A review of the measurements of alpha for Pu-239 in the energy range 100 eV to 1 MeV

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Abstract

A review has been made of the differential measurements of the ratio of the capture to fission cross-sections (alpha) for Pu-239 in the energy range 100 eV to 1 MeV. The methods of measuring alpha are discussed and it is concluded that no detector system used to date is perfect. The history of measurements made prior to 1967 is presented and from this the dangers of relying upon calculations for accurate data can be seen. The alpha measurements in the energy range 100 eV to 30 keV, where the data are most discrepant, are considered in detail and possible sources of error in the measurements are identified. An evaluation covering the energy region 100 eV to 1 MeV is performed using the data available in March 1971 and the recommended values are considered to be accurate to approximately ±10°/o below 30 keV increasing to ±20°/o at 100 keV and ±30°/o at 1 MeV. These recommended values are then compared with the new differential measurements published between March and December 1971 and with integral data and it is concluded that the agreement is satisfactory. A number of recommendations regarding further measurements are summarised in the conclusions.

1. Introduction

At the IAEA experts' meeting on the status of α (Pu-239) data held at Studsvik, Sweden in June 1970, it was recommended that a review of all available alpha data should be written. In this paper, which results from this recommendation, the data on Pu-239 alpha, the ratio of the neutron induced capture ($\sigma_{n\gamma}$) and fission (σ_{nf}) cross-sections, are reviewed in the energy range above 100 eV. We have chosen to neglect the energy range below 100 eV because a review in this energy range cannot be divorced from a detailed discussion of individual resonance parameters and the data at thermal energies have recently been considered in detail(1). It should be remembered from the start, however, that most users of the data would like information on $\sigma_{n\gamma}$ rather than on alpha, but as we will see later experimental considerations make it much easier to measure the latter.

A knowledge of the variation of alpha for Pu-239 as a function of neutron energy is important for a variety of reasons. For instance a knowledge of alpha combined with data on the fission and total cross-sections gives information on resonance parameters and their distributions which are important for nuclear structure considerations. However, the main reason why alpha above 100 eV is so important lies in the development of large dilute oxide fuelled fast reactors. These are attractive for a number of reasons.

(a) They produce power cheaply

(b) They can breed more Pu-239 from the U-238 in the reactor core and blanket than is consumed and hence they increase the world's limited supply of fissile material and

(c) They use Pu-239 which is produced as a by-product in thermal power reactors.

A knowledge of alpha is required in order to be able to calculate the critical size of the reactors and also to be able to predict important quantities like the doppler temperature coefficients, the reactor fuel inventory and the flux distribution across the reactor. However, as has been demonstrated many times it is most important in calculating the breeding gain, G (the number of Pu-239 atoms produced per Pu-239 atom consumed minus 1). The value of alpha directly enters the calculation of G because a neutron captured in Pu-239 is effectively a neutron which cannot be captured in U-238 to breed more fissile material.

Information on alpha can be obtained from integral reactor experiments as well as from differential cross-section measurements and, of course, it is the "integral" value of alpha that the reactor designer wishes to predict. In sodium cooled oxide fuelled power reactors the median energy of neutrons captured in Pu-239 is 20 keV but neutrons with energies as low as a few hundred eV will be important. This means that integral experiments in existing fast power reactors are not particularly useful because their neutron spectra are too hard. Direct integral measurements are difficult in zero energy critical assemblies which have a satisfactory softer spectrum because the half-life of the Pu-240 formed by neutron capture is so long that the activation technique is useless. This means that the Pu-240 content of irradiated samples must be obtained by mass spectrometric techniques and these require irradiations in a high neutron flux unless the starting material has a very low Pu-240 content (a few parts in 10^9). However, even if a suitable direct measurement is made, great care is necessary to interpret the result because the value of alpha obtained is strongly dependent upon the neutron spectrum in the reactor. In this review we are therefore going to concentrate on the differential measurements of alpha, particularly those giving data below 30 keV where there are serious discrepancies.

Differential measurements of alpha for Pu-239 are acknowledged to be difficult to make because the activation method cannot be used and the relatively short α decay half life of Pu-239 makes it difficult to put more than tens of milligrams of material in fission chambers. This has meant that until recently the experimental data have been rather sparse and it was necessary to interpolate using what appeared to be sound theoretical ideas to get values between 100 eV and 30 keV. It was generally realised at the time of the Karlsruhe Conference on Fast Reactor Physics in 1967 that this interpolation could be wrong. The provisional data of Schomberg et al[2] gave values between 1 and 10 keV which were up to a factor of two higher than the values given by typical evaluations based upon interpolations of the old KAPL integral data (e.g. Schmidt[3] and Greebler et al[4]). Such values, however, were not entirely unexpected because similar values had been calculated from total and fission cross-section measurements[5] and the integral measurements by, for instance, Fox et al[6] indicated that α was underestimated in the then current nuclear data sets. The reason for the interpolation being incorrect is now well understood (see for example Patrick and James[7]), following the discovery of intermediate structure in sub-threshold fission by Paya et al[8] and Migneco and Theobald[9].

The history of the discovery that Pu-239 alpha is "high" between 1 and 10 keV is important because it shows the dangers of relying upon theory to determine important parameters. In this review we are therefore going to devote a section to the history of the measurements of Pu-239 alpha in the years before 1967. The remainder of the review will be divided into 9 sections. In the first of these the methods of making differential measurements of alpha will be discussed while the second will be the historical review. In the subsequent two sections the differential data above and below 30 keV available in March 1971 will be discussed. In Section 6 all these data will be evaluated to give recommended values of alpha as a function of neutron energy and these in turn will be compared with data published between March and December 1971. Section 7 will deal with the interpretation of the evaluated alpha values while Section 8 considers the comparison of the evaluated data with the integral information now available. Finally in Section 9 a number of conclusions reached in the review will be summarised.

2. Methods of measuring alpha

The measurements of alpha for Pu-239 that have been made over the years are essentially aimed at obtaining information on the capture cross-section. In the energy region being considered here the partial cross-sections and the total cross-section are related through the formula:

$$\sigma_{nT} = \sigma_{nf} + \sigma_{n\gamma} + \sigma_{nn} + \sigma_{nn'} \qquad (1)$$

where σ_{nT}, σ_{nn} and $\sigma_{nn'}$ are the total, elastic scattering and inelastic scattering cross-section respectively. Therefore one method that can be used to obtain $\sigma_{n\gamma}$ is to measure all the other cross-sections and find $\sigma_{n\gamma}$ by subtraction. In practice σ_{nn} has not been measured accurately and it has to be obtained from the accurately known shape elastic scattering cross-section (σ_{se})[10] and relatively inaccurate calculated values of the compound elastic scattering cross-section (σ_{ce}). The average values of $\sigma_{n\gamma}$ ($<\sigma_{n\gamma}>$) decrease with increasing energy but the average values of σ_{ce} are essentially constant. Hence this method can only give significant data below 1 keV where $<\sigma_{n\gamma}>$ is greater than $<\sigma_{ce}>$.

An alternative method of obtaining $\sigma_{n\gamma}$ is to measure the absorption cross-section $(\sigma_{nA} = \sigma_{n\gamma} + \sigma_{nf})$ and find $\sigma_{n\gamma}$ by subtracting the fission cross-section measured at the same energy. This is usually done by the shell transmission technique which to first order gives σ_{nA} rather than σ_{nT}. The problem with fissile materials is that the transmitted neutrons have to be distinguished from the fission neutrons. Results for Pu-239 have been obtained by this technique in the keV energy range but in general the capture cross-section values obtained have been relatively inaccurate.

Another method of obtaining information about alpha is to measure η, the number of neutrons produced per neutron absorbed. η is related to α through the relationship:

$$\eta = \frac{\bar{\nu}}{1 + \alpha} \qquad (2)$$

where $\bar{\nu}$ is the average number of neutrons per fission. Two different types of measurement have been made which give data in the eV and keV energy ranges respectively. For the low energy range a sample is placed in a neutron beam and the number of fast neutrons produced in the sample is measured. If Y is the number of these detected per incident neutron

$$Y = \epsilon(1 - T)\,\eta\left(1 - \frac{\sigma_{nn} + \sigma_{nn'}}{\sigma_{nT}}\right) + Ms \qquad (3)$$

where ϵ is the efficiency of the detector, T is the sample transmission, Ms is the multiple scattering correction and σ_{nn}, is usually zero. Thus by measuring Y, T and σ_{nT} as a function of neutron energy, η can be determined if Ms can be calculated. Ms is small at the peak of strong resonances in the eV energy range where σ_{nn}/σ_{nT} is small and T can be made zero. At higher neutron energies σ_{nn}/σ_{nT} increases and multiple scattering corrections can be large for Pu-239 if the sample is thick enough for T to be small. As with the first method, errors in σ_{nn} seriously limit the accuracy above a few hundred electron volts.

For the measurements of η in the keV energy range the samples are placed around a neutron source and the fission neutrons produced and the source neutrons transmitted are observed. In these experiments multiple scattering corrections are not too important because the neutrons scattered by the sample, which are later absorbed in the sample, have on average the same η as the neutrons of the source energy. Therefore if it is possible to measure the total number of neutrons which escape from the sample without being absorbed and also the number of fission neutrons produced then η can be obtained. This method cannot be extended to the MeV energy range because of the difficulty of differentiating between source and fission neutrons. The difference in the two types of measurements is basically that with the low energy measurements in the eV range the neutrons absorbed are determined from transmission measurements and a calculated correction is applied for those scattered. In the second method the neutrons scattered are correctly identified as those which are not absorbed. This method could be used in the low energy region with beam geometry if the total number of neutrons scattered from the sample could be determined.

It is usually assumed in η measurements that $\bar{\nu}$ can be assumed to be constant below a few keV; however, recent measurements by Weinstein et al[11] and Ryabov et al[12] have shown that $\bar{\nu}$ for $J^{\pi} = 0^{+}$ resonances differs by 3°/o from that for $J^{\pi} = 1^{+}$ resonances. Unfortunately the measurements are discrepant as Weinstein et al suggest that the 0^{+} resonances have the higher $\bar{\nu}$ while Ryabov et al find the reverse. Data obtained by Weston et al[13], however, suggest there is little difference in $\bar{\nu}$ for the resonances of the two spin states. One can only conclude from this that there is uncertainty particularly in the energy range between 100 eV and 30 keV where there are few measurements and consequently the values of α deduced from η can be seriously in error when α is small. In addition η measurements only give useful data when alpha does not change significantly within the neutron energy resolution of the experiment because the reactor physicist requires the average capture cross-section ($\langle\sigma_{n\gamma}\rangle$) or its ratio to the average fission cross-section ($\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$) rather than average α *. These limitations mean that the

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* In all Sections of the paper except this, α usually means $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$.

beam geometry η experiments can only provide useful data below a few hundred eV while the shell geometry measurements have their greatest accuracy around 30 keV.

All the other experimental methods which have been used to obtain data on the capture cross-section of Pu-239 are direct determinations. Because the half-life of Pu-240 is so long (6,600 y) the activation technique cannot be used in differential measurements and it is necessary to detect neutron capture by observing the prompt gamma-rays emitted as the Pu-240 compound nucleus decays to its ground state. Since the spectrum of these gamma-rays can vary significantly from resonance to resonance it is vital that the efficiency of the gamma ray detector for capture events should be independent of the shape of the spectrum particularly if the capture cross-section is to be measured for or normalised on individual resonances. There are at present essentially three satisfactory types of capture detector:

(a) a large liquid scintillator which has an efficiency of almost 100°/o for any capture event.

(b) a Moxon-Rae detector[14] whose efficiency is proportional to gamma-ray energy and the efficiency for capture events is therefore independent of the form of the γ-ray cascade.

(c) the system proposed by Maier-Leibnitz and described by Macklin and Gibbons[15]. In this system corrections are applied to the pulse height distribution from the detector to give it a Moxon-Rae characteristic.

Using these systems it is not possible to distinguish the capture gamma-rays from those produced in fission and the detectors therefore respond to both fission and capture events. In principle the capture detector can be combined with a fission detector and by using anticoincidence techniques all fission events measured by the capture detector can be identified. In practice experimental considerations have kept the efficiency of fission detectors well below 100°/o and so it has been necessary to perform experiments where both the capture and fission cross-sections or alpha have been determined.

