and as has already been noticed (see σ_t of ^{239}Pu) these data are systematically 3-5 % higher than other published data. For the present evaluation, therefore, the data of Cabé et al. are reduced by 3 % and combined with the experimental data of Foster and Glasgow /12/ and Schwartz et al. /15/. The experimental data and the presently and previously recommended data are shown in Fig. 28. The main difference between the old and the new evaluated data is in the energy region from 1.5 to 6 MeV with a maximum deviation of 4.5 % at 4 MeV.

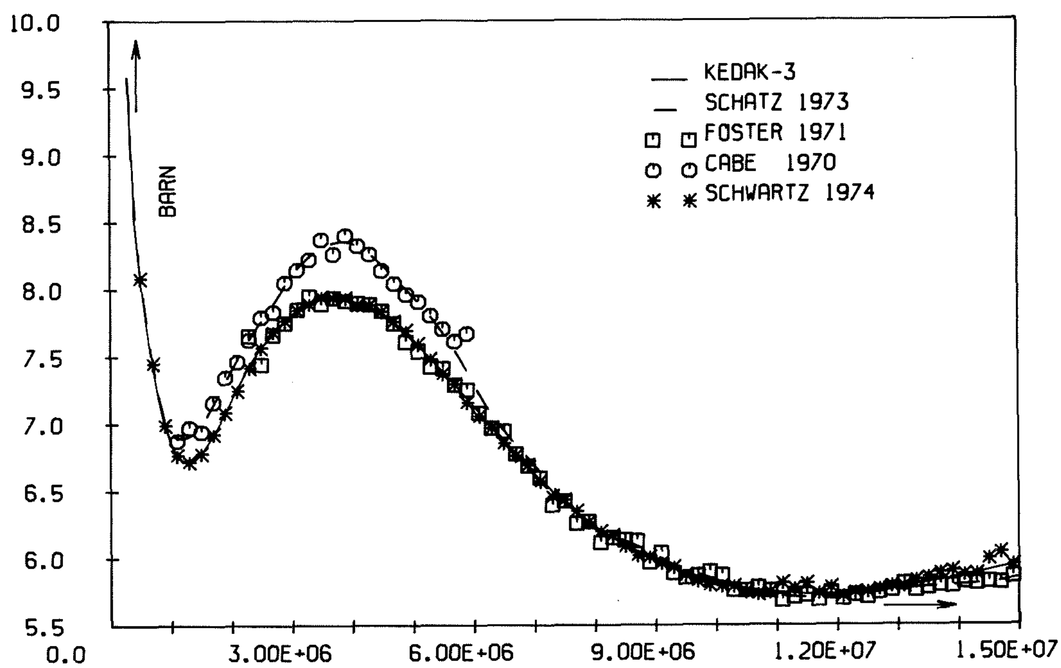


Fig. 28: Total cross section for ^{235}U from 100 keV to 15 MeV.

7.2 Fission Cross Section

In the 1973 evaluation of the ^{235}U fission cross section /4/, above 1 MeV highest preference was given to the data of Hansen, McGuire and Smith /23/, who revised the original σ_f values of Smith, Henkel and Nobles /24/ on the basis of calculated scattering corrections. It seems, however, that there are some inconsistencies in the data set of Hansen et al. /25/. The publication of a new measurement series from 3 to 20 MeV /161/ was a further argument for a reevaluation of this important cross section. The new evaluation is based mainly on the data of ref. /161/, /162/ and /165/. Due to normalization uncertainties the data of ref. /163/ and /164/ are considered with reduced weight. The old Kalinin data /166/ are not taken into account.

In Fig. 29 the new and old evaluations are shown together with the experimental data which in the case of Czirr and Sidhu /161/ are averages over certain energy intervals. It is seen that the main difference between the two evaluations is in the energy region of 9 MeV to 13 MeV which reflects the difference between the data of Hansen et al. /23/ and those of Czirr and Sidhu /161/, amounting to about 12 % at 11 MeV.

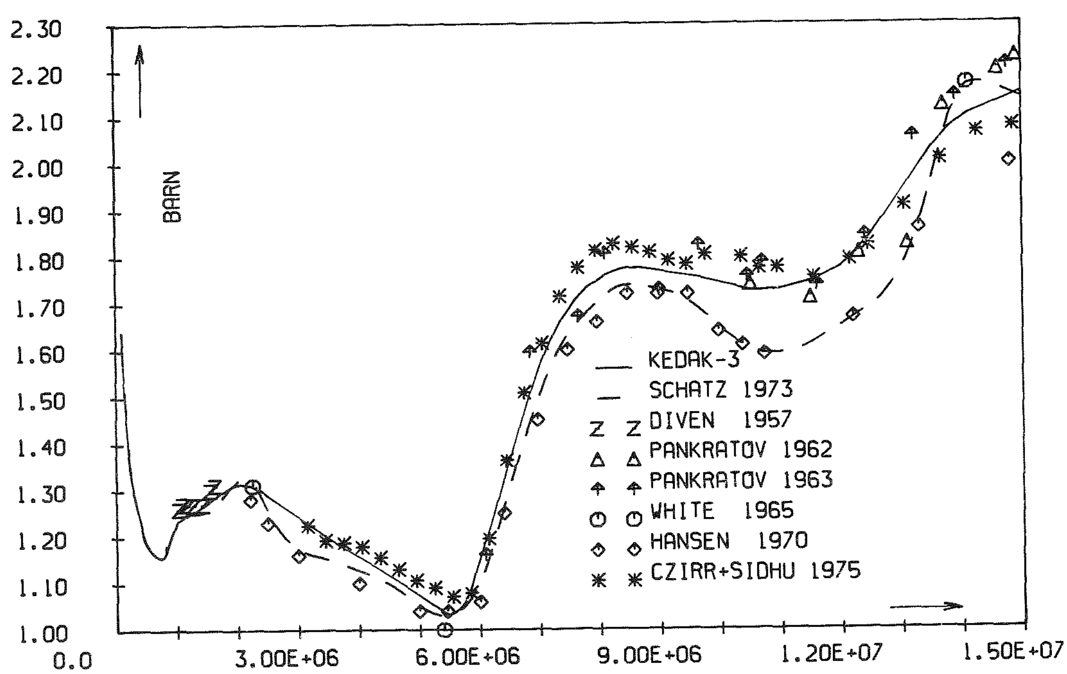


Fig. 29: Fission cross section for ^{235}U in MeV-range. Experimental data from ref. 161 to 166.

In Fig. 30 the evaluated ^{235}U fission curve is compared with the recent experimental data of Leugers et al. /160/, which were measured after the evaluation was completed. It is interesting to see that in the energy region from 8 to 12 MeV most of these data lie below the recommended curve, while the data of Czirr and Sidhu, which were taken into account in this evaluation, lie a little above the curve.

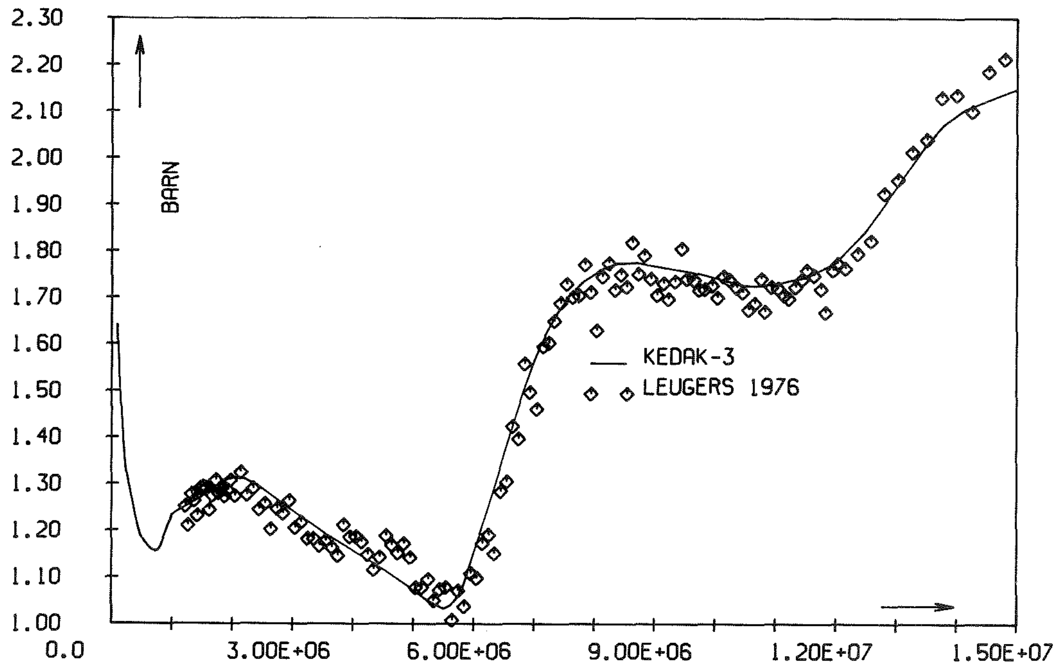


Fig. 30: Comparison of the fission cross section for ^{235}U between KEDAK-3 and Leugers et al. (ref. /160/) from 1 MeV to 15 MeV.

8. Concluding Remarks

In the foregoing chapters the evaluations performed at this laboratory during the period 1973 to 1976 are described. The status of these evaluations can be dated to the end of 1975. In Table 8 the demands regarding the accuracy of these cross sections by the users of the nuclear data libraries i.e. reactor physicists as given in the WRENDA 1976/77 are reproduced. Only priority 1 requests are included in this table. In the last column of Table 8 the uncertainties of the present evaluations are given. While assigning an accuracy to the evaluations, one has to rely on the information furnished by the experimentators. Thus in general the evaluation accuracies given in Table 8 are not likely to be more reliable than those given by experimentators, although care has been taken to exclude unreliable data from this evaluation. It is seen that for many cross sections evaluated the requests are almost satisfied e.g. for σ_t and $\bar{\nu}$ for ^{235}U, ^{238}U and ^{239}Pu. There are other cases like σ_c for ^{240}Pu and ^{241}Pu where the accuracy requirements could not be met because of the lack of experimental information. Cross sections, like σ_f of ^{235}U, ^{238}U and ^{239}Pu belong to the third category, where inspite of heavy experimental work uncertainties could not be reduced to less than 3 % although the demands are of the order of 1 %. In a recent specialist meeting on fast neutron fission cross sections /167/ it was felt that the possibilities of determining the fission cross section for ^{235}U better than 3 % are rather low. Since, this is a standard cross section against which most of the other cross sections are measured, reactor physicists may have to reconsider their accuracy requirements.

To check the quality of the presently evaluated data in reactor physics calculations, their effect on k_{eff} of a large variety of critical assemblies is studied. For this purpose group cross sections from the evaluated data were generated in the well known ABBN 26 group structure with the help of the computer program MIGROS3 /168/. These group cross sections were then incorporated in the KFKINR-set /79/. The KFKINR-set is an admixture of partly corrected and adjusted original ABBN- and KEDAK-2 data. For most data of essential importance for reactor physics calculations reasonable agreement between the measured and calculated results of experiments in fast critical assemblies has been achieved with the KFKINR-set. With the modified (KEDAK-3) KFKINR-set zero dimensional diffusion calculations were performed for a large number of critical assemblies with different neutron spectra.

Table 8: Status of the accuracies demanded and achieved for the data presented in this report

Evaluated data	Energy region of the evaluation	Greeblers Goal for 1975	WRENDA 1976/77 Priority 1 requests	uncertainties of this evaluation
$^{239}Pu\ \sigma_t$	> 100 keV	-	2 - 3 %	2 %
$^{239}Pu\ \sigma_f$	1 - 30 keV 2 MeV 15 MeV	2 % 2 %	1 % 3 - 5 %	~ 4 % ~ 9 %
$^{239}Pu\ \alpha$	1 keV - 1 MeV	3 % for σ_c below 500 keV	4 - 8 %	5 - 10 % below 30 keV > 10 % above 30 keV
$^{239}Pu\ \bar{\nu}$	1 meV to 15 MeV	0.5 %	0.5 %	0.5 %
$^{239}Pu\ \sigma(n,2n)$	Thr. to 15 MeV	-	10 %	6 - 20 %
$^{239}Pu\ \sigma(n,3n)$	"	-	20 %	50 %
$^{240}Pu\ \sigma_c$	4 keV - 1 MeV	10 %	10 %	> 20 %
$^{241}Pu\ \sigma_f$	160 eV 300 keV	10 %	1 - 5 %	6 - 10 %
$^{241}Pu\ \sigma_c$	"	-	3 - 8 %	15 - 25 %
$^{238}U\ \sigma_t$	4 keV - 15 MeV	-	-	< 5 %
$^{238}U\ \sigma_f$	Thr. - 15 MeV	3 %	1 - 5 %	5 %
$^{238}U\ \sigma_c$	4 keV - 15 MeV	2 % up to 1 MeV	3 - 6 % below 1 MeV 10 % above 1 MeV	7 - 10 % below 1 MeV 10 - 40 % above 1 MeV
$^{238}U\ \sigma_{in}$	Thr. - 15 MeV	5 %	4 % below 1 MeV	< 20 %
$^{238}U\ \sigma(n,2n)$	"	-	7 %	7 - 10 %
$^{238}U\ \bar{\nu}$	Thr. - 15 MeV	-	1 %	1 - 2 %
$^{235}U\ \sigma_t$	1 MeV to 15 MeV	-	-	2 %
$^{235}U\ \sigma_f$	"	-	1 %	4 - 7 %

The results of these zero dimensional diffusion calculations are corrected to approximately correspond to exact two-dimensional transport calculations. This is done by adding δk to these results. δk is the difference between the k_{eff} values obtained out of the two dimensional and zero dimensional diffusion calculations using the original KFKINR-set. The results of the two dimensional calculations reported in table 9 are corrected to account for the difference between the transport and diffusion calculations by applying the so called S_n-correction /79/. This procedure is justified for most of the assemblies studied here. It may however, lead to somewhat misleading results in cases where the corrections like heterogeneity and elastic removal corrections are large and strongly dependent on group constant set. Among all the assemblies listed in table 9 heterogeneity corrections are large only for ZPR III48 and ZPR III55, being of the order of 1.5 %. Elastic removal corrections are small in all cases listed in table 9.

Table 9 Effect of the evaluated data on the calculation of k_{eff} for some of the critical assemblies studied.

No	Critical Assembly	k_{eff} Experiment	k_{eff} Calculated KFKINR 2D	k_{eff} Calculated KFKINR 0D	δk KFKINR 2D-0D	k_{eff} modified KFKINR 0D	k_{eff} calculated 0D+δk	$\frac{C-E}{E}$ %
1	SNEAK 3A1	1.0	1.0035	0.9948	+0.0087	0.9941	1.0028	+0.28
2	SNEAK 3A2	1.0	1.0008	0.9896	+0.0112	0.9892	1.0004	+0.04
3	ZPR III 55	1.0	1.011	0.9952	+0.0158	0.9836	0.9994	-0.06
4	ZPR IX 25	1.0	0.9950	0.9953	-0.0003	1.0115	1.0112	+1.12
5	SNEAK 8	1.0065	0.9970	0.9987	-0.0017	1.0165	1.0148	+0.82
6	SNEAK 7A	1.001	1.012	1.0175	-0.0055	1.0060	1.0005	+0.05
7	SNEAK 7B	1.0016	1.0088	1.0538	-0.045	1.0448	0.9998	-0.18
8	VERA 11A	1.0	1.0064	0.9537	+0.0527	0.9449	0.9976	-0.24
9	ZPR III 48	1.0	1.0065	0.9762	+0.0303	0.9680	0.9983	-0.17
10	ZEBRA 3	1.0	0.9972	1.0017	-0.0045	1.0111	1.0066	+0.66
11	ZEBRA 2	1.0	0.9874	0.9822	+0.0052	0.9818	0.987	-1.3
12	ZPR III 6F	1.0	1.0021	1.0017	+0.0004	1.0118	1.0122	+1.22
13	ZPR III 56B	1.0	1.0037	1.0057	-0.002	0.9953	0.9933	-0.67

Although a thorough assessment of the quality of the KEDAK-3 data will be defered till a complete new group constant set primarily based on KEDAK-3 is ready, it can be seen from the table 9 that the experimental k_{eff} values are reasonably well reproduced with the KFKINR-set modified with KEDAK-3 data, without requiring any adjustment of group cross sections.