In order to do this it is necessary to use two detectors, one of these being a capture detector and the other a fission detector. Consider these two detectors observing the fission and capture events in the same sample. If N_γ and N_F are the number of counts for a given incident neutron energy or per time-of-flight channel then these are related to the number of fission (n_f) and capture (n_c) events in the sample by the equations

$$N_\gamma = \epsilon_{cf}\, n_f + \epsilon_{cc}\, n_c \qquad (4)$$

$$N_F = \epsilon_{ff}\, n_f + \epsilon_{fc}\, n_c \qquad (5)$$

where ϵ_{cf} and ϵ_{cc} are the efficiencies of the capture detector for fission and capture events respectively and ϵ_{ff} and ϵ_{fc} are the corresponding efficiencies for the fission detector. The values of n_c and n_f depends on the cross-sections through the following relationships:

$$n_c = \phi(1-T) \left\{ \frac{\sigma_{n\gamma}}{\sigma_{nT}} + \frac{\sigma_{nn}}{\sigma_{nT}} \left< (1-T') \frac{\sigma_{n\gamma'}}{\sigma_{nT'}} \right> + \dots \right\} \quad (6)$$

$$n_f = \phi(1-T) \left\{ \frac{\sigma_{nf}}{\sigma_{nT}} + \frac{\sigma_{nn}}{\sigma_{nT}} \left< (1-T') \frac{\sigma_{nf'}}{\sigma_{nT'}} \right> + \dots \right\} \quad (7)$$

where ϕ is the incident neutron flux and T is the transmission of the sample. The triangular brackets denote averages taken over the volume of the sample and over the possible scattering angles and the quantity in these brackets gives the probability of a scattered neutron causing a further reaction; the primed quantities are the values of the cross-sections etc. after scattering. These equations are simplifications as they do not allow for the sample can or impurities in the sample. However, except where there are strong resonances (e.g. at 1 eV in Pu-240 or at 35 keV in Al) these effects can be neglected. Dividing equation (6) by (7) and simplifying we obtain

$$\frac{n_c}{n_f} = \alpha \frac{\left\{ 1 + \frac{\sigma_{nn}}{\sigma_{nT}} \left< (1-T') \frac{\sigma_{nT}}{\sigma_{nT'}} \frac{\alpha'}{\alpha} \frac{\sigma_{nf'}}{\sigma_{nf}} \right> + \dots \right\}}{\left\{ 1 + \frac{\sigma_{nn}}{\sigma_{nT}} \left< (1-T') \frac{\sigma_{nT}}{\sigma_{nT'}} \frac{\sigma_{nf'}}{\sigma_{nf}} \right> + \dots \right\}} \quad (8)$$

where $\alpha = \sigma_{n\gamma}/\sigma_{nf}$ and $\alpha' = \sigma_{n\gamma'}/\sigma_{nf'}$. These equations can be simplified to give

$$\frac{n_c}{n_f} = \alpha S = \frac{A \frac{N_\gamma}{N_F} - 1}{B - C \frac{N_\gamma}{N_F}} \quad (9)$$

where S is the multiple scattering correction and $A = \epsilon_{ff}/\epsilon_{cf}$, $B = \epsilon_{cc}/\epsilon_{cf}$ and $C = \epsilon_{fc}/\epsilon_{cf}$. In the majority of experiments C is zero or very small. These equations show several important features:

(a) Multiple scattering corrections are zero or negligible when either σ_{nn}/σ_{nT} is small, or the sample is thin (i.e. $(1-T')$ is small) or α is constant as a function of neutron energy ($\alpha = \alpha'$).

(b) S is unity on the peaks of the strong resonances below 100 eV because α tends to be a constant through a resonance and σ_{nn}/σ_{nT} is small. Therefore, since α values are known for the resonances, experiments are frequently normalised by determining A, B and C from the values of N_γ/N_f measured for these resonances.

(c) The corrections for scattering (and also self screening) are minimised by measuring α rather than $\sigma_{n\gamma}$.

(d) Errors are minimised if N_γ and N_f are measured with samples of the same thickness.

(e) If ϵ_{fc} is zero and S is unity there is a linear relationship between N_γ/N_f and α.

In practice since the reactor physicist requires $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ rather than the average value of alpha, the corrections are more complex to formulate. However, the features noted in (c), (d) and (e) above still apply. In calculating values of $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ care has to be taken to minimise the effects of self screening particularly in the energy region below 30 keV where most experiments have been performed using pulsed neutron sources with white neutron spectra and the time-of-flight technique. However, if reasonably thin samples are used (e.g. samples of thickness 10^{-3} atoms per barn at neutron energies above 100 eV), multiple scattering corrections can be neglected and reasonable corrections for self screening made if equation (9) is modified so that $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ is given by

$$\frac{\langle\sigma_{n\gamma}\rangle}{\langle\sigma_{nf}\rangle} = \frac{AR - 1}{B - CR} \qquad (10)$$

and R comes from the following equation

$$R = \frac{\sum_{i_1}^{i_2} \dfrac{N_\gamma(i)\ \sigma_{nT}(i)\ \Delta E(i)}{\emptyset(i)\ (1 - T(i))}}{\sum_{i_1}^{i_2} \dfrac{N_F(i)\ \sigma_{nT}(i)\ \Delta E(i)}{\emptyset(i)\ (1 - T(i))}} \qquad (11)$$

Here $N_\gamma(i)$ and $N_f(i)$ are the number of capture and fission counts, $\sigma_{nT}(i)$ is the total cross-section, $\emptyset(i)$ is the incident neutron flux, T(i) is the transmission and $\Delta E(i)$ is the energy interval for the i^{th} timing channel. Timing channels i_1 and i_2 correspond to the energy limits over which the cross-section average is taken. N_γ and N_f must be measured for samples of the same thickness and the neutron energy resolution must be reasonably good over the energy range where the samples are not thin.

In the experiments made using Van de Graaff accelerators in the 10 keV to 1 MeV energy range, the values of the efficiencies (ϵ_{cf}, ϵ_{cc} and ϵ_{ff}) have been found absolutely. For the lower energy experiments in the 100 eV to 30 keV energy range the values of the efficiencies have been found by normalising the experiments in the thermal and/or 5 eV to 100 eV energy ranges. When this is done it is assumed that the efficiencies are independent of neutron energy. This assumption is known to be correct for ϵ_{cc} but there must be doubts about ϵ_{cf} and ϵ_{ff}. ϵ_{cf} depends upon the total energy and spectrum of the prompt gamma rays emitted in fission. These quantities are known only moderately well at thermal neutron energies and there are no data on them at higher energies. The changes in the relative fission gamma-ray yield as a function of fragment mass have been measured[16] and found to be ~50°/o of the variations of the number of neutrons emitted. It follows, therefore, that the experiments normalised below 100 eV could be in error at higher energies where p-wave effects become significant and the mass distributions consequently change. The agreement between the Van de Graaff experiments and the lower energy experiments in the region of 30 keV probably confirms that ϵ_{cf} can be taken as constant. However, this effectively means that the experiments are normalised at 30 keV as well as at low energies and therefore we should give the greatest weight to the Van de Graaff experiments in the energy range above 20 keV.

Consideration of the constancy of ϵ_{ff} as a function of neutron energy depends upon the detector system used for detecting fission events. Essentially three methods have been used

(a) detection of fission fragments (i.e. fission chamber)
(b) detection of the fast neutrons emitted in the fission process and
(c) detection of fission gamma-rays using the "high bias technique".

(The total energy of capture gamma-rays is 6.45 MeV at zero incident neutron energy and if the bias of a large liquid scintillator is set at a significantly higher energy, at say 11 MeV, only fission events will be detected.)

Such a variety of techniques have been used because the high specific α activity of Pu-239 (2.3×10^9 disintegrations per gram per second) makes it extremely difficult to have sufficient fissile material in a fission chamber to enable measurements to be made in the keV energy range. Where a fission chamber has been used[17] in a laboratory experiment its efficiency was low (~50°/o) and it therefore could be sensitive to the known changes in the fission fragment angular distribution in the energy range where p-wave interactions become important. In this experiment the fission chamber was at the centre of a large liquid scintillator and fission events were selected by taking coincidences between the two detectors. It has recently been found by Soleihac et al[18] that under these conditions, coincidences are most likely to occur when the number of neutrons emitted per fission (ν) is large. The reason for this effect is not understood but since ν is large when the total gamma ray energy per fission is likely to be small, it could possibly lead to errors in alpha.

Where the fission events are identified by neutron detection, ϵ_{ff} can vary since $\bar{\nu}$ may depend upon the spin of the resonance[11]. Where measurements have been made, corrections can be applied but it is probable that $\bar{\nu}$ is not known to better than ± 2°/o between 100 eV and 30 keV. If the neutron detectors subtend a small solid angle at the sample ϵ_{ff} can also change with the fission fragment angular distribution. The "high bias" technique selects fission events which have a large total gamma-ray energy. Since we know essentially nothing on how the fission gamma-rays depend upon incident neutron energy, errors in alpha due to variation in ϵ_{ff} are possible. However, where this technique has been used by Gwin et al[17] measurements were also made with the 50°/o efficient fission chamber. Since they agree, this probably suggests that the assumption of ϵ_{ff} being a constant is valid.

As a result of this discussion the following conclusions can be drawn:-

(a) Determinations of the capture cross-section from total, scattering and fission cross-section values lead to reasonably accurate data only below 1 keV.

(b) η measurements only give useful data on α for energies below ~100 eV unless the technique correctly identifies the difference between absorbed and transmitted neutrons.

(c) Where direct measurements of alpha are made it is advisable that the two detectors used should look at the same "thin" sample so that self screening and multiple scattering errors are minimised.

(d) The capture detector used should be insensitive to the changes in capture and fission gamma-ray spectra and in the total energy of fission gamma-rays. It is probable that detectors with Moxon-Rae characteristics are preferable to most large liquid scintillators as far as the changes of gamma-ray spectra are concerned but the situation is reversed when total energy is considered.

(e) The efficiency of the "fission" detector should be insensitive to changes in the fission process. No detector that has been used is perfect but it is probable that errors from the imperfections are in general not significant.

3. Historical Review

Essentially all reactors made in the early years of the world's nuclear energy programmes were thermal reactors; fast reactors were not constructed until the mid-1950s or later. It is not surprising therefore that the first knowledge on α for Pu-239 was confined to the energy range thermal to 0.3 eV. As early as 1947 it was known that relative to U-235 the Pu-239 α values were high in this energy range and a programme of measurements was started at the Knolls Atomic Power Laboratory, USA to see if α was smaller at higher neutron energies. The principal motive of the work was to see if the breeding of fuel might be feasible in an intermediate reactor spectrum (i.e. the motive for α measurements has not changed over the last 25 years!). The results of this programme were reported by Kanne et al[19] in 1955 and subsequently summarised by Sampson and Molino[20] in 1957. Two types of measurement were performed. In the first α was measured by irradiating Pu-239 (48 - 197 ppm Pu-240) in a thermal reactor, under neutron shields designed to give neutron transmissions of 0.33 at 5, 30, 200 and 5000 eV; an unshielded exposure was also performed to check the technique. The numbers of fissions in the samples were measured by the chemical analysis of the fission products and the number of captures by measuring the spontaneous fission rates of Pu-240. The results are given in Table 1.

Table 1

KAPL Foil measurements of α

Cut-off energy (eV)	Median fission energy (eV)	Pu-239 $\sigma_{n\gamma}/\sigma_{nf}$
None	Pile spectrum	0.42±0.08
5	30	0.65±0.14
30	100	0.80±0.17
200	1200	0.60±0.12
5000	15000	0.45±0.08

The values of the median fission energies for the cut-off energies of 200 and 5000 eV have been recently re-evaluated as 1450-1500 eV and 25-30 keV by Barré et al[21]. It has usually been assumed that these KAPL results are equivalent to mono-energetic determinations at the median energy - this is undoubtedly false.

The second set of KAPL measurements were reactivity measurements where effectively $\bar{\nu}$ -1-α was determined. The experiments were made in a preliminary pile assembly and hence are often called the KAPL PPA measurements. As with the KAPL foil measurements the data are associated with a median fission energy and the results are given in Table 2.

Table 2

KAPL PPA Measurements of α

Median fission energy (keV)	α
0.15	0.70±0.10
3	0.53±0.18
225	0.10±0.10

At about the same period, measurements of η and σ_{nA} in the keV region became available. These are summarised in Table 3 and the values of α deduced using up to date values of $\bar{\nu}$ and σ_{nF} are given and are plotted in Fig. 1. The past

Table 3

Values of α deduced from measurements of σ_{nA} and η in the keV energy range made in the years before 1960

Authors	Neutron[+] energy (keV)	σ_{nA} (barns)	η	α deduced	$\bar{\nu}$ [×] assumed	σ_{nf}[*] assumed
Flerov and Polikanov (1954) (22)	24 (30)		2.22±0.16	0.30±0.10	2.884	
Macklin et al (1956) (23)	4.4	4.4 ±0.6		0.83±0.25		2.40
	11.8	3.2 ±0.5		0.69±0.27		1.89
	33.1	1.7 ±0.5		0.08±0.32		1.57
	39.6	2.2 ±0.5		0.47±0.33		1.50
	44.0	2.4 ±0.5		0.61±0.34		1.49
	48.8	2.5 ±0.5		0.68±0.34		1.49
Spivak et al (1956) (24)	24 (30)		2.01±0.05	0.43±0.04	2.884	
	140 (140)		2.35±0.12	0.23±0.06	2.900	
	265 (250)		2.60±0.18	0.12±0.08	2.916	
	265 (250)		2.50±0.11	0.17±0.05	2.916	
	960 (900)		2.57±0.12	0.17±0.06	3.009	
Andreev (1958) (25)	24 (24)		2.17±0.07	0.33±0.04	2.884	
	265 (240)		2.82±0.12	0.03±0.04	2.916	
	960 (880)		3.00±0.19	0.00±0.07	3.009	
	24 (24)	2.56±0.09		0.50±0.05		1.71
	265 (240)	1.89±0.11		0.24±0.07		1.53
	960 (880)	1.79±0.13		0.05±0.08		1.70

+ Energy quoted in original publication is in brackets
* Data taken from evaluation of Hart (26)
× Data taken from evaluation of Mather and Bampton (27)

ten years has seen significant reductions in the recommended values of σ_{nf} in this energy range and so the deduced values of α obtained from these σ_{nA} data have tended to rise. The value of Macklin et al at 4.4 keV gives an alpha which is consistent with the modern values. However, when the experiment was performed a fission cross-section of 3.5 barns was used in the analysis of the data and this gives an alpha of 0.26±0.17 which is more consistent with the KAPL data described above.

Measurements of eta and the total and fission cross-sections were gradually extended to higher energies with improved neutron energy resolution during these years. In 1958 the measurements of Bollinger et al[28] provided the first comprehensive set of s-wave resonance parameters which covered the energy range up to ~50 eV. The partial cross-sections can be calculated at higher energies from the average values and distributions of these parameters; the average partial cross-section $<\sigma_{nx}>$ being given by

$$<\sigma_{nx}> = 2\pi^2 \lambda\!\!\!^{-2} \sum_J \frac{g_J}{D_J} < \frac{\Gamma_n \Gamma_x}{\Gamma} >_J \qquad (12)$$

where $\lambda\!\!\!^{-}$ is the wave length of the incident neutron divided by 2π, g_J is the spin weighting factor, D_J is the level spacing, Γ_n and Γ are the neutron and total widths and Γ_x is the width for the reaction x. The summation is over the possible spin states (J) of the compound nucleus and the triangular brackets represent averages. Now

$$< \frac{\Gamma_n \Gamma_x}{\Gamma} > = R \frac{<\Gamma_n> <\Gamma_x>}{<\Gamma>} \qquad (13)$$

where R is a parameter known as the fluctuation factor which can be calculated from the mean values and distributions of the partial widths. Calculations of the fission and capture cross-section and hence α were undoubtedly made in this period but since the results did not contradict the KAPL data they were not used in the early evaluations of Pu-239 data for fast reactor calculations.

One of the first comprehensive and well documented studies leading to a data set for fast reactor calculation was made by Yiftah et al[29] in 1960 (the YOM set). They adopted, with some reservation, the Pu-239 α-curve of Sampson and Molino[20] shown in Fig. 1 which was largely based on the KAPL data. The data in Table 3 did not contradict the curve and they felt there was little basis for attempting marginal improvement on the earlier analysis. They did, however, recommend that reliable monochromatic measurements would be the real answer to the problem.

The first direct monochromatic measurements of alpha were those of Hopkins and Diven[30] in the energy range above 30 keV. These fixed the shape of the α-curve above 30 keV and the evaluation of Schmidt shown in Fig. 1 was essentially based on the KAPL data at low energies and these data at higher energies. This evaluation of α or ones similar in shape have been in common use until about three years ago when the direct α measurements between 100 eV and 30 keV became available and were accepted.

However, even in the early sixties there was evidence that the KAPL data at 1.2 and 3 keV were too low. Uttley[10] in 1964 made accurate measurements of the Pu-239 total cross-section from 100 eV to 100 keV. From his data he obtained an accurate value of the shape elastic scattering cross-section and he also calculated the compound elastic cross-section. When the resultant absorption cross-section obtained by subtraction was combined with the fission cross-section measurements of James[31] values of alpha greater than 1 in the keV region were obtained. However, Uttley and James noted that $<\sigma_{nf}> \sqrt{E}/S_o$ (S_o is the s-wave strength function and E is the neutron energy) was lower above 600 eV than below. The reason for this was not understood as it can be seen from equation (12) that below 1 keV, where p-wave effects are unimportant, the quantity should be constant. It was therefore felt that the calculation of the compound elastic scattering cross-section might be in error. However, in 1966 Hart[32] produced an evaluation of the Pu-239 cross-sections in which the high α curve of Uttley and James was selected. At the first IAEA Conference on Nuclear Data for Reactors in 1966 there was much discussion, mainly informal, on Pu-239 alpha. There were three important points in the discussion

(a) Was the approach of Uttley and James reasonable or did the change in $<\sigma_{nf}> \sqrt{E}/S_o$ above 600 eV invalidate the method?

(b) If the value of alpha was ~1 in the keV region, then it was not consistent with the resonance parameters measured below 300 eV by Derrien et al[33].

(c) The values calculated from resonance parameters (see the curve of Greebler et al[4] in Fig. 1) were consistent with the KAPL data.

After the Conference, Sowerby and Patrick[5] made an evaluation of α and decided to use the Uttley and James technique. They decided that the fluctuation in $<\sigma_{nf}> \sqrt{E}/S_o$ was unlikely to affect the calculation of σ_{CE} and obtained the curve shown in Fig. 1. This agrees reasonable well with the most recent data and perhaps the lesson to be learned from their evaluation when compared to earlier ones is the importance of making sure that evaluated cross-sections are consistent with the usually accurately measured total cross-section. Other data became available during 1967, e.g. the integral α data of Fox et al[16], which suggested that the earlier evaluated alpha values were too low. The provisional results of the direct measurement by Schomberg et al, which confirmed that alpha in the 1-5 keV region was ~1, were presented at the Karlsruhe Conference on Fast Reactor Physics. Other integral data which supported them were also presented at the same conference and from this an explosion in the number of integral and differential measurements started.

At this point it is important to look back and consider the lessons one can learn from this series of events. Undoubtedly the reason that the KAPL data were accepted as correct in the keV range for so long was that they agreed with the values calculated from resonance parameters. These calculations gave values consistent with the available data above 30 keV and in the resonance region and therefore the calculations could be considered as an interpolation rather than as an extrapolation. The warning that these calculations were suspect lies in the behaviour of $<\sigma_{nf}> \sqrt{E}/S_o$ which would essentially be independent of neutron energy if the calculations were correct. As we will see later the explanation of the behaviour lies in the discovery of intermediate structure in sub-threshold fission by Paya et al [8] and Migneco and Theobald [9]. Since the fission through the channels with spin 1^+ is sub-threshold the assumptions made in the calculations about the mean fission widths of the 1^+ resonances are no longer correct. There are three important points resulting from this discussion.

(a) If it is important to know a quantity accurately, then if possible it must be measured directly and accurately.

(b) Theoretical calculations are only as good as the data they are based upon. Even what appears to be a reasonable calculation can be in serious error if the assumptions made cannot be tested.

(c) Even when a calculation appears to fit the data in two energy ranges, it does <u>not</u> automatically follow that it is correct elsewhere.

4. Alpha measurements in the energy region from 0.1 to 30 keV

During the period 1967 to March 1971 several experimental measurements of the α-values for Pu-239 in the energy region below 30 keV have been published and our knowledge has advanced considerably. Essentially seven different laboratories have contributed to these measurements - Oak Ridge, USA (the measurements of Gwin et al. (17), (34)), Harwell, UK (the measurements of Schomberg et al. (35)), Livermore, USA (the measurements of Czirr and Lindsey (36)), Moscow, USSR (the measurements of Beljaev et al. (37)), Los Alamos, USA (the measurements of Farrell et al. (38)), Dubna and Obninsk, USSR (the measurements of Kononov et al. (39) and Ryabov et al. (40)). All these measurements differ in method and experimental technique as well as in normalization procedure. They can be divided into two groups depending on whether or not fission neutrons were used to identify fission events. The measurements of Schomberg et al., Czirr and Lindsey, Belyaev et al., and Ryabov et al. belong to the first group while the remainder (Gwin et al., Farrell et al. and Kononov et al.) belong to the second group. The first group of measurements is, in principle, subject to a larger uncertainty caused by the spin-dependence uncertainty in $\bar{\nu}$ -values. We have accepted that this uncertainty might be as much as 2°/o in $\bar{\nu}$ and 5°/o in α.

In order to ease the task of the reader we have prepared abstracts for the seven works mentioned above, which are given in the Appendix, where all necessary information such as accuracy, fission and capture detectors, sample details, experimental arrangement, data normalization, corrections and errors, authors' comments and our comments are presented. In this way the reader need not consider details of the experiments unless he wishes to do so. In the present Section the results and the errors are as given by the authors.

(a) Measurements of Gwin et al. (17), (34)

The details of this experiment are given in abstract 1. The first data set for α measured by Gwin et al. was published in reference (17), and the second set which supersedes the first one, is given in reference (34). The main differences between them is that (a), in the latest analysis Gwin uses a different procedure for the normalization of the metal foil data by equating the energy integrals of the neutron fission and capture cross-sections over the energy range from 7.3 to 100 eV to the values derived from the measurements using the ionization chamber, and (b), the time-dependent background in the experiments was interpreted differently.

The latest set of the data for alpha reported by Gwin et al. (34) is given in Table 4. The results were obtained with an 11-gram metal foil up to 30 keV and with a fission chamber up to 4 keV. The two sets are shown separately because except for normalisation the methods used were independent of each other. A comparison of the results, shown in Table 4, obtained for the metal foil with those using the fission chamber indicates agreement within experimental uncertainties.

Table 4

The results for $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$, $\langle\sigma_{nf}\rangle$ and $\langle\sigma_{nA}\rangle$ obtained by Gwin et al. (34)

Energy Interval (keV)	$\langle\sigma_{nA}\rangle$ (barns)		$\langle\sigma_{nf}\rangle$ (barns)		$\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$	
	11 g-foil	Ionisation chamber	11 g-foil	Ionisation chamber	11 g-foil	Ionisation chamber
0.1- 0.2	35.4 ±2.3	36.4±1.8	18.1 ±0.73	18.2 ±0.51	0.96±0.12	1.00±0.15
0.2- 0.3	35.3 ±2.3	35.6±1.8	17.2 ±0.66	17.4 ±0.5	1.06±0.12	1.05±0.15
0.3- 0.4	18.6 ±1.2	18.7±1.3	7.94±0.38	8.3 ±0.27	1.34±0.14	1.25±0.18
0.4- 0.5	13.95±0.9	14.4±1.3	9.42±0.41	9.5 ±0.27	0.48±0.09	0.52±0.10
0.5- 0.6	27.6 ±1.8	27.3±1.7	15.5 ±0.56	15.3 ±0.39	0.78±0.11	0.78±0.13
0.6- 0.7	11.8 ±0.76	12.9±1.4	4.12±0.24	4.4 ±0.17	1.87±0.18	1.93±0.24
0.7- 0.8	11.2 ±0.72	12.3±1.8	5.57±0.26	5.70±0.18	1.00±0.12	1.16±0.17
0.8- 0.9	9.61±0.62	10.4±1.3	4.64±0.23	5.04±0.17	1.07±0.14	1.06±0.16
0.9- 1.0	14.5 ±0.93	16.0±1.4	8.17±0.32	8.50±0.23	0.77±0.10	0.88±0.14
1.0- 2.0	8.23±0.53	9.0±1.3	4.28±0.19	4.36±0.13	0.92±0.12	1.06±0.16
2.0- 3.0				3.33±0.16		1.38
3.0- 4.0				3.12±0.16		1.26
4.0- 5.0	4.44±0.51		2.24±0.15	2.34±0.12	0.98±0.13	
5.0- 6.0	3.98±0.34		2.08±0.14	2.09±0.11	0.91±0.12	
6.0- 7.0	3.81±0.34		2.03±0.14	2.05±0.11	0.88±0.12	
7.0- 8.0	3.57±0.34		2.10±0.16	2.13±0.12	0.71±0.11	
8.0- 9.0	3.49±0.33		2.21±0.17	2.22±0.12	0.58±0.10	
9.0-10.0	3.04±0.29		1.85±0.14	1.88±0.10	0.64±0.11	
10.0-15.0	2.87±0.27		1.82±0.14	1.83±0.10	0.58±0.10	
15.0-20.0	2.61±0.25		1.80±0.14	1.79±0.10	0.45±0.09	
20.0-25.0	2.51±0.24		1.80±0.14	1.78±0.10	0.39±0.09	
25.0-30.0					0.44±0.15	

(b) Measurements of Schomberg et al. (2), (35)

The provisional results of this experiment were given by Schomberg et al. (2) while the final results are given in reference (35). The details of these measurements are given in abstract 2. The latest alpha data set obtained by Schomberg et al. which is given in Table 5 supersedes all the previous data of the same authors. The main differences between the latest data set and the previous ones are in the experimental technique, the experimental conditions used and in the resonance alpha values which have been used for normalization purposes.

Table 5

Values of $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$, $\langle\sigma_{nf}\rangle$ and $\langle\sigma_{nA}\rangle$ obtained by Schomberg et al. (35)

Energy Interval (keV)	$\langle\sigma_{nA}\rangle$ (barns)	$\langle\sigma_{nf}\rangle$ (barns)	$\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$
0.1 - 0.2	36.36±2.40	18.55±0.59	0.96±0.12
0.2 - 0.3	32.99±2.61	18.43±0.58	0.79±0.13
0.3 - 0.4	18.66±1.55	8.76±0.30	1.13±0.16
0.4 - 0.5	14.04±1.17	9.75±0.31	0.44±0.11
0.5 - 0.6	25.56±1.43	15.68±0.50	0.63±0.08
0.6 - 0.7	11.71±0.85	4.80±0.19	1.44±0.15
0.7 - 0.8	10.65±0.79	5.49±0.28	0.94±0.13
0.8 - 0.9	8.23±0.95	5.38±0.19	0.53±0.16
0.9 - 1.0	12.46±0.83	8.04±0.27	0.55±0.09
1.0 - 2.0	7.96±0.57	4.71±0.16	0.69±0.10
2.0 - 3.0	6.59±0.51	3.43±0.13	0.92±0.13
3.0 - 4.0	5.38±0.41	3.11±0.11	0.73±0.12
4.0 - 5.0	4.18±0.30	2.43±0.08	0.72±0.11
5.0 - 6.0			0.80±0.11
6.0 - 7.0	3.43±0.27	2.03±0.07	0.69±0.12
7.0 - 8.0	3.43±0.24	2.16±0.07	0.59±0.10
8.0 - 9.0	3.43±0.23	2.20±0.08	0.56±0.09
9.0 - 10.0	3.12±0.21	1.90±0.06	0.64±0.10
10.0 - 15.0	2.61±0.16	1.72±0.06	0.52±0.08
15.0 - 20.0	2.34±0.13	1.60±0.05	0.46±0.07
20.0 - 25.0	2.26±0.13	1.56±0.05	0.45±0.07
25.0 - 30.0	2.17±0.13	1.62±0.06	0.34±0.06

(c) Measurements of Czirr and Lindsey (36)

The results of the measurements of Czirr and Lindsey are published in reference (36) and details of the measurement are presented in abstract 3. The results are given in Table 6.