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Appendix

Some Special Aspects of the Evaluation of the Inelastic Neutron Scattering on ^{238}U

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I. Introduction

For the design and optimization of reactors a precise knowledge of the microscopic neutron data is needed. One of the important cross sections for the calculation of fast reactor parameters is the inelastic scattering of neutrons from ^{238}U. Therefore, precise data on inelastic scattering cross sections are desired. But unlike in the case of the total and fission cross sections the uncertainty in the microscopic data, and consequently in the evaluation of the inelastic scattering cross section, is at present fairly large. Usually a combined evaluation of elastic, nonelastic and partial inelastic cross sections is performed for the evaluation of the total inelastic cross section keeping the evaluated total neutron cross section unchanged. But for a certain energy interval the resulting curve of the total inelastic cross section depends on the cross sections which have been primarily evaluated. In cases where error analysis does not allow a unique decision between the different methods of the evaluation of the total inelastic scattering cross section, the information provided by integral neutron spectrum measurements may help in choosing the evaluation procedure. Finally, the evaluated data can be checked by investigating their influence on the criticality of fast critical assemblies.

All hitherto known evaluations of the total inelastic scattering cross section of ^{238}U derived from evaluated individual inelastic excitation cross sections give values of k_{eff} which are too low for a large number of critical assemblies. This would implicate a reduction in these evaluated inelastic scattering cross sections.

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II. Method and Problems of the Evaluation

In Fig.1 the KEDAK-2 [1] and the ENDF/B-IV [2] evaluations of the total inelastic scattering cross section of ^{238}U are shown together with the KFK-INR 26-group cross section set [3]. It is seen that the main deviations between these cross section curves are within the energy interval from 1 MeV to 6 MeV. The maximum deviation is at 1.5 MeV where the KEDAK-2 cross section is about 50 % and that of ENDF/B-IV about 20 % higher than the KFK-INR group cross section, above 2 MeV the KEDAK curve is about 20 % and that of ENDF/B-IV about 15 % higher than the KFK-INR group cross section curve.

It is known that with a few exceptions the KFK-INR 26 group cross section set is reproducing the criticalities k_{eff} of the critical assemblies to within $\pm$ 1 %. Since for the calculation of integral nuclear quantities a criticality uncertainty Δk of $\pm$ 1 % caused by the combined effects of all nuclear data uncertainties is considered to be tolerable at present [4], the KFK-INR set is used as a nuclear data basis in our investigation.

The results in Table 1 show the sensitivity of the criticality on certain changes in the total inelastic scattering cross section performing zero-dimensional calculations. In the second column criticalities of some critical assemblies using the KFK-INR set are given. The third column shows the resulting criticalities if in this nuclear data base the inelastic scattering cross section of ^{238}U is replaced by the KEDAK-2 evaluation, changing the elastic scattering cross section correspondingly to keep the total cross section in the basis set unchanged and using the scattering matrix of the KFK-INR set. The relative changes in the criticality are shown in column 4 which demonstrates the large effect of the inelastic scattering data of ^{238}U on the criticality of the assemblies considered in our investigation. Since the changes in the criticality in Table 1 are all negative, the results lead to the indication that the KEDAK-2 inelastic cross section of ^{238}U is too large.

This conjecture is further supported by the results of the integral neutron spectrum measurements of Bluhm [5] which are shown in Fig.2 together with the KEDAK-2 evaluation and the KFK-INR set. In this experiment a ^{3}He-semiconductor-sandwich-spectrometer for in-core spectrum measurements in the energy region from 100 keV to 5 MeV and spherical proton recoil counters are used for the measurements of the neutron spectra on the axis of a massive block of depleted uranium. The measured spectra are then compared to calculated multigroup spectra. The sensivity of the spectra against changes of the ^{238}U cross sections is determined by variation of the relevant nuclear data. In this way values for the capture and inelastic scattering cross sections were deduced from the discrepancies between theoretical prediction and experiment. These cross sections deduced in the energy region up to 2 MeV are able to reproduce the measured spectra at all positions of the uranium block axis within the experimental errors. As shown in Fig.2 in the energy interval between 2 and 6 MeV the inleastic cross section is taken to be equal to the KEDAK-2 value at 6 MeV and above 6 MeV equal to the KEDAK-2 curve.

A combined evaluation of the elastic, inelastic and nonelastic cross sections was performed using the relation

$$\sigma_t = \sigma_{el} + \sigma_a + \sigma_{in} = \sigma_{el} + \sigma_{nel}$$

In principle there are the following three different methods for the evaluation of the total inelastic scattering cross section

$$\sigma_{in} = \sum_k \sigma_{in}^{(k)} \qquad (1)$$

$$\sigma_{in} = \sigma_t - \sigma_{el} - \sigma_a \qquad (2)$$

$$\sigma_{in} = \sigma_{nel} - \sigma_a \qquad (3)$$

In the energy region below 1.8 MeV, where the discrete excited levels can be resolved, the partial inelastic scattering cross sections of these levels are measured and method (1) can be used. Thus, the error in the total inelastic scattering cross section derived in this way is determined by the error in the measurements of the individual levels or groups of levels. On the other hand if the inelastic cross section is inferred from methods (2) or (3), the uncertainties in the cross sections σ_t, σ_a, σ_{el} or σ_{nel} determine the uncertainty in the resulting total inelastic cross section. Therefore it has to be decided for each energy region which of the possible methods leads to the smallest uncertainties in the resulting cross section.

It has been shown in an investigation of Smith [6)] that in the energy interval from 50 keV to about 1 MeV the estimated uncertainties of the resulting total inelastic cross section if inferred from the elastic scattering cross section are rather large. This is shown in Fig.3 which is equal to Fig.4 of ref.6. The upper and lower creditable limits deviate by about 25% at 0.8 MeV from the average, ultimately amounting to about 65% at 0.15 MeV. Since in this energy region the discrete excited levels of ^{238}U are well resolved, the uncertainties of method (1) are estimated to be smaller than those of method (2). Because the nonelastic cross section is measured only in the energy region above 2 MeV, method (3) is not possible below 2 MeV, therefore method (1) was chosen for the evaluation of the total inelastic scattering cross section up to 0.8 MeV, which corresponds to the evaluation of Kanda [7)].

Between 1 and 2 MeV error analysis, which is shown in Table 2, does not allow a unique decision between the methods (1) and (2), because the uncertainties in both methods are estimated to be about 15-25%. In this case we consider the results of the neutron spectrum measurements as an independent physical criteria. Although the neutron spectrum measurements cannot reproduce the exact shape of the inelastic cross section, they provide decisive information about its overall behavior. Thus method (2) was chosen because it leads to a cross section which is more similar to that inferred from neutron spectrum measurements [5].

In the energy region between 2 and 5 MeV the method (2) was preferred because the uncertainties of the old nonelastic cross section measurements [1] lead to uncertainties of the resulting cross section of the method (3) which are estimated to be larger or not smaller than those of method (2). The evaluation of the elastic scattering cross section in the energy range from 1 MeV to 5 MeV is based mainly on the new microscopic data of Smith [6]. In the energy range above 6 MeV the nonelastic cross section was evaluated. In addition to the data sets used for the KEDAK-2 evaluation of the nonelastic cross section [1], the data of Voignier [8] were included which are the only data published after 1966. The difference between the previous and the present data for σ_{in} on KEDAK in this energy region is therefore mainly due to the different values of σ_a.