Table 6

Values of $<\sigma_{n\gamma}>/<\sigma_{nf}>$, $<\sigma_{nf}>$ and $<\sigma_{nA}>$ obtained by Czirr and Lindsey (36)

Energy Interval (keV)	$<\sigma_{nA}>$ (barns)	$<\sigma_{nf}>$ (barns)	$<\sigma_{n\gamma}>/<\sigma_{nf}>$
0.1 - 0.2	30.6	17.2	0.78±0.05
0.2 - 0.3	32.3	17.4	0.86±0.06
0.3 - 0.4	17.5	8.3	1.11±0.07
0.4 - 0.5	12.8	8.8	0.45±0.03
0.5 - 0.6	23.4	14.2	0.65±0.05
0.6 - 0.7	10.4	4.0	1.60±0.13
0.7 - 0.8	8.6	4.5	0.90±0.08
0.8 - 0.9	8.5	5.2	0.64±0.05
0.9 - 1.0	12.1	7.1	0.70±0.06
1.0 - 2.0	7.8	4.2	0.85±0.07
2.0 - 3.0	6.1	3.0	1.01±0.08
3.0 - 4.0	5.25	2.8	0.88±0.07
4.0 - 5.0	4.25	2.32	0.80±0.07
5.0 - 6.0			0.87±0.08
6.0 - 7.0			0.87±0.08
7.0 - 8.0			0.62±0.07
8.0 - 9.0			0.55±0.06
9.0 - 10.0			0.62±0.07
10.0 - 15.0			0.42±0.05
15.0 - 20.0			0.41±0.05
20.0 - 30.0			0.37±0.04

(d) Measurements of Belyaev et al. (37)

The results of the measurements of Belyaev et al. (37) are given in Table 7, and the details of the measurement are presented in abstract 4.

Table 7

Values of $<\sigma_{n\gamma}>/<\sigma_{nf}>$, $<\sigma_{nf}>$ and $<\sigma_{nA}>$ obtained by Belyaev et al. (37)

Energy Interval (keV)	$<\sigma_{nA}>$ (barns)	$<\sigma_{nf}>$ (barns)	$<\sigma_{n\gamma}>/<\sigma_{nf}>$	$<\sigma_{n\gamma}>/<\sigma_{nf}>$ (NaI and ZnS)	$<\sigma_{n\gamma}>/<\sigma_{nf}>$ (stilbene)
0.1 - 0.2	33.15	17.65	0.88±0.03	0.87±0.03	0.92±0.07
0.2 - 0.3	33.5	16.18	1.07±0.04	1.09±0.04	1.03±0.07
0.3 - 0.4	20.3	9.09	1.23±0.05	1.24±0.06	1.20±0.10
0.4 - 0.5	13.05	9.00	0.45±0.05	0.47±0.05	0.42±0.10
0.5 - 0.6	22.3	12.77	0.75±0.05	0.76±0.06	0.73±0.10
0.6 - 0.7	14.4	5.29	1.72±0.13	1.71±0.15	1.74±0.24
0.7 - 0.8	10.2	5.28	0.94±0.09	0.92±0.10	0.99±0.20
0.8 - 0.9	10.0	5.64	0.78±0.09	0.87±0.11	0.63±0.17
0.9 - 1.0	10.75	6.29	0.71±0.08	0.75±0.09	0.63±0.17
1.0 - 2.0	8.75	4.33	1.02±0.06	1.06±0.07	0.96±0.10
2.0 - 3.0	7.14	3.20	1.23±0.08	1.23±0.09	1.23±0.17
3.0 - 4.0	5.40	2.76	0.96±0.11	0.98±0.13	0.92±0.20
4.0 - 5.0	4.72	2.58	0.83±0.10	0.87±0.11	0.76±0.20
5.0 - 10.0	3.73	2.23	0.67±0.07	0.67±0.08	0.66±0.14

The errors quoted are statistical. An additional error, which is approximately ±5°/o for α values between 0.6 and 1.1, must be added to allow for normalization uncertainties. The $<\sigma_{nf}>$ values are given without corrections for self screening.

(c) Measurements of Farrell et al. (38)

The results of the measurements of Farrell et al. (38) are given in Table 8, and the details of the measurements are presented in abstract 5.

Table 8

Values of $<\sigma_{n\gamma}>/<\sigma_{nf}>$, $<\sigma_{nf}>$ and $<\sigma_{nA}>$ obtained by Farrell et al. (38)

Energy Interval (keV)	$<\sigma_{nA}>$ (barns)	$<\sigma_{nf}>$ (barns)	$<\sigma_{n\gamma}>/<\sigma_{nf}>$
0.1 - 0.2	35.25	21.1	0.67±0.09
0.2 - 0.3	34.40	20.6	0.67±0.09
0.3 - 0.4	18.3	9.43	0.94±0.11
0.4 - 0.5	16.2	10.3	0.57±0.10
0.5 - 0.6	26.6	16.2	0.64±0.11
0.6 - 0.7	12.05	4.50	1.68±0.18
0.7 - 0.8	11.3	6.11	0.85±0.11
0.8 - 0.9	9.7	5.43	0.79±0.11
0.9 - 1.0	14.7	8.67	0.70±0.10
1.0 - 2.0	9.7	4.47	1.17±0.12
2.0 - 3.0	8.0	3.47	1.31±0.13
3.0 - 4.0	6.4	3.28	0.95±0.11
4.0 - 5.0	4.92	2.59	0.90±0.11
5.0 - 6.0	5.0	2.59	0.93±0.11
6.0 - 7.0	4.15	2.23	0.86±0.11
7.0 - 8.0	4.10	2.44	0.68±0.11
8.0 - 9.0	3.92	2.48	0.58±0.10
9.0 - 10.0	3.70	2.11	0.74±0.11
10.0 - 20.0	3.10	1.94	0.60±0.10
20.0 - 30.0	2.74	1.85	0.48±0.09

The errors quoted in Table 8 are standard deviations and include statistics, error in fission gamma subtraction, and estimates of systematic errors due to target density, detector efficiency and solid angle etc.

(f) Measurements of Kononov et al. (39)

The results of the measurements of Kononov et al. (39) are given in Table 9. The details as well as discussion of the measurement are presented in abstract 6.

TABLE 9

Values of $<\sigma_{n\gamma}>/<\sigma_{nf}>$ and $<\sigma_{nf}>$ obtained by Kononov et al. (39)

Energy Interval (keV)	Resolution 15 nsec/m $<\sigma_{n\gamma}>/<\sigma_{nf}>$	Resolution 220 nsec/m $<\sigma_{n\gamma}>/<\sigma_{nf}>$	Resolution 15 nsec/m $<\sigma_{nf}>$ ($\pm 15^{\circ}/o$) (barns)*	Resolution 220 nsec/m $<\sigma_{nf}>$ (barns)*
0.1- 0.2	0.71±0.07	0.73±0.05	21.63	18.94
0.2- 0.3	1.31±0.23	0.72±0.16	17.88	18.39
0.3- 0.4	1.71±0.28	0.82±0.23	7.30	8.77
0.4- 0.5	0.48±0.16	0.60±0.12	12.30	9.38
0.5- 0.6	0.68±0.10	0.70±0.10	18.33	15.61
0.6- 0.7	0.75±0.13	0.92±0.21	7.34	7.32
0.7- 0.8	1.03±0.07	0.70±0.16	6.57	5.34
0.8- 0.9	0.68±0.14	0.63±0.14	7.03	5.68
0.9- 1.0	0.48±0.11	0.65±0.15	10.93	7.16
1.0- 2.0	0.65±0.14	0.78±0.13	5.56	5.01
2.0- 3.0	0.89±0.14	0.83±0.14	3.61	2.91
3.0- 4.0	0.67±0.08	0.77±0.11	3.65	2.95
4.0- 5.0	0.95±0.08	0.71±0.08	2.65	2.36
5.0- 6.0	0.90±0.05	0.65±0.09	2.36	2.20
6.0- 7.0	0.97±0.08	0.59±0.10	2.13	2.18
7.0- 8.0	0.46±0.07	0.44±0.08	2.55	2.39
8.0- 9.1	0.49±0.06	0.43±0.08	2.32	2.26
9.1-10.1	0.43±0.06	0.46±0.09	2.22	2.17
10.1-29.5	0.48±0.10	0.36±0.08		

* The fission cross-section values measured are of illustrative nature only, as σ_{nf} and α-values have been obtained with different normalization.

(g) Measurements of Ryabov et al. (40)

The results of measurements of Ryabov et al. (40) are presented in Table 10 and the details and discussion of the measurement are given in abstract 7.

TABLE 10

Values of $<\sigma_{n\gamma}>/<\sigma_{nf}>$ and $<\sigma_{nf}>$ obtained by Ryabov et al. (40)

Energy Interval (keV)	$<\sigma_{n\gamma}>/<\sigma_{nf}>$	$<\sigma_{nf}>$ (barns)
0.1 - 0.2	0.85±0.11	18.1
0.2 - 0.3	1.00±0.10	17.8
0.3 - 0.4	1.00±0.18	5.8
0.4 - 0.5	0.89±0.09	3.7
0.5 - 0.6	0.84±0.08	16.4
0.6 - 0.7	1.44±0.43	4.6
0.7 - 0.8	1.31±0.13	6.1
0.8 - 0.9	1.15±0.16	6.1
0.9 - 1.0	1.21±0.18	8.5
1.0 - 2.0	1.04±0.13	4.9
2.0 - 3.0	1.09±0.18	3.2
3.0 - 4.0	0.96±0.14	3.1
4.0 - 5.0	0.78±0.05	2.6
5.0 - 6.0	0.82±0.14	1.8
6.0 - 7.0	0.75±0.18	1.9
7.0 - 8.0	0.60±0.17	2.1
8.0 - 9.0	0.50±0.07	2.0
9.0 - 10.0	0.43±0.08	1.8
10.0 - 20.0	0.37±0.05	1.55

5. Results of alpha measurements at energies higher than 20 keV

As in the previous Section, only data published in the period up to March 1971 are considered in this Section. The measurements in this energy range are not as discrepant as those below 30 keV and so the experiments will not be considered in the same detail. Except in the case of η measurements the results and errors will be as given by the authors. For the η measurements the values of $\bar{\nu}$ used to derive α are taken from the recent evaluation of Mather and Bampton (21).

(a) Experiments of Spivak et al. (24)

Measurements of ν_{eff} (= η) were carried out by Spivak et al. with photoneutrons with energies of 24, 140, 265 and 960 keV. They measured neutron absorption and fission neutron production by means of two detectors having different sensitivities for different neutron energy ranges. The measurements were performed with the source alone and then with the source embedded in a plutonium sphere. The experimental results obtained are presented in Table 11.

TABLE 11

The experimental results obtained by Spivak et al. (24)

Neutron Energy (keV)		$\bar{\nu}_{eff} = \eta$	$\bar{\nu}$	α
1st detector	24 keV	2.01±0.05	2.884	0.43±0.04
	140	2.35±0.12	2.900	0.23±0.06
	265	2.60±0.18	2.916	0.12±0.08
2nd detector	265 keV	2.50±0.11	2.916	0.17±0.05
	960	2.57±0.12	3.009	0.17±0.06

(b) Experiments of Andreev (25)

Photoneutrons with energies of 24 keV, 265 keV and 960 keV were used. Andreev used a sphere 1 cm thick and with an internal diameter of 5 cm. The fission detector (ionization chambers with U-235 and U-238) was set up inside and the neutron source outside the sphere. The experimental results obtained are given in Table 12.

TABLE 12

The experimental results obtained by Andreev et al. (25)

Neutron Energy (keV)	η	$\bar{\nu}$	α
24	2.17 ± 0.07	2.884	0.33 ± 0.04
265	2.82 ± 0.12	2.916	0.03 ± 0.04
960	3.00 ± 0.19	3.009	0.00 ± 0.07

(c) Experiments of Hopkins and Diven (30)

The neutrons were obtained with the primary protons being produced by means of the reactions Li-7(p,n) for 30 keV neutrons and T(p,n) for neutrons in the range 60 keV - 1 MeV. Capture or fission events were detected in a large liquid scintillator by means of their prompt gamma rays. Fission was identified by the delayed pulses produced by capture in the scintillator of the fission neutrons. The experimental results obtained by Hopkins and Diven are given in Table 13. The standard deviation for α are a combination of both statistical uncertainties and the uncertainties in the extrapolation of the spectra to zero energy.

TABLE 13

Experimental results obtained by Hopkins and Diven (30)

Neutron Energy (keV)	α
30 ± 10	0.343±0.038
60 ± 15	0.145±0.017
175 ± 25	0.142±0.023
250 ± 50	0.106±0.016
400 ± 90	0.089±0.009
600 ± 76	0.065±0.009
750 ± 70	0.046±0.010
900 ± 63	0.035±0.012
1000 ± 58	0.027±0.007

(d) Experiments of Van'kov and Stavisskii (41)

Photoneutrons of energy 24 keV were used to measure η and σ_{nA}. The detector system consisted of a water tank containing small moveable fission chambers and the neutron source was contained in a 1 m diameter cavity. The changes in count rate were measured at various distances from the source and η and σ_{nA} deduced. The results are presented in Table 14 and it can be seen that the two values of α deduced are discrepant.