The presently recommended total inelastic cross section is compared with the previous KEDAK-2 evaluation and with the KFK-INR group cross sections in Fig.4. It is appreciably smaller than the former KEDAK-2 evaluation in the energy region from 1 MeV to 6 MeV with a maximum deviation of 60% at about 1.5 MeV and 25-30% above 2 MeV. In this energy region it is also 20-25% lower than the ENDF/B-IV evaluation. A comparison with Fig.3 shows that it is also smaller than the corresponding cross section of Fig.3, this can probably be explained by slightly different values for the cross sections σ_t, σ_a and σ_{el} used in the evaluations. In addition, we took the new data for the elastic scattering cross section from the figures in the paper of A.B.Smith [6], because the exact data were not available to us. Therefore, the presently recommended total inelastic scattering cross section is preliminary.

III. Check of the Evaluated Data

To check the quality of the evaluated data, group cross sections were generated in the well-known ABBN-26 [9] group structure. These group constants were incorporated in the KFK-INR set [3], which is not only based on KEDAK, but rather has been established by investigation of both differential and especially integral physical experiments *. With a few exceptions this set reproduces the experimental k_{eff}-values within a $\pm$ 1% margin (column a) in Table 4), and is therefore used as a nuclear data basis in our calculations. With the modified data basis zero-dimensional calculations were performed for a variety of critical assemblies with different neutron spectra. The bucklings in the zero-dimensional calculations were taken unchanged from the original KFK-INR set.

Table 1 shows the results of zero-dimensional calculations for the criticalities of some critical assemblies if the data basis is modified by the inelastic scattering cross section and the inelastic scattering matrix of KEDAK-2. The strong influence of both the inelastic scattering cross section and the scattering matrix is evident. The inelastic scattering matrix of KEDAK-2 in the energy range from 10.5 to 0.046 MeV is given in Table 5. and that of the KFK-INR set in Table 6. A preliminary inelastic scattering matrix for ^{238}U of KEDAK-3 was generated using partly (up to 4 MeV) the data of Smith [6] and is shown in Table 7.

The probability distributions of these inelastic scattering matrices in the energy range 10.5 - 0.046 MeV (group 1 to group 9) are compared in Fig. 5. The influence of the inelastic scattering probabilities on the criticality of a certain assembly depends on the neutron importance of this critical assembly. It is seen from Fig. 5 that the KEDAK-2 and KEDAK-3 probabilities for scattering into the low energy region (groups 7, 8 and 9) are larger in the mean than that of the KFK-INR scattering matrix. In view of the neutron importance [3] for SNEAK-3A1 in Fig.6 and ZPR-III-55 in Fig.7 it is therefore easy to understand that the criticality of SNEAK-3A1

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* Most of the data included in the KFK-INR set are taken from the original Russian ABBN set or have been derived from KEDAK-data, if available. For some data of essential importance for neutron reactor physics calculations the data based on KEDAK have been modified in order to obtain reasonable agreement between calculated and measured results for benchmark results of experiments in fast critical assemblies.

is increased and that of ZPR-III-55 decreased if the nuclear data basis is modified only by the new scattering matrix (column 4 in Table 3). The columns 5 and 6 of Table 3 show the changes in the k_{eff}-values which result if in the nuclear data basis σ_{in} and the scattering matrix P_{ij} are modified by the KEDAK-3 and by the KEDAK-2 data, respectively. The improvement obtained with the inelastic scattering data of KEDAK-3 is remarkable. It should be noted that with the inelastic cross section the elastic scattering cross section in the used nuclear data basis was correspondingly changed in order to keep the total cross section of the data basis unchanged.

The results given in Table 4 are obtained if not only the inelastic scattering data of ^{238}U are included in the calculations but also the other presently recommended cross sections in the energy region above the resolved resonances, mainly those of ^{238}U and ^{239}Pu. In all cases the $\bar{\nu}$-values have not been replaced in the KFK-INR set. This was done because it was intended to study the cross section effect separately. The present uncertainty in $\bar{\nu}$ is of the order of 1% which leads to almost the same uncertainty in the value of k_{eff}.

It is seen that good agreement between the k_{eff}-values obtained with the KFK-INR set (column 4) and those with the KFK-INR set modified with KEDAK-3 (column 5) is achieved. This is further emphasized by comparison with the results obtained with similar calculations using the KEDAK-2 cross sections (column 7). Really one should perform two-dimensional calculations with all required corrections and compare the results with the experimental criticality $k_{eff} = 1$. By comparing the k_{eff}-values in the columns 3, 4 and 5 one can conclude that by a more exact calculation (corresponding column 3) the criticalities of the assemblies ZPR-III-55, VERA-11A and ZPR-III-48 in column 5 will increase to values between 1 and 0.99 so that in nearly all cases the experimental value is reproduced within about $\pm$ 1%.

IV. Conclusions

In view of the strong influence of the total inelastic scattering cross section of ^{238}U on integral nuclear quantities a precise knowledge of this cross section is desired. But unlike in the case of the total and fission cross sections the uncertainty in the microscopic data and therefore in the evaluation of the inelastic scattering cross section is at present fairly large. The results of integral neutron spectrum measurements indicate that the cross sections which are inferred from the evaluated partial inelastic cross sections may be too large. In the present contribution a preliminary cross section is proposed which is lower than most of the formerly recommended evaluations and leads to acceptable values of k_{eff}. In view of the further on existing large uncertainties the problem cannot be considered to be solved. Rather further experimental and theoretical efforts are necessary to improve the knowledge on this important neutron cross section.

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Table 1

Critical assembly	k_{eff} KFKINR set	k_{eff} KFKINR set modified with σ_{in} of KEDAK-2	% change in k_{eff} if KFKINR set is modified by		
			σ_{in} of KEDAK-2	P_{ij} of KEDAK-2	σ_{in} and P_{ij} of KEDAK-2
SNEAK 3A1	0.995	0.992	- 0.28	0.02	- 0.27
SNEAK 3A2	0.990	0.988	- 0.15	0.04	- 0.11
ZPR III 55	0.995	0.972	- 2.28	- 0.65	- 2.94
ZPR IX 25	0.995	0.960	- 3.55	- 1.15	- 4.69
SNEAK-8	0.999	0.961	- 3.77	- 1.23	- 4.98
SNEAK-7A	1.017	1.015	- 0.21	- 0.06	- 0.28
ZPR III-48	0.976	0.971	- 0.54	- 0.1	- 0.65
SNEAK-2AR1	1.011	1.009	- 0.29	0.02	- 0.27
SNEAK 6A-Z1	1.006	0.999	- 0.75	- 0.19	- 0.96
SNR 300	1.037	1.031	- 0.56	- 0.16	- 0.73

Table 2

Estimated Uncertainties of σ_{in}

Energy region	Primarily evaluated cross section		
	$\sum \sigma_{in}(K)$	σ_{el}	σ_{nel}
50 keV - 1 MeV	± 10 %	± 25 %	-
1 MeV - 2 MeV	± 20 %	+ 15 % - 25 %	-
2 MeV - 6 MeV	-	+ 15 % - 25 %	± 25 %
6 MeV - 15 MeV	-	-	± 30 %