TABLE 14

Experimental Results obtained by Van'kov and Stavisskii (41)

η	σ_{nA} (barns)	α	$\bar{\nu}$ assumed	σ_{nf} (barns) assumed
2.15±0.06		0.34±0.04	2.884	
	2.75±0.16	0.61±0.10		1.71

In this evaluation we will only consider the value based upon η as the value of σ_{nA} appears high compared to other data.

(e) Experiments of Lottin et al. (42)

The principle was the same as in the experiments of Hopkins and Diven. A signal recorded by the spherical scintillator (gamma rays and recoil protons) corresponded to a fission event if it was followed by at least one other signal within 30 µsec (capture of a neutron by the gadolinium). The neutrons were produced by means of the reaction Li-7(p,n) with a Van de Graaff accelerator generating the primary proton beam. Below 100 keV a thick target was used and the neutron energies were determined by the time-of-flight method. Above 100 keV they used a thin target and it was possible to obtain monoenergetic neutrons with good resolution. The results of these measurements in the energy region 17 to 600 keV are shown in Table 15. The total error in alpha is given at 30.1 keV, and alpha-values at other energies were normalized to the α-value at 30.1 keV and only the statistical error is given for the other energies. The statistical uncertainty in the alpha value at 30.1 keV was assumed to be 6.5°/o and the systematic uncertainty at this energy was accepted as 7.6°/o, giving the total error of 10°/o at 30.1 keV. For evaluation purposes we have taken the value of 7.6°/o as a systematic error to be added to all the error values given in Table 15 (except at 30.1 keV).

TABLE 15

Alpha-values obtained by Lottin et al. (42)

Neutron Energy (keV)	α	Neutron Energy (keV)	α
17.7	0.395±0.108	38.5	0.253±0.017
18.3	0.490±0.109	40.5	0.226±0.016
18.8	0.443±0.097	42.3	0.246±0.016
19.4	0.442±0.089	44.5	0.244±0.017
20.2±0.6	0.350±0.075	46.7	0.286±0.017
21.0	0.353±0.071	48.5	0.199±0.027
21.7	0.406±0.071	51.0±2.5	0.198±0.028
22.4	0.409±0.048	54.5	0.195±0.030
23.1	0.371±0.040	57.5	0.178±0.032
23.9	0.353±0.036	60.7	0.176±0.025
24.8	0.350±0.034	64.0	0.174±0.022
25.7	0.355±0.030	68.0	0.169±0.021
26.8	0.327±0.027	72.0	0.165±0.020
27.9	0.289±0.025	77.0	0.160±0.021
29.0	0.281±0.023	82.0±5.0	0.172±0.034
30.1±1.2	0.329±0.033	200.0±7.0	0.127±0.008
31.0	0.297±0.020	300.0±6.0	0.116±0.011
32.3	0.303±0.019	400.0±6.0	0.078±0.011
33.8	0.288±0.019	500.0±6.0	0.065±0.005
35.3	0.299±0.019	600.0±5.0	0.035±0.005
37.0	0.228±0.017		

The agreement between these data and those of Hopkins and Diven (30) is satisfactory, but both of these data were obtained by very similar techniques with the net result that there may be some systematic error associated with these measurements.

(f) Experiment of Bandl et al. [43]

The shapes of α and η have been measured in the neutron energy region from 8 to 60 keV. The neutrons were obtained by means of the reaction Li-7(p,n)Be-7 at a Van de Graaff accelerator. The absorption was found by a comparison of the scattered neutrons from the Pu-sample with those from a non-absorbing lead sample. The scattered neutrons were detected by a Li-6 glass scintillator and fission neutrons were simultaneously measured by an organic liquid scintillator with pulse shape discrimination against γ-radiation.

The α-values obtained were normalized to the data of Lottin et al. in the energy region from 40 to 50 keV. The statistical uncertainties in the α-values measured are 5-10$^{o}/o$, systematic uncertainties are about 10$^{o}/o$, and uncertainty due to normalization is about 10$^{o}/o$, giving the total errors of 15-20$^{o}/o$. The α-data obtained by Bandl et al. are given in Table 16.

TABLE 16

Alpha-values obtained by Bandl et al. [43]

Energy Interval (keV)	α(Pu-239)
8-9	0.687
9-10	0.689
10-11	0.617
11-12	0.604
12-13	0.505
13-14	0.539
14-15	0.566
15-16	0.450
16-17	0.381
17-18	0.386
18-19	0.389
19-20	0.388
20.0-22.5	0.354
22.5-25.0	0.304
25.0-27.5	0.287
27.5-30.0	0.284
30.0-35.0	0.291
35.0-40.0	0.280
40.0-45.0	0.244
45.0-50.0	0.236
50.0-60.0	0.218

6. An Evaluation of Alpha

(a) Energy range 100 eV to 30 keV

The evaluation of alpha is best considered in two overlapping energy ranges; 100 eV to 30 keV and 20 keV to 1 MeV. In the energy range from 100 eV to 30 keV there are now a number of measurements which have been discussed in Section 4. The results of these are collected together in Table 17 and plotted in Fig. 2. The data of Bandl et al. and Lottin et al., which overlap the two energy ranges are also considered. It can be seen that the results are not in good agreement and it is the aim of this section of the paper to obtain the best values from the available data.

There are a number of possible reasons why the various low energy experiments may give discrepant results:

(a) the experiments are not all normalized in a consistent manner

(b) the errors in some of the experiments have been underestimated

(c) there are flaws in the experimental techniques used in some of the experiments and

(d) the experiments which use the detection of fast fission neutrons to select fission events will get different answers if $\bar{\nu}$ fluctuates as a function of incident neutron energy.

(i) Normalization

The simplest way to check that the normalizations are consistent is to compare the α-values obtained (or used for normalization) for well resolved resonances below 100 eV. The available results are shown in Table 18 and it can be seen that on the whole the agreement between experiments is reasonably good particularly when one considers all the resonances simultaneously. The normalization of the remaining experiment of Farrell et al. is discussed in the appendix and though we do not have the exact values of the resonance α-values obtained it is our opinion that they are probably consistent with the numbers in Table 18. Therefore, since the differences between the alpha values are much smaller than the differences between the measurements of $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$, we consider that effectively all the experiments are consistently normalised. In virtually all the experiments the normalization is essentially based on the α-values in the thermal energy range. At least two values are required to obtain the values of A and B in equation (10) and though the thermal α value is accurately known (1) the values at other energies are relatively inaccurate and this limits the accuracy to which α can be measured. We consider that this limiting accuracy can be expressed as ~1 % of (1+3.3α) for the α values between 0 and 3, (i.e. ±0.02, 0.043, 0.06 and 0.11 for α = 0.3, 1, 1.5 and 3 respectively).

(ii) Experimental Errors

It is difficult to assess whether or not realistic errors are quoted in the various experiments. At certain energies it looks as if the spread in values is

TABLE 17

Measurements of Alpha belo

Energy Interval (keV)		Gwin et al. (34)		Schomberg et al. (35)	Czirr and Lindsey (36)	Belyaev et al. (37)	Farrell et al. (38)
		Foil	Fission chamber				
0.1	0.2	0.96±0.12	1.00±0.15	0.96±0.12	0.78±0.07	0.88±0.07	0.67±0.09
0.2	0.3	1.06±0.12	1.05±0.15	0.79±0.13	0.86±0.08	1.07±0.08	0.67±0.09
0.3	0.4	1.34±0.14	1.25±0.18	1.13±0.16	1.11±0.10	1.23±0.09	0.94±0.11
0.4	0.5	0.48±0.09	0.52±0.10	0.44±0.11	0.45±0.04	0.45±0.09	0.57±0.10
0.5	0.6	0.78±0.11	0.78±0.13	0.63±0.08	0.65±0.07	0.75±0.09	0.64±0.11
0.6	0.7	1.87±0.18	1.93±0.24	1.44±0.15	1.60±0.17	1.72±0.17	1.68±0.18
0.7	0.8	1.00±0.12	1.16±0.17	0.94±0.13	0.90±0.10	0.94±0.13	0.85±0.11
0.8	0.9	1.07±0.14	1.06±0.16	0.53±0.16	0.64±0.06	0.78±0.13	0.79±0.11
0.9	1.0	0.77±0.10	0.88±0.14	0.55±0.09	0.70±0.08	0.71±0.12	0.70±0.10
1.0	2.0	0.92±0.12	1.06±0.16	0.69±0.10	0.85±0.09	1.02±0.10	1.17±0.12
2.0	3.0		1.38 *	0.92±0.13	1.01±0.10	1.23±0.12	1.31±0.13
3.0	4.0		1.26 *	0.73±0.12	0.88±0.09	0.96±0.15	0.95±0.11
4.0	5.0	0.98±0.13		0.72±0.11	0.80±0.09	0.83±0.14	0.90±0.11
5.0	6.0	0.91±0.12		0.80±0.11	0.87±0.10		0.93±0.11
6.0	7.0	0.88±0.12		0.69±0.12	0.87±0.10		0.86±0.11
7.0	8.0	0.71±0.11		0.59±0.10	0.62±0.08	} 0.67±0.11 (5.0–10.0)	0.68±0.11
8.0	9.0	0.58±0.10		0.56±0.09	0.55±0.07		0.58±0.10
9.0	10.0	0.64±0.11		0.64±0.10	0.62±0.08		0.74±0.10
10.0	15.0	0.58±0.10		0.52±0.08	0.42±0.06		} 0.60±0.10 (10.0–20.0)
15.0	20.0	0.45±0.09		0.46±0.07	0.41±0.06		
20.0	25.0	0.39±0.09		0.45±0.07			
25.0	30.0	0.44±0.15		0.34±0.06	} 0.37±0.05 (20.0–30.0)		} 0.48±0.09 (20.0–30.0)

* Error not given but assumed to be ±0.30 in this evaluation

SECTION 1

TABLE 17

Measurements of Alpha below 30 keV

Czirr and Lindsey (36)	Belyaev et al. (37)	Farrell et al. (38)	Kononov et al. (37) 15 ns/m	Kononov et al. (37) 220 ns/m	Ryabov et al. ([illegible])	Lottin et al. (42)	Bandl et al. ([illegible])
0.78±0.07	0.88±0.07	0.67±0.09	0.71±0.07	0.73±0.05	0.85±0.14		
0.86±0.08	1.07±0.08	0.67±0.09	1.31±0.23	0.72±0.16	1.00±0.14		
1.11±0.10	1.23±0.09	0.94±0.11	1.71±0.28	0.82±0.23	1.00±0.22		
0.45±0.04	0.45±0.09	0.57±0.10	0.48±0.16	0.60±0.12	0.89±0.18		
0.65±0.07	0.75±0.09	0.64±0.11	0.68±0.10	0.70±0.10	0.84±0.12		
1.60±0.17	1.72±0.17	1.68±0.18	0.75±0.13	0.92±0.21	1.44±0.45		
0.90±0.10	0.94±0.13	0.85±0.11	1.03±0.07	0.70±0.16	1.31±0.18		
0.64±0.06	0.78±0.13	0.79±0.11	0.68±0.14	0.63±0.14	1.15±0.20		
0.70±0.08	0.71±0.12	0.70±0.10	0.48±0.11	0.65±0.15	1.21±0.25		
0.85±0.09	1.02±0.10	1.17±0.12	0.65±0.14	0.78±0.13	1.04±0.17		
1.01±0.10	1.23±0.12	1.31±0.13	0.89±0.14	0.83±0.14	1.09±0.21		
0.80±0.09	0.96±0.15	0.95±0.11	0.67±0.08	0.77±0.11	0.96±0.17		
0.80±0.09	0.83±0.14	0.90±0.11	0.95±0.08	0.71±0.08	0.78±0.09		
0.87±0.10	}	0.93±0.11	0.90±0.05	0.65±0.09	0.82±0.18		
0.87±0.10	}	0.86±0.11	0.97±0.08	0.59±0.10	0.75±0.21		
0.62±0.08	} 0.67±0.11	0.68±0.11	0.46±0.07	0.44±0.08	0.60±0.19		
0.55±0.07	}	0.58±0.10	0.49±0.06	0.43±0.08	0.50±0.10		0.726±0.12
0.62±0.08	}	0.74±0.10	0.43±0.05	0.46±0.09	0.43±0.10		0.729±0.12
0.42±0.06		} 0.60±0.10	}	}	}		0.602±0.10
0.41±0.06		}	} 0.48±0.10	} 0.36±0.08	} 0.37±0.07		0.431±0.056
0.37±0.05		} 0.48±0.09	}	}		0.390±0.045	0.360±0.047
						0.332±0.037	0.315±0.041

.30 in this evaluation

SECTION 2

Table 18

Resonance α-values

Resonance Energy (eV)	Gwin et al. (17) (a)	Schomberg et al. (35) (b)	Czirr and Lindsey (36) (a)	Belyaev et al. (37) (a)	Kononov et al (39) (15ns/m and 220 ns/m) and Ryabov et al (40) (b)
7.83	0.85±0.05	0.86±0.04	0.82	0.86±0.03	0.89
10.9	0.27±0.06	0.33±0.03	0.26		0.27
11.9	1.56±0.10	1.52±0.07	1.57		1.66
15.5	0.14±0.06	0.11±0.05			
17.7	1.14±0.06	1.13±0.05	1.04	1.14±0.05	1.01
22.3	0.64±0.04	0.66±0.04	0.63	0.60±0.04	0.67
26.3	0.91±0.05	0.90±0.05	0.88	0.99±0.06	0.87
44.5	9.38±0.70	8.94±0.60	9.79	9.60±0.60	8.36

(a) Values obtained from experiment

(b) Values used for normalisation

greater than expected and so we must now consider if all experiments are equally reliable. If there are flaws in any experiment then its results should be either neglected or down weighted. We have seen from the previous sections of this review that virtually all α measurements below 30 keV essentially consist of the measurement of the number of fissions (N_F) and the number of gamma-ray events (N_γ). The count to background ratios are higher for N_F than N_γ and this means that background uncertainties in N_γ lead to larger errors in α than those in N_F. From the measurements of N_F the values of $<\sigma_{nF}>$ can be obtained and, since the background levels are low, the results from the various experiments should agree when they are consistently normalized. If any experiment disagrees with the general trend then this probably suggests that there are background errors in the measurement. Since similar errors, which will have larger effects on α, will have probably been made in the N_γ measurement we will down weight experiments in the energy ranges where the $<\sigma_{nf}>$ and α data are both discrepant.

In principle before we consider the values of $<\sigma_{nf}>$ some of the measurements require correcting to allow for self screening effects and for the non 1/v behaviour of the B-10(n,α) cross-section. However, we have accepted all measurements without adjustment because we are only interested in discrepancies far larger than the magnitude of the corrections. In order to compare the experiments we have normalized the results to unity between 5 and 10 keV and the data are presented in Table 19. This energy range was chosen because both of the above corrections and the backgrounds in the fission measurements should be small. If one considers large differences (~15°/o or more) from the bulk of the data it appears that the following energy regions are correlated with rather discrepant α values:

Ryabov et al.	0.3 - 0.5 and 0.7 - 2.0 keV
Kononov et al. (15 ns/m)	0.3 - 0.4, 0.6 - 0.7 and 0.8 - 2 keV
Kononov et al. (220 ns/m)	0.6 - 0.7 and 2 - 3 keV

We will therefore down weight these experiments in these energy ranges.

(iii) Possible Flaws in Experimental Technique

In Section 2 it was concluded that the gamma ray detectors used in the experiments should be insensitive to the changes in the capture and fission gamma ray spectra and to the total energy of fission gamma rays. Table 20 summarises the gamma ray detectors used in the various experiments. Moxon-Rae type detectors were used for three experiments and these had a variety of values for the ratio of efficiencies for fission and capture events ($\epsilon_{cf}/\epsilon_{cc}$). (The expected value is ~1-1.3 for a detector with a Moxon-Rae characteristic). Schomberg et al. have shown (35) that their early data taken when $\epsilon_{cf}/\epsilon_{cc}$ ~2.5 are correct (the high ϵ_{cf} is due to enhanced detection of fission events). Belyaev et al. have shown that ϵ_{cc} for their detectors is not sensitive to changes in the capture gamma ray spectra in the resonance

TABLE 19

Comparison of $<\sigma_{nF}>$ data normalised to unity between 5 to 10 keV

Energy (keV)	Gwin et al.	Schomberg et al.	Czirr and Lindsey (a)	Belyaev et al. (a)	Farrell et al.	Kononov et al. 15 ns/m expt.	Kononov et al. 220 ns/m expt.	Ryabov et al. (a)
0.1- 0.2	8.8	8.82	8.1	7.91	8.9	9.34	8.45	9.4
0.2- 0.3	8.4	8.76	8.2	7.26	8.7	7.72	8.21	9.3
0.3- 0.4	3.87	4.16	3.9	4.08	3.98	3.15	3.91	3.0
0.4- 0.5	4.59	4.63	4.2	4.04	4.3	5.31	4.19	1.9
0.5- 0.6	7.6	7.45	6.7	5.73	6.8	7.91	6.97	8.5
0.6- 0.7	2.01	2.28	1.9	2.37	1.90	3.17	3.27	2.4
0.7- 0.8	2.71	2.61	2.1	2.37	2.58	2.84	2.38	3.2
0.8- 0.9	2.26	2.56	2.5	2.53	2.29	3.04	2.54	3.2
0.9- 1.0	3.98	3.82	3.3	2.82	3.66	4.72	3.20	4.4
1.0- 2.0	2.08	2.24	2.0	1.94	1.89	2.40	2.24	2.6
2.0- 3.0		1.63	1.4	1.43	1.46	1.56	1.30	1.7
3.0- 4.0		1.48	1.3	1.24	1.38	1.58	1.32	1.6
4.0- 5.0	1.09	1.15	1.12	1.16	1.09	1.14	1.05	1.4
5.0- 6.0	1.01		} 1.01 (5.0–7.0)	} 1.0 (5.0–10.0)	1.09	1.02	0.98	0.9
6.0- 7.0	0.99	0.96			0.94	0.92	0.97	1.0
7.0- 8.0	1.02	1.03	} 0.99 (7.0–10.0)		1.03	1.10	1.07	1.1
8.0- 9.0	1.08	1.05			1.05	1.00	1.01	1.0
9.0-10.0	0.90	0.90			0.89	0.96	0.97	0.9
10.0-15.0	0.89	0.82	} 0.90 (10.0–20.0)		} 0.82 (10.0–20.0)	} 0.90 (10.0–20.0)		0.8
15.0-20.0	0.88	0.76						0.8
20. -25.	0.88	0.74	} 0.86 (20.–30.)		} 0.78 (20.–30.)	} 0.89 (20.–30.)		
25. -30.		0.77						

(a) Requires correction for self screening

Table 20

Comparison of types of capture detector.

Experiment	Type of Detector	Comment
Gwin et al.	Large liquid scintillator	
Schomberg et al.	Modified Moxon-Rae	$\varepsilon_{cf}/\varepsilon_{cc} \sim 2.5$ for early runs $\sim 1.5 \pm 0.2$ with modified detector
Czirr and Lindsey	Modified Moxon-Rae	$\varepsilon_{cf}/\varepsilon_{cc} = 0.86$
Belyaev et al.	8 x 8 cm NaI or 7 x 5 cm Stilbene	For NaI, γ-rays in range 1-2 MeV only detected
Farrell et al.	Solid State Moxon-Rae	$\varepsilon_{cf}/\varepsilon_{cc} = 1.27 \pm 0.08$
Kononov et al.	500 l large liquid scintillator loaded with boron	Detector divided into 2 halves connected in coincidence
Ryabov et al.	500 l large liquid scintillator loaded with Cd	Probably divided into 2 halves connected in coincidence

region. Of the experiments using large liquid scintillators, two (Kononov et al. and Ryabov et al.) were probably done by taking coincidences between two sections and this could lead to errors. Moreover, liquid scintillators, unless they are very large, are liable to be more sensitive to changes in capture gamma ray spectra than Moxon-Rae detectors. We will accept the data obtained with Moxon-Rae detectors (Schomberg et al., Czirr and Lindsey and Farrell et al.) with reservations because the $\epsilon_{cf}/\epsilon_{cc}$ values are not the same and we do not know which value is correct. The experiment of Gwin et al. is also acceptable but there must be some doubts about the experiments of Belyaev et al., Kononov et al. and Ryabov et al. because of their possible sensitivity to changes in capture and fission gamma ray spectra. The problem of total fission gamma ray energy varying with incident neutron energy was discussed in Section 2 where it was concluded that we could accept ϵ_{cf} as being constant and the experiments correct if we assume that they are essentially normalized at ~30 keV as well as at low energies.

Table 21 shows that the various experiments have used a variety of techniques to measure N_F. We noted above that there may be errors due to the variation in $\bar{\nu}$ as a function of the spin of the compound nucleus. It will be seen later by comparing results of experiments using neutron detection with those using other methods that there is some evidence for significant errors due to this effect. In Section 2 other possible errors associated with the techniques were discussed and it was concluded that, while no detection method was perfect in that it was insensitive to possible changes in the fission process as a function of incident neutron energy, we feel the errors arising from these effects are not in general significant. It is worth noting that at 25 keV ~60°/o of the fissions are produced by p-wave neutrons. This percentage reduces to ~25°/o at 5 keV so it is likely that errors associated with changes in the fission process due to the increase in p-wave interactions will only be significant above 5 keV.

There can in principle be serious errors in a cross-section measurement due to self screening and multiple scattering effects. We have seen earlier that these are minimized by measuring a ratio of cross-sections, such as alpha, under experimental conditions where the two detector systems observe the same "thin" sample. (More detail of the experimental conditions under which the corrections are minimized are given in Section 2). As can be seen from Table 21 all the experiments except those of Farrell et al. and Kononov et al. used a single sample which had acceptable thickness (~10^{-3} atoms/barn). The data of Farrell et al. are probably acceptable because they made corrections for self screening effects and Gwin et al. (64) have shown that with a sample of 5.9×10^{-4} atoms per barn errors of ~2°/o in average cross-section are expected in the resonance region due to multiple scattering. Kononov et al. made corrections for sample thickness when obtaining their normalisation constants but no corrections were made above 100 eV and hence we must down weight their experiments.

It is likely that the most serious errors in the alpha experiments are due to errors in background determination. It is difficult for us to assess the background measurements made in the various experiments mainly because of lack of data but also because each experimental installation tends to have different problems which are only fully understood by the people working there. For example in the Harwell experiments there will be a high constant background due to delayed neutrons - the use of the multiplying neutron source with a multiplication of 10 increases the percentage background produced by the delayed neutrons from the source by the same factor. However, the increased background will be independent of time-of-flight and so can "easily" be determined. Backgrounds which vary as a function of time-of-flight are much more difficult to measure, particularly if they are changing rapidly. Now nearly all the experiments giving data between 0.1 and 10 keV use the time-of-flight technique and therefore in principle a comparison of count to background ratios should tell us a lot. However, because of the considerations mentioned above we need the background divided into its time constant and time dependent components and also wish to have data on the rate of change of background. This information is not available and therefore we have not attempted to assess the background measurements. It seems to us though that if backgrounds are measured using the resonance filter technique then results at energies greater than the highest energy filter (see Table 22) may be suspect. Extrapolation of the measured background to twice the highest filter energy is probably satisfactory but at higher energies we feel that the measurements should be down weighted. We will, therefore, down weight the results of Czirr and Lindsey, Belyaev et al. and Kononov et al. at energies above ~6 keV. Schomberg et al. (35) noted in their paper that their results in the 0.8-3 keV energy range would be particularly sensitive to background errors. We will therefore down weight their results in this energy range.

Errors could arise in the experiments if the delayed gamma rays produced by fission events are recorded as capture events. Walton and Sund (44) have shown that for Pu-239 3.2°/o of fission events produce isomers with half lives of between 3 and 80 µs. The total gamma ray energy produced during the decay of an isomer is always less than 2 MeV. Unfortunately there appears to be little data on delayed gamma rays with half lives less than 3 µsec. However, even if we double the number of isomers produced to 6°/o the errors in alpha are small because the bias of large liquid scintillators is usually set above 2 MeV and the characteristic of Moxon-Rae detectors ensures that the isomer decays are detected with ~1/3 of the efficiency of capture events. Perhaps the most serious effect of the isomers is to produce a time dependent background in the gamma ray detector at high energies. In typical white spectrum time-of-flight measurements approximately 50°/o of the source neutrons do not interact with the moderator round the pulsed neutron source. These fast neutrons produce a large number of fission interactions in the samples and the resulting delayed gamma-rays produce a time dependent background. The effect of this at a given energy is a

Table 21

Comparison of experimental arrangements

Experiment	Fission detector	Gamma-ray detector	Sample Thickness	Nominal time of flight resolution (ns/m)
Gwin et al	Fission chamber Large liquid scintillator High bias technique	Large liquid scintillator Large liquid scintillator	1.4 g Pu-239 in fission chamber Final data from 5.9 x 10^{-4} atoms/barn	>7.1
Schomberg et al	Fast neutron detection in liquid scintillator with P.S.D.	Modified Moxon-Rae	2.9 x 10^{-4} - 4.4 x 10^{-3} atoms/barn. Most data from 0.0012 atoms/barn	7.2
Czirr and Lindsey	Fast neutron detection in liquid scintillator with P.S.D.	Modified Moxon-Rae	4.3 x 10^{-4} atoms/barn	50
Belyaev et al	Fast neutron detection in Stilbene (with P.S.D.) Fast neutron detection in ZnS	Stilbene NaI	2.2 x 10^{-3} atoms/barn	217
Farrell et al	Solid state fission chamber	Moxon-Rae	1.4 x 10^{-6} atoms/barn 8.3 x 10^{-4} and 5.8 x 10^{-3} atoms/barn	>4
Kononov et al 15 ns/m 220 ns/m	Fission chamber	Large liquid scintillator	120 mg of Pu-239 in chamber 7 x 10^{-4} atoms/barn	15 220
Ryabov et al	Fast neutron detection by observing neutrons captured in large liquid scintillator	Large liquid scintillator	2.9 x 10^{-4} - 2.7 x 10^{-3} atoms/barn	60

Table 2.2

Comparison of highest energy resonance filter

Experiment		Highest energy resonance filter
Gwin et al	Fission chamber	35 keV Al
	Foil	35 keV Al
Schomberg et al		35 keV Al
Czirr and Lindsey		2.8 keV Na
Belyaev et al		2.8 keV Na
Farrell et al		Filter technique not used
Kononov et al		2.8 keV Na
Ryabov et al		17.5 keV Ti

function of flight path length, the longest flight paths being the best. Where the flight paths are short it is important to measure the background by the "black resonance technique at as many points as possible so that the background shape can be followed. (Background shapes measured by inserting a lead scatterer instead of Pu-239 would, of course, be in error). We feel that only small errors in α of ± 0.02 or less will be produced by these gamma-rays at energies lower than 30 keV but for high accuracy measurements that may be performed in the future their effects will need careful evaluation.