Table 3

Critical assembly	k_{eff} KFKINR set	% change in k_{eff} if KFKINR set is modified by			
		σ_{in} of KEDAK-3	P_{ij} of KEDAK-3	σ_{in} and P_{ij} of KEDAK-3	σ_{in} and P_{ij} of KEDAK-2
SNEAK 3A1	0.995	0.07	0.45	0.51	- 0.27
SNEAK 3A2	0.990	0.04	0.46	0.49	- 0.11
ZPR III 55	0.995	0.5	- 0.53	- 0.03	- 2.94
ZPR IX 25	0.995	0.46	- 1.38	- 0.89	- 4.69
SNEAK-8	0.999	0.49	- 1.44	- 0.91	- 4.98
SNEAK-7A	1.017	0.02	0.02	0.04	- 0.28
ZPR III-48	0.976	0.09	0.07	0.16	- 0.65
SNEAK-2AR1	1.011	0.07	0.47	0.53	- 0.27
SNEAK 6A-Z1	1.006	0.11	- 0.19	- 0.09	- 0.96
SNR 300	1.037	0.08	- 0.19	- 0.11	- 0.73

Table 4

No.	Critical assembly	k_{eff} KFK INR-set a)	k_{eff} KFK INR-set b)	k_{eff} KFK INR-set modified with KEDAK-3 b)	% change in k_{eff} c)	k_{eff} KFK INR-set modified with KEDAK-2 b)	% change in k_{eff} c)
1	SNEAK 3A1	1.004	0.995	0.998	+ 0.30	0.984	- 1.12
2	SNEAK 3A2	1.001	0.990	0.993	+ 0.37	0.980	- 0.92
3	ZPR III 55	1.011	0.995	0.975	- 2.02	0.930	- 6.57
4	ZPR IX 25	0.995	0.995	0.990	- 0.55	0.946	- 4.99
5	SNEAK-8	0.999	0.999	0.994	- 0.51	0.947	- 5.17
6	SNEAK-7A	1.012	1.017	1.007	- 1.0	0.999	- 1.78
7	VERA 11A	1.0064	0.954	0.944	- 0.98	0.946	- 0.76
8	ZPR III-48	1.007	0.976	0.968	- 0.82	0.953	- 2.39
9	SNEAK-2AR1	1.013	1.011	1.015	+ 0.34	1.002	- 0.91
10	SNEAK 6A-Z1	1.007	1.006	0.996	- 1.05	0.979	- 2.70
11	SNR 300	-	1.037	1.025	- 1.17	1.010	- 2.58

a) 2-dimensional calculation with all required corrections, e.g. heterogeneity and transport corrections, (ref. 38)

b) zero-dimensional calculations

c) with respect to zero dimensional calculations with KFK INR-set

Table 5

KEDAK-2 scattering matrix

U 238	$P_{in, h \to h+i}$									
h \ i →	0	1	2	3	4	5	6	7	8	9
1	0.0	0.001	0.02	0.15	0.29	0.31	0.15	0.05	0.017	0.004
2	0.0	0.007	0.09	0.25	0.35	0.20	0.076	0.025	0.006	
3	0.002	0.04	0.19	0.36	0.25	0.11	0.04	0.009		
4	0.032	0.23	0.52	0.20	0.02	0.003	0.0			
5	0.41	0.28	0.20	0.09	0.02	0.002				
6	0.78	0.20	0.01	0.007	0.002					
7	0.66	0.33	0.02	0.0						
8	0.53	0.46	0.004							
9	0.25	0.57								

Table 6

Scattering matrix used in the KFK-INR nuclear data basis

U 238	$P_{in,h \to h+i}$									
h \ i →	0	1	2	3	4	5	6	7	8	9
1	0.0	0.004	0.04	0.16	0.25	0.29	0.17	0.06	0.019	0.008
2	0.0015	0.025	0.16	0.29	0.31	0.15	0.05	0.016	0.004	
3	0.007	0.09	0.25	0.35	0.19	0.08	0.025	0.006		
4	0.035	0.19	0.46	0.23	0.06	0.015	0.0034			
5	0.54	0.23	0.16	0.06	0.014	0.005				
6	0.79	0.19	0.0	0.01	0.006					
7	0.71	0.27	0.02							
8	0.58	0.42	0.0							
9	0.37	0.47	0.16							

Table 7

U 238 KEDAK-3 scattering matrix a) $P_{in,h \to h+i}$										
h \ i	0	1	2	3	4	5	6	7	8	9
1	0.0	0.001	0.02	0.15	0.29	0.31	0.15	0.05	0.017	0.004
2	0.0	0.07	0.09	0.25	0.35	0.20	0.076	0.025	0.006	0.001
3	0.05	0.12	0.29	0.28	0.17	0.07	0.02			
4	0.14	0.20	0.36	0.19	0.07	0.03				
5	0.31	0.23	0.197	0.151	0.064					
6	0.72	0.23	0.012	0.02						
7	0.65	0.33	0.025	0.001						
8	0.47	0.51	0.013							
9	0.15	0.47	0.21							

a) Based on the microscopic data of ref. 6.

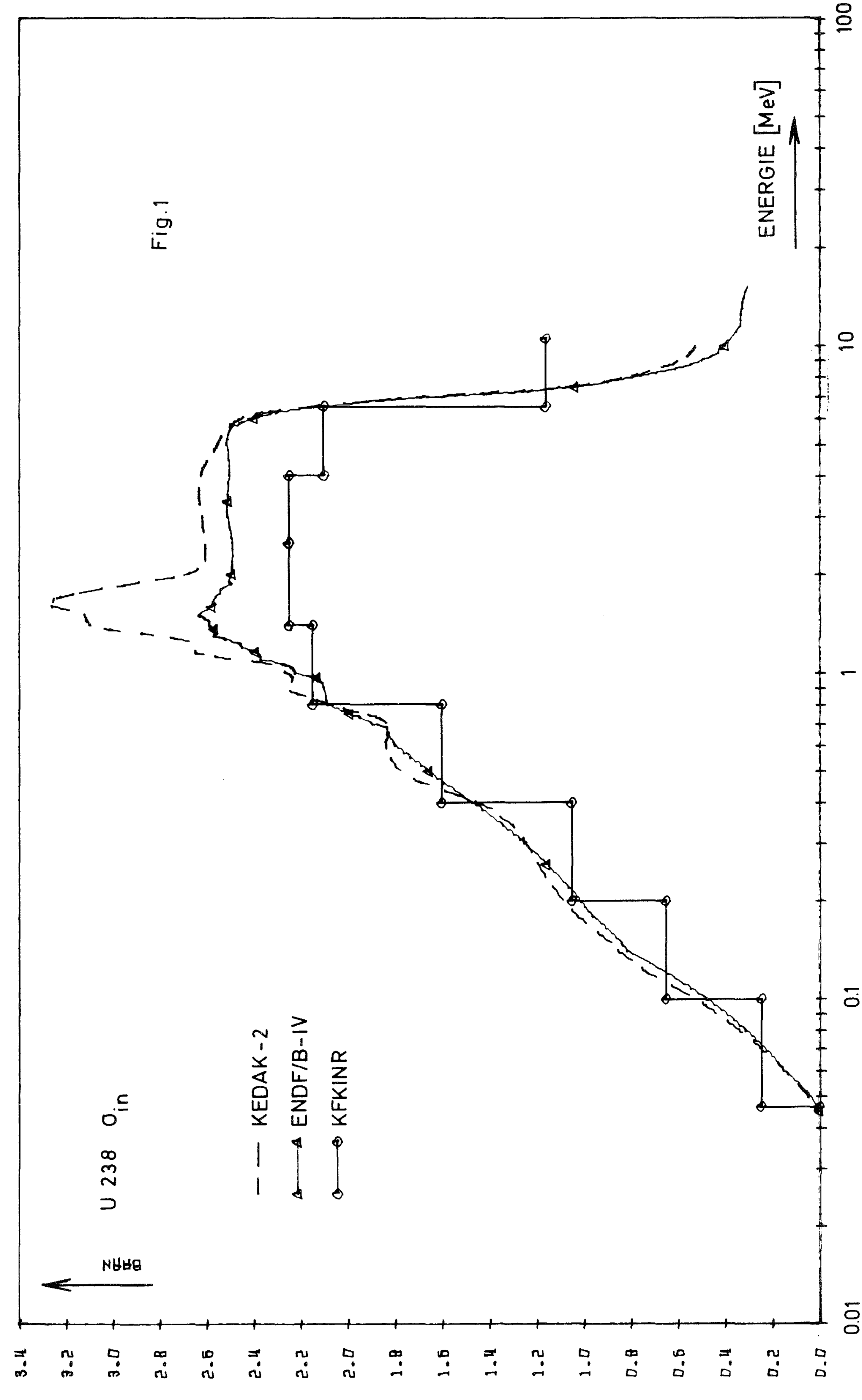
Fig.1
U 238 σin
KEDAK-2
ENDF/B-IV
KFKINR
BARN
ENERGIE [MeV]
0.01
0.1
1
10
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4