The values of $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ given in Table 17 are mainly given for 100 eV intervals below 1 keV, 1 keV intervals from 1 to 10 keV and 5 keV or greater intervals above 10 keV. Now there is appreciable structure in $\langle\sigma_{nf}\rangle$ and $\langle\sigma_{n\gamma}\rangle$ due to both resonance fine structure and intermediate structure. Thus if we are to compare average cross-sections from different experiments it is important to recognise that errors in the energy scales of the experiments and differences in neutron energy resolution can make comparisons difficult. We have no evidence that there are problems of energy scale errors but resolution is very significant. In all time-of-flight experiments it is necessary to make a compromise between energy resolution and count rate. Good resolution is required for two purposes (1) to measure the structure in the cross-section and (2) to make good background measurements using the resonance filter technique. We have seen above that for some of the experiments the highest energy resonance filter was (due mainly to resolution limitations) ~3 keV and we plan to down weight these experiments above 6 keV. We must now also decide if some of the results quoted for particular energy intervals should be down weighted because the neutron energy resolution of the experiment is large compared to the energy interval. It is difficult to make a general rule about this but it would seem that the minimum number of resolution widths should be 2 (when ~12°/o of the reactions are produced by neutrons of the wrong energy). On this account we must therefore down weight the results of Belyaev et al. and Kononov et al. (220 ns/m) from 400 eV to 1 keV and above 2 keV and Ryabov et al. and Czirr and Lindsey from 5 keV to 10 keV. One way to overcome the resolution problem is to compare the values of $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ over the intervals 0.1-10, 10-30 and 0.1-30 keV. The results still show a fairly wide spread but agree better than the values over narrow energy intervals suggesting that differences in energy resolution and errors in background over limited energy ranges are responsible for some of the discrepancies.

The data of Kononov et al. are a problem. They performed experiments with good (15 ns/m) and poor (220 ns/m) energy resolution but neither experiment observed the structure visible in the results of other experiments in the 400-700 eV range. Structure is observed in their results on fission cross-sections (see Table 19) and so we must conclude that there are errors in the Kononov et al. $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ data because as we can see from Table 23 the structure can be inferred from measurements of

Table 23

Values of $<\sigma_{n\gamma}>/<\sigma_{nf}>$ deduced from $<\sigma_{nT}>$ and $<\sigma_{nf}>$ data

Energy Interval (keV)		Evaluated $<\sigma_{nT}>$ (barns)	Evaluated $<\sigma_{nf}>$ (barns)	σ_{se} (barns)	σ_{ce} + $\sigma_{nn'}$ (barns)	Total scattering cross-section (barns)	Deduced $\frac{<\sigma_{n\gamma}>}{<\sigma_{nf}>}$	Error in $\frac{<\sigma_{n\gamma}>}{<\sigma_{nf}>}$	Earlier[⁎](..) Calculation scattering cross-section (barns)	Calculated from resonance parameters[+] $<\sigma_{nn}>$ (barns)	Calculated from resonance parameters[+] $\frac{<\sigma_{n\gamma}>}{<\sigma_{nf}>}$
0.1	0.2	49.64	18.95	10.29	4.83	15.12	0.87	.10	15.39	14.08	0.80
0.2	0.3	49.82	18.02	10.29	6.78	17.07	0.82	.14	18.19	15.72	0.89
0.3	0.4	32.52	8.82	10.28	3.75	14.03	1.10	.17	14.04	14.02	0.90
0.4	0.5	25.79	9.48	10.28	1.70	11.98	0.46	.09	12.54	11.47	0.40
0.5	0.6	43.71*	15.36	10.27	8.31	18.58	0.64	.20	18.43	17.94	0.56
0.6	0.7	23.91	4.49	10.27	2.80	13.07	1.41	.23	12.53		
0.7	0.8	23.23	5.63	10.27	2.26	12.53	0.90	.16	12.66		
0.8	0.9	22.10	4.96	10.26	2.39	12.65	0.91	.19	12.60		
0.9	1.0	27.23	8.17	10.26	3.95	14.21	0.59	.18	14.91		
1.0	2.0	21.31	4.27	10.24	2.67	13.91	0.97	.24	13.07		
2.0	3.0	19.31	3.19	10.22	2.64	12.86	1.02	.31	12.98		
3.0	4.0	17.99	2.92	10.20	2.38	12.58	0.85	.30	12.79		
4.0	5.0	17.25	2.30	10.18	2.60	12.78	0.94	.41	12.59		
5.0	6.0	17.50	2.13	10.16	3.04	13.20	1.02	.65	12.47		
6.0	7.0	16.55	1.96	10.13	2.61	12.74	0.95	.51	12.33		
7.0	8.0	15.88	2.07	10.11	2.12	12.23	0.76	.37	12.23		
8.0	9.0	15.77	2.23	10.09	2.14	12.23	0.59	.34	12.13		
9.0	10.0	15.25	1.86	10.07	2.05	12.12	0.68	.41	12.04		
10.0	20.0	14.41	1.74	9.96	1.82	11.78	0.51	.43			
20.0	30.0	13.79	1.61	9.76	1.63	11.39	0.49	.43			

* σ_{nT} data give 40.71 barns - value arbitrarily increased to be more consistent with $<\sigma_{n\gamma}>/<\sigma_{nf}>$ and $<\sigma_{nf}>$

\+ Ribon(45)

⁎ No allowance for inelastic scattering and p-wave contribution

σ_{nT} and σ_{nf}. [The calculation of σ_{ce} and $\sigma_{nn'}$ used in the Table was made to be fairly consistent with evaluated values of $<\sigma_{nT}>$, $<\sigma_{nf}>$ and $<\sigma_{n\gamma}>/<\sigma_{nf}>$. However, it can be seen that the values are in good agreement ($\sim \pm 20$°/o) with an earlier calculation of σ_{ce} and also agree to a similar accuracy with values deduced from recommended resonance parameters.] We therefore propose to neglect the data of Kononov et al.

The possible errors in the various experiments discussed above are gathered together in Table 24. When it is thought that there is no error under a particular heading the letters O.K. are used. The errors of the experiments of Kononov et al. are given even though we propose to neglect the experiment.

(iv) Evaluation and Assessment of Errors

In order to obtain a set of recommended values from all the experimental data we have taken averages by a variety of methods:

(a) Down weighted the experiments as discussed above by adding a ± 5°/o error in quadrature to the authors' errors for every defect given in Table 24 and obtained the weighted average (assuming 1, 2 and 3 defects when the background is extrapolated to 2, 4 and 6 times the energy of the highest energy resonance filter). The value of ± 5°/o was chosen so that roughly four defects will alter the weight of an experiment by a factor 2.

(b) Giving equal weights to all experiments since there must be some doubt that all experimenters have been equally rigorous in their error analyses and our recommended down weighting procedure is subjective.

(c) Obtaining the best $<\sigma_{nA}>$ from the experiment where these values are reliable (Gwin et al., Schomberg et al. and Farrell et al.) by a weighted average and combining these values with evaluated $<\sigma_{nf}>$ data (46). (Most alpha experiments measure σ_{nA} accurately because the capture or gamma ray detectors usually have similar efficiencies for fission and capture events (ϵ_{cf} and ϵ_{cc} in Equation 4). Hence the absorption cross-section is essentially proportional to the count of the capture detector).

The results are given in Table 25. In evaluations (a) and (b) the data of Bandl et al. have been included above 8 keV and in the 20-30 keV range the data of Lottin et al. have been given twice the weight of all the other experiments combined. (The normalizations of these two experiments are discussed later). It can be seen that except between 0.4-0.5 keV and 0.8-0.9 keV the results of evaluations (a) and (b) agree to better than ± 10°/o. Evaluation (c) gives higher results above 1 keV but this is not a significant discrepancy and it is due in the main to the relatively high σ_{nA} values of Farrell et al. It also confirms that the normalizations of the experiments are reasonable because the σ_{nA} and σ_{nf} data are virtually independent of the normalization of alpha.

Table 24

Summary of possible errors in experiments

Experiment	Normalisation	Comparison of $<\sigma_{nF}>$	Performance of γ-ray detector	Performance of fission detectors	Detectors observe single sample	Background and high energy resonance filter	Neutron energy resolution
Gwin et al	O.K.	O.K.	O.K.	O.K.*	O.K.	O.K.	O.K.
Schomberg et al	O.K.	O.K.	Down weight	O.K.*	O.K.	Down weight 0.8-3 keV	O.K.
Czirr and Lindsey	O.K.	O.K.	Down weight	O.K.*	O.K.	Down weight >6keV	Down weight 5-10 keV
Belyaev et al	O.K.	O.K.	Down weight	O.K.*	O.K.	Down weight >6keV	Down weight 0.4-1 and >2keV
Farrell et al	O.K.	O.K.	Down weight	O.K.*	O.K.?	O.K.	O.K.
Kononov et al + (15 ns/m)	O.K.	Down weight 0.3-0.4, 0.6-0.7 and 0.8-2keV	Down weight	O.K.*	Down weight	Down weight >6keV	O.K.
Kononov et al + (220 ns/m)	O.K.	Down weight 0.6-0.7, and 2-3 keV	Down weight	O.K.*	Down weight	Down weight >6keV	Down weight 0.4-1 and >2keV
Ryabov et al	O.K.	Down weight 0.3-0.5, and 0.7-2keV	Down weight	O.K.*	O.K.	O.K.	Down weight 5-10keV

* All possibly slightly suspect above 10 keV

+ These experiments are neglected - see text

Table 25

Evaluated $<\sigma_{n\gamma}>/<\sigma_{nf}>$ data below 30 keV+

Energy Interval (keV)		Evaluation (a) (Weighted average)	Evaluation (b) (Equal weights*)	Evaluation (c) (From σ_{nA} and σ_{nf})	Evaluation type (b)	
					Experiments dependent on $\bar{\nu}$	Experiments independent of $\bar{\nu}$
0.1	0.2	0.845	0.871	0.89	0.868	0.876
0.2	0.3	0.912	0.929	0.92	0.930	0.927
0.3	0.4	1.150	1.143	1.09	1.118	1.177
0.4	0.5	0.483	0.543	0.51	0.558	0.523
0.5	0.6	0.704	0.724	0.72	0.718	0.733
0.6	0.7	1.673	1.669	1.65	1.550	1.827
0.7	0.8	0.973	1.014	0.97	1.023	1.003
0.8	0.9	0.778	0.860	0.89	0.775	0.973
0.9	1.0	0.717	0.789	0.70	0.792	0.783
1.0	2.0	0.927	0.964	0.96	0.900	1.050
2.0	3.0	1.108	1.136	1.23	1.062	1.333
3.0	4.0	0.895	0.929	0.97	0.883	1.053
4.0	5.0	0.821	0.835	0.88	0.783	0.940
5.0	6.0	0.867	0.860	0.92	0.833	0.920
6.0	7.0	0.816	0.804	0.86	0.772	0.870
7.0	8.0	0.629	0.635	0.73	0.605	0.695
8.0	9.0	0.575	0.576	0.59	0.539	0.580
9.0	10.0	0.617	0.625	0.72	0.565	0.690
10.0	15.0	0.509	0.528	0.51	0.441	0.616
15.0	20.0	0.419	0.439		0.410	0.487
20.0	25.0	0.402	0.404	0.46	0.436	0.421
25.0	30.0	0.347	0.355		0.329	0.475

* Gwin et al data obtained with ionisation chamber given half weight from 2-4 keV

\+ Neglecting the data of Kononov et al.

Also given in Table 25 are the results of evaluations of type (b) where those experiments sensitive to $\bar{\nu}$ variations are considered separately from the others. It can be seen that above 0.6 keV there are appreciable differences between the two types of experiments and hence we might suspect that changes in $\bar{\nu}$ as a function of neutron energy are responsible for this. However, if this is true one would expect that the shapes of the fission cross-section data of Gwin et al. and Schomberg et al. would be different. Careful examination of their data after correcting the former for the non 1/v energy dependence of the B-10(n,α) reaction shows that below 10 keV the agreement is very good while above 10 keV the differences are not significant. The errors in the two sets of alpha values are difficult to assess but we feel that for alpha values ~0.9 and for comparison purposes they are ~ ±0.07 and ~ ±0.09 for the $\bar{\nu}$ dependent and independent experiments respectively. Therefore the differences in $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ are probably not significant at the present time and we shall assume that the results of all the experiments can be combined together. However, we cannot rule out that $\bar{\nu}$ is varying in this energy range and since there are virtually no measurements, more are urgently required.

We consider that the best set of alpha data are obtained from evaluation (a). Giving equal weight to each experiment has its attractions but it must be better to rely upon the errors quoted by the different authors even though in certain cases they may be underestimated. It is difficult to assess the errors in our recommended curve because the errors in the experiments are mainly systematic. It has been seen earlier that, due to normalization errors and errors caused by delayed fission gamma rays, uncertainties of ±0.01 (1+3.33α) and ±0.02 can be expected. These are systematic errors and they set an upper limit to the accuracy that can be achieved. There are other systematic errors such as the energy dependence of $\bar{\nu}$, the variation of total fission gamma ray energy and the sensitivity of capture detectors to changes with neutron energy of the capture gamma ray spectra. These are difficult to assess, particularly since the various experiments are sensitive by differing amounts to the errors. However, we feel that the systematic errors in the evaluated numbers are not too large since the low energy measurements which are normalised in the resonance region agree with the higher energy data at 30 keV and we estimate that a systematic error of ±5°/o in alpha will cover these effects. The main error in all the alpha measurements is probably due to background uncertainties and these errors are probably random between experiments. Therefore it is reasonable to estimate the random errors in the weighted mean values of $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ by normal statistical methods and obtain the total errors by combining these in quadrature with the systematic errors discussed above. The resultant errors are given in Table 26 and it can be seen that the values are typically ±10-12°/o. The errors quoted are essentially arbitrary but they do not appear unreasonable when one considers the differences between the experiments.