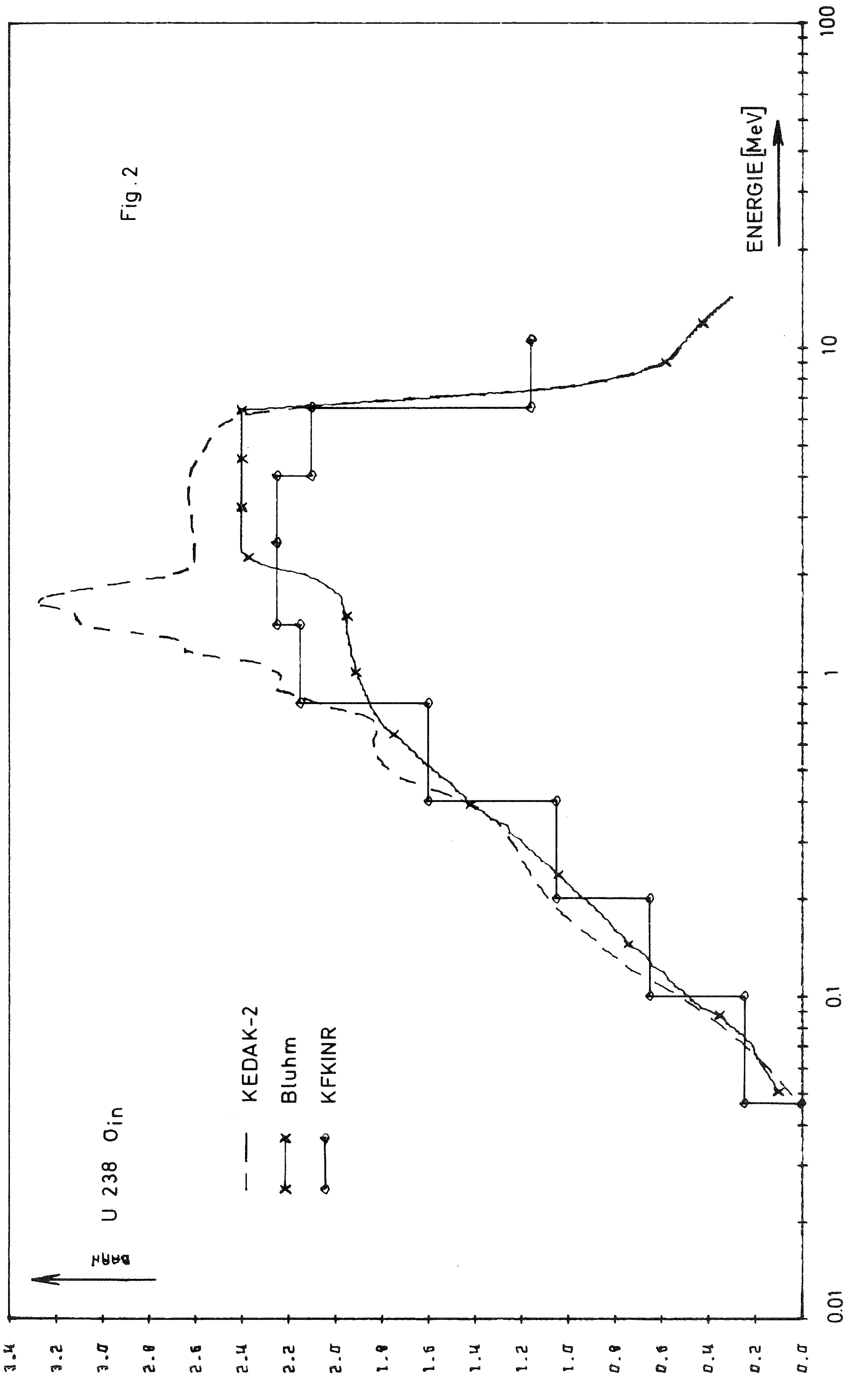
Fig. 2
U 238 σin
KEDAK-2
Bluhm
KFKINR
BARN
ENERGIE [MeV]
0.01
0.1
1
10
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4

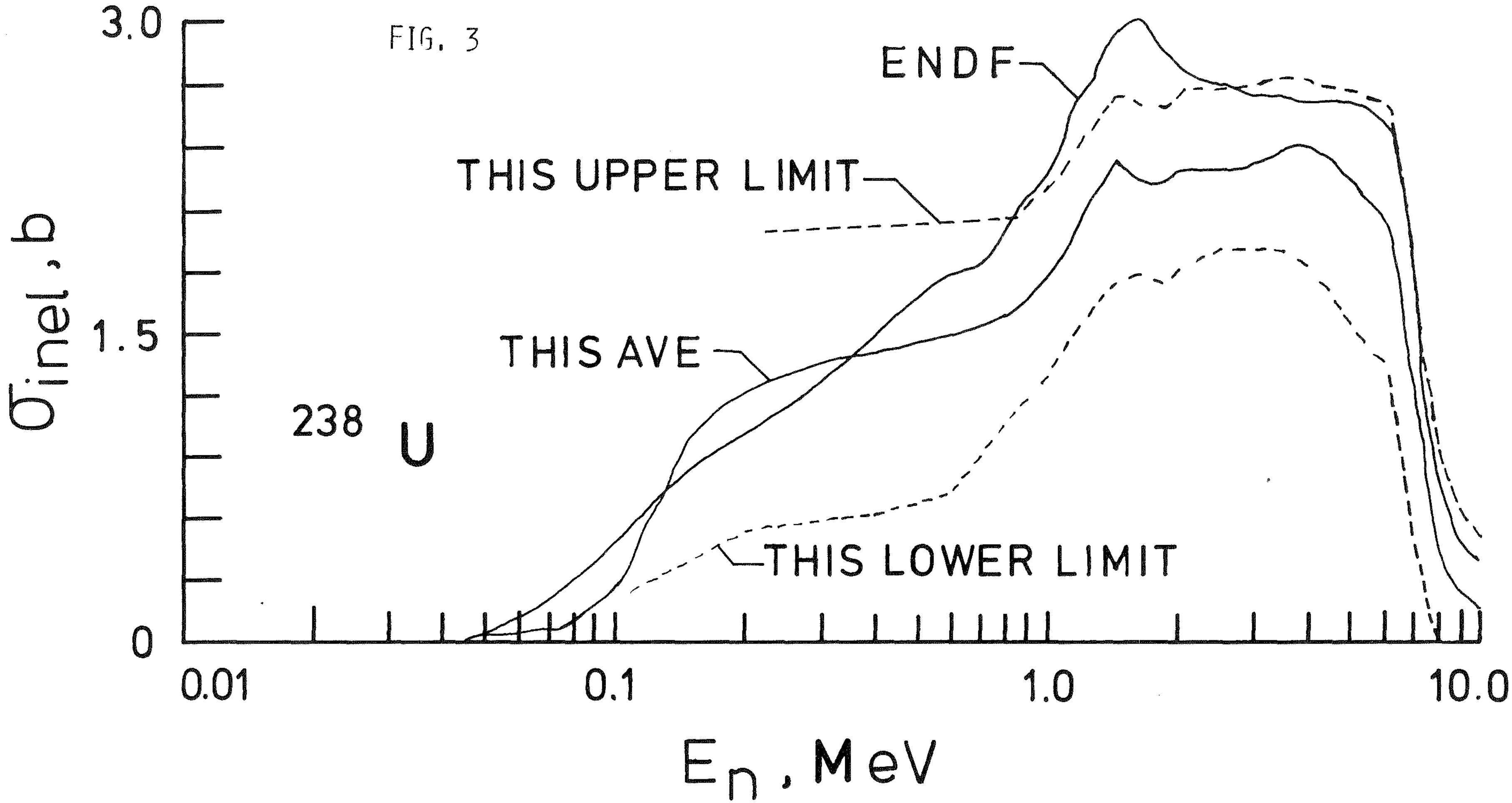
3.0
1.5
0
ENDF
THIS UPPER LIMIT
THIS AVE
THIS LOWER LIMIT
238 U
σinel , b
0.01
0.1
1.0
10.0
En , MeV