Table 26

Errors in Evaluated $<\sigma_{n\gamma}>/<\sigma_{nf}>$ data below 30 keV

Energy Interval (keV)		Systematic Errors				Error in weighted mean	Evaluated $\frac{<\sigma_{n\gamma}>}{<\sigma_{nf}>}$	Total Error in $\frac{<\sigma_{n\gamma}>}{<\sigma_{nf}>}$
		Delayed Fission γ-rays	Normalisation [.01(1+3.33a)]	Other Errors	Total Systematic			
.1	.2	.03	.04	.04	.064	0.042	0.845	.077
.2	.3	.03	.04	.05	.071	0.061	0.912	.094
.3	.4	.03	.05	.06	.084	0.053	1.150	.099
.4	.5	.03	.03	.02	.047	0.033	0.483	.058
.5	.6	.03	.03	.04	.058	0.037	0.704	.069
.6	.7	.03	.07	.08	.108	0.078	1.673	.133
.7	.8	.03	.04	.05	.071	0.051	0.973	.087
.8	.9	.03	.04	.04	.064	0.078	0.778	.101
.9	1.0	.03	.03	.04	.058	0.051	0.717	.077
1.0	2.0	.03	.04	.05	.071	0.060	0.927	.093
2.0	3.0	.03	.05	.05	.078	0.068	1.108	.103
3.0	4.0	.03	.04	.04	.064	0.057	0.895	.086
4.0	5.0	.03	.04	.04	.064	0.046	0.821	.079
5.0	6.0	.03	.04	.04	.064	0.055	0.867	.084
6.0	7.0	.03	.04	.04	.064	0.057	0.816	.086
7.0	8.0	.03	.03	.03	.052	0.050	0.629	.073
8.0	9.0	.03	.03	.03	.052	0.038	0.575	.064
9.0	10.0	.03	.03	.03	.052	0.041	0.617	.067
10.0	15.0	.03	.03	.02	.047	0.038	0.509	.060
15.0	20.0	.03	.02	.02	.041	0.031	0.419	.051
20.0	25.0)	Evaluation primarily based on Lottin et al data					0.402	.046
25.0	30.0)						0.347	.038

It is important to compare the evaluated data with other information which is available. Values of $<\sigma_{n\gamma}>/<\sigma_{nf}>$ can be obtained from $<\sigma_{nf}>$ and $<\sigma_{nT}>$ data. As discussed in Section 2 this method only leads to significant data below 1 keV and it can be seen by comparing the values deduced in Table 23 that the results are not inconsistent. It is also found, by renormalizing the values of $<\sigma_{n\gamma}>/<\sigma_{nf}>$ obtained in 100 eV energy intervals above 1 keV by Schomberg et al. to the evaluated curve, that the value of 1.26±0.32 obtained by Simpson et al. (41) at 2 keV with the scandium filtered beam agrees well with our recommended curve. Thus we can conclude that all available data are consistent with our curve.

(b) <u>Energy range 20 keV to 1 MeV</u>

For the evaluation of α in the region from 20 keV to 1 MeV we have accepted two main data sets in this energy region: The data of Lottin et al. (42) and the data of Hopkins and Diven (30). The data of Bandl et al. (43) as well as the photoneutron measurements of Spivak et al. (24), Andreev (25) and Van'kov and Stavisskii (41) were also included in the analysis.

The data of Lottin et al. had originally been normalized at one energy point only - at 30.1±1.2 keV (α = 0.329). In the experiment of Hopkins and Diven the α-values were measured absolutely at each neutron energy. For evaluation purposes we renormalized the data of Lottin et al. to the mean α-value at 30±10 keV obtained from their own measurements and that of Hopkins and Diven. The mean α-value obtained was 0.326 at 30±10 keV (the Lottin et al. α-value is 0.309 for 30±10 keV, and the renormalization coefficient for the Lottin data was 1.053). The data of Bandl et al., who measured η, were also renormalized in the energy region from 20 to 40 keV, using the formula: $(1 + \alpha_{revised}) = (1 + \alpha_{original}) \cdot 1.326/1.296$. The data of Hopkins and Diven were taken in their original form.

The first experimental points of Spivak et al. and Andreev and the value of Van'kov and Stavisskii were considered as applying to an energy of 24 keV which is a compromise between the most recent measurements of Lalovic and Werle (48), who determined the average neutron energy of the first group from the Sb/Be-source as 26.0±1.3 keV, Schmitt's (49) measurement of 24.8±2.4 keV and the result of Ryves and Beale (50) of 22.8±1.0 keV. The mean α-value from the measurements of Spivak et al., Andreev and Van'kov and Stavisskii is 0.37±0.03 which agrees very well with the renormalized α-value of De Saussure et al. ($\bar{\alpha}$ = 0.37 at 24-26 keV). Their α-values at other energies have low accuracy, because they have been obtained as the difference between two nearly identical values of $\bar{\nu}$ and η. Nevertheless, we have used the α values obtained by Spivak et al. at two more energy points - 140 and 265 keV - and renormalized them to the mean α-value of Spivak et al., Andreev and Van'kov and Stavisskii at 24-26 keV. For the energy of 265 keV the α-values obtained by Spivak with two detectors were averaged, and the α-value at 960 keV was not included in the analysis due to disagreement with the superior Van de Graaff measurements.

The data accepted for the evaluation in the region from 20 keV to 1 MeV are shown in Figs. 3 and 4. The "best curve" through the data was determined by using a weighted least-squares orthogonal polynomial fitting programme (51) which incorporates a statistical analysis of the fitted curve, enabling statistical confidence limits to be assigned to each point on the fitted curve. The weight assigned to each experimental point for α was taken as proportional to the inverse square of the total relative error. The errors shown in Figs. 3 and 4 represent the total errors which are a combination of statistical and systematic uncertainties. For the data of Lottin et al. a systematic uncertainty of about 8°/o was added to the data presented in Table 15 to allow for normalization errors, giving a total error of about 10-20°/o; for Hopkins and Diven data the total uncertainty is about 10-15°/o, and for Bandl et al. data the total error is about 15-20°/o with a systematic component of about 15°/o.

The evaluated α-values obtained are given in Table 27. The evaluations of the low and high energy regions overlap from 20-30 keV and as might be expected the results are in excellent agreement. For our evaluated curve we will take the values between 20 and 30 keV from the higher energy evaluation. Above 20 keV the evaluation is essentially based on the measurements of Lottin et al. and Hopkins and Diven and since these use essentially the same method it is possible that there are common systematic errors. It is obviously very important that further measurements by alternative techniques should be made in this region.

(c) Comparison of evaluation with recent data

In this section we will compare our evaluated data with the results of Gwin et al. (52), Kononov et al. (53) and Bergman et al. (54) which became available in the period March to December 1971 and so were too late to be included in the evaluation.

The measurements of Gwin et al. are a continuation of those reported earlier (34). They were performed using a pulsed source of neutrons produced by a different accelerator (ORELA) using a fission chamber in the centre of a new large liquid scintillator. The experiments are basically the same as the fission chamber measurements of the earlier series though in this case absorption events were only recorded when there was a coincidence between the two optically divided sections of the large liquid scintillator. The preliminary results, which cover the energy range up to 400 keV, are compared in Fig. 5 with our evaluated curve and it can be seen that the agreement is fairly good particularly in the important region above 5 keV. The agreement above 40 keV is important as these data have been measured using a different technique to that adopted in the accurate measurements of Hopkins and Diven and Lottin et al. who have high weight in the evaluation. At low energies the new Gwin et al. data have a tendency to be higher than the evaluation and to be similar to the original Gwin et al. data (34).

Table 27

(a)

Evaluated α-values for Pu-239 in the energy region above 20 keV

$\bar{E}_n$, keV	α
20 - 25	0.395 ± 0.046
25 - 30	0.350 ± 0.038
30 - 35	0.312 ± 0.034
35 - 40	0.280 ± 0.030
40 - 45	0.252 ± 0.026
45 - 50	0.232 ± 0.032
50 - 55	0.213 ± 0.033
55 - 60	0.199 ± 0.032
60 - 70	0.182 ± 0.025
70 - 80	0.165 ± 0.025
80 - 90	0.159 ± 0.030
90 - 100	0.160 ± 0.030
150	0.170 ± 0.028
250	0.126 ± 0.018
350	0.095 ± 0.011
450	0.077 ± 0.010
550	0.063 ± 0.011
650	0.053 ± 0.010
750	0.045 ± 0.010
850	0.038 ± 0.010
950	0.032 ± 0.010

Table 27

(b)

Evaluated α values for Pu-239 in the energy range below 20 keV

Energy Interval (keV)	Evaluated $\frac{\langle\sigma_{n\gamma}\rangle}{\langle\sigma_{nf}\rangle}$	Error
0.1 - 0.2	0.845	0.077
0.2 - 0.3	0.912	0.094
0.3 - 0.4	1.150	0.099
0.4 - 0.5	0.483	0.058
0.5 - 0.6	0.704	0.069
0.6 - 0.7	1.673	0.133
0.7 - 0.8	0.973	0.087
0.8 - 0.9	0.778	0.101
0.9 - 1.0	0.717	0.077
1.0 - 2.0	0.927	0.093
2.0 - 3.0	1.108	0.103
3.0 - 4.0	0.895	0.086
4.0 - 5.0	0.821	0.079
5.0 - 6.0	0.867	0.084
6.0 - 7.0	0.816	0.086
7.0 - 8.0	0.629	0.073
8.0 - 9.0	0.575	0.064
9.0 - 10.0	0.617	0.067
10.0 - 15.0	0.509	0.060
15.0 - 20.0	0.419	0.051

Kononov et al. have measured alpha over the energy range 10 keV to 1 MeV using a similar method to Lottin et al. Between 10 and 70 keV the experiment was performed using a continuous neutron spectrum produced by using the Li-7(p,n) reaction with a thick target and employing the time-of-flight technique to measure neutron energies. Above 100 keV monoenergetic neutrons were used and the time-of-flight technique employed to reduce the background levels. The values of alpha obtained, which are shown in Fig. 5, have an accuracy varying between $\sim \pm 10\%$ from 20 to 150 keV to $\sim \pm 100\%$ at 1 MeV. There is a tendency for the data to be lower than the evaluation below 300 keV, and between 16 and 30 keV and 110 to 200 keV the differences are particularly marked. However, in the energy region below 70 keV the signal to background ratio for the capture channel is very poor being 0.1 around 20 keV.

The measurements of Bergman et al. have been performed using a lead slowing down spectrometer - a technique not previously discussed in this paper. The basic feature of the method is that the sample and detector are placed in an isotropic neutron flux which is not altered as a result of neutron scattering in the sample and detector. The capture detector was a gas proportional counter with Moxon-Rae characteristics which was used with samples ranging in thickness between 4.4×10^{-3} and 1.7×10^{-4} atoms per barn and the fission detector was a fission chamber. The experiment was normalized at thermal energies. The results are shown in Fig. 5 and it can be seen that on the whole they tend to be higher than the evaluated curve. However, the differences are probably not significant as the large discrepancies between 0.1 and 1 keV are due to the poor neutron energy resolution.

The three experiments discussed above on the whole support our evaluated curve. There is some evidence from the Gwin et al. and Bergman et al. data that the evaluation may be too low below a few keV while the Kononov et al. data suggest that it may be too high between 10 and 300 keV. We consider, however, that we should not alter our evaluation at the present time for the following reasons:

(a) The data of Gwin et al. are preliminary[+]

(b) The data of Bergman et al. are unreliable because they used the lead slowing down spectrometer which often appears to give discrepant results

(c) The data of Kononov et al. have a poor signal to background ratio below 70 keV and at higher energies they tend to be rather discrepant with data we consider to be superior.

[+] Even if the data of Gwin et al. were not preliminary we consider that either these or the fission chamber series of the earlier Gwin et al. data should have low weight in the energy range of overlap below 4 keV because basically the same technique was used.

7. Interpretation of Energy Variation of Alpha

In Section 3 it was pointed out that the high values of alpha between 1 and 10 keV are inconsistent with the values calculated from the average resonance parameters measured in the resonance region. Therefore, initially it was very difficult for people to accept that alpha was high in this energy range. However, the evaluation of Sowerby and Patrick (5) shown in Fig. 1 and the provisional results of Schomberg et al. (2) presented at the Karlsruhe Fast Reactor Conference led to attempts to calculate the fission and capture cross-sections by using the channel theory of fission to obtain the average values and energy dependence of the fission widths. Both Kikuchi and An (55) and Durston and Katsuragi (56) obtained high values of alpha in the keV energy range and a reasonable energy dependence above 10 keV by placing the first 1^+ transition state in the energy range 50 to 150 keV above the neutron threshold. However, the calculated values of alpha below ~600 eV tended to be systematically high though the fluctuations in alpha calculated by Durston and Katsuragi suggested that this could possible be due to statistical fluctuations. However