FIG. 3

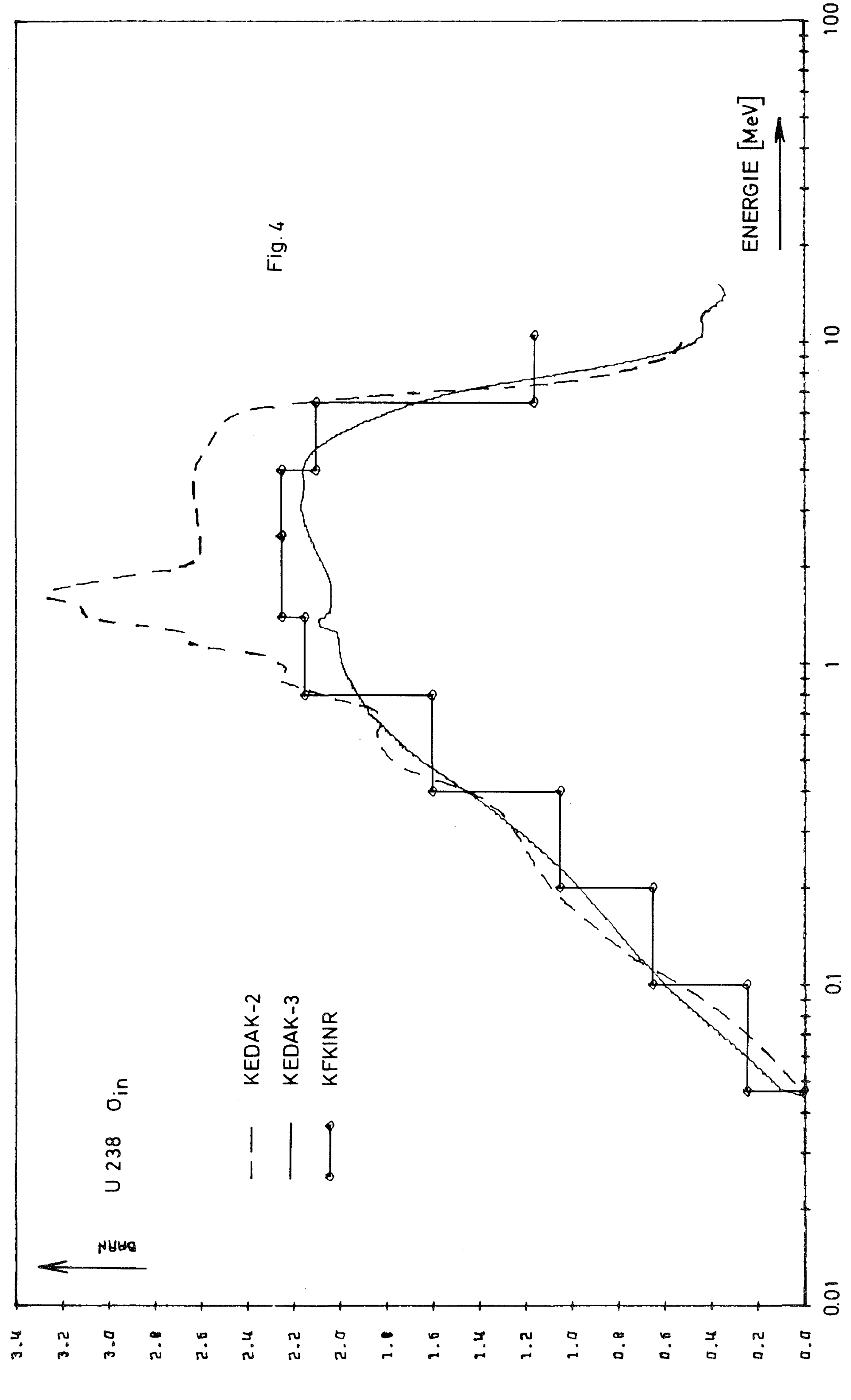
U 238 σin
KEDAK-2
KEDAK-3
KFKINR
BARN
ENERGIE [MeV]
0.01
0.1
1
10
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4

Fig. 4

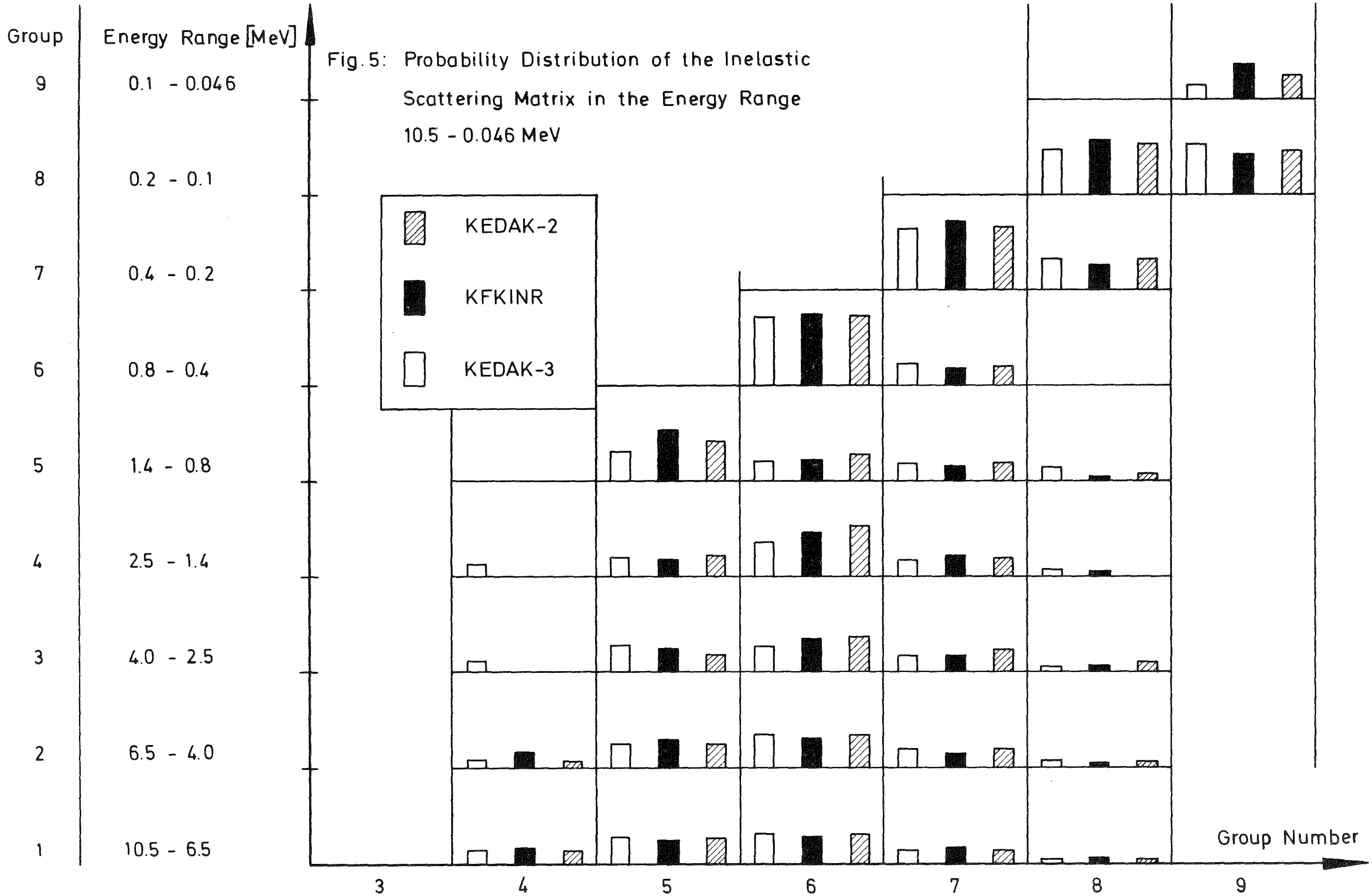

Fig. 5: Probability Distribution of the Inelastic Scattering Matrix in the Energy Range 10.5 - 0.046 MeV

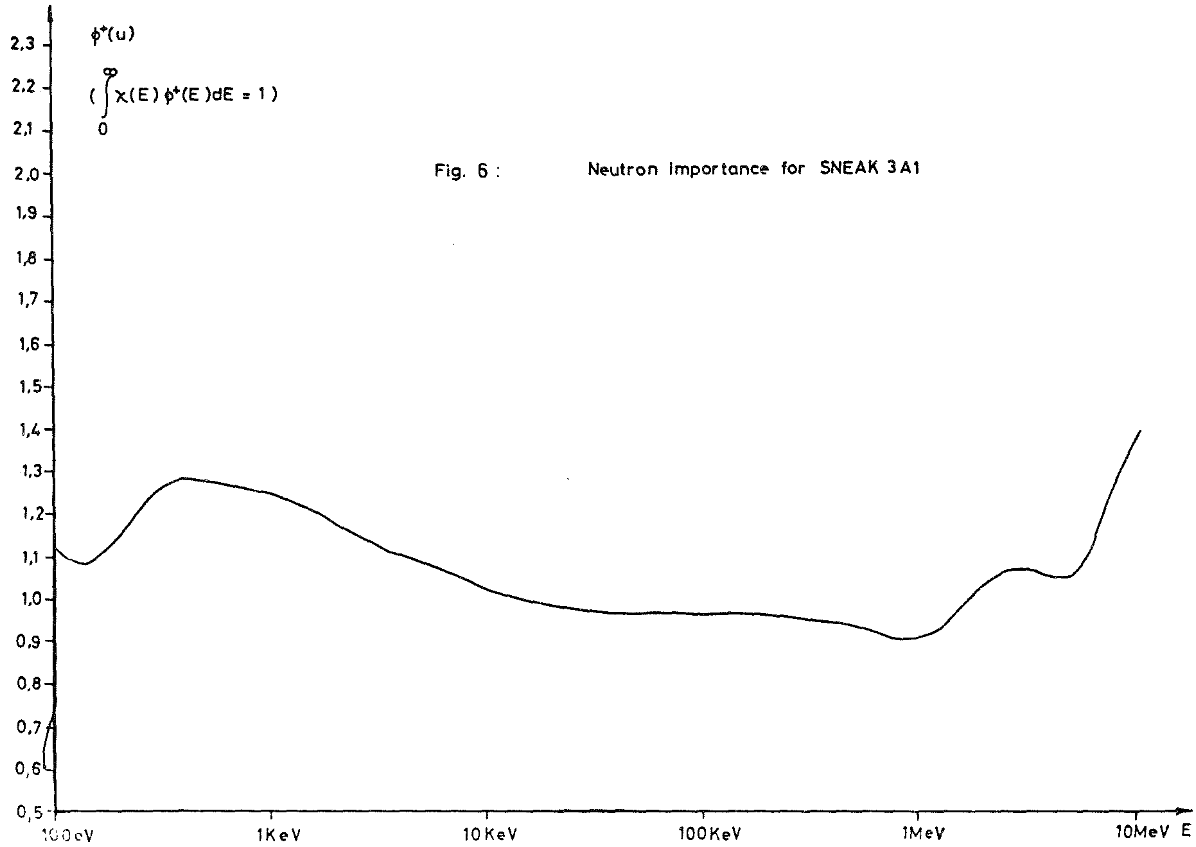

Fig. 6 : Neutron importance for SNEAK 3A1

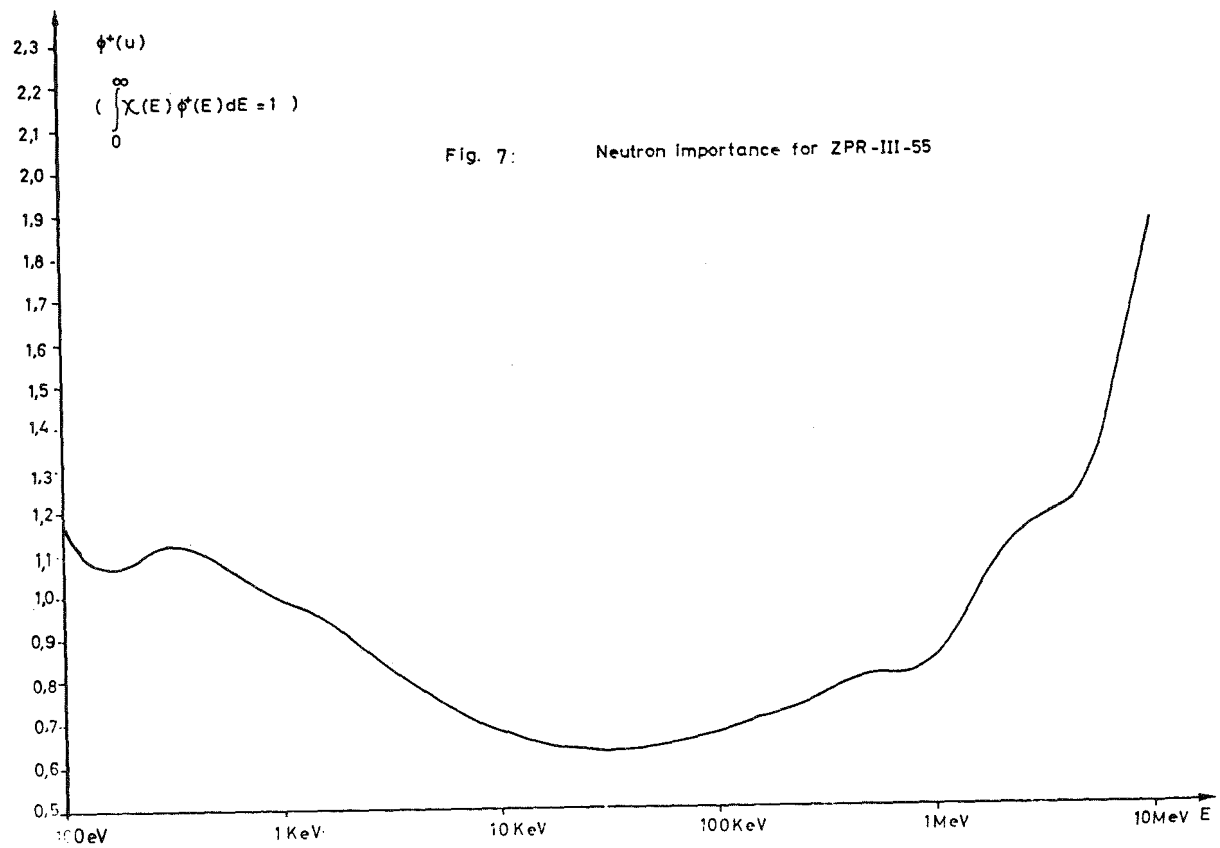

Fig. 7: Neutron importance for ZPR-III-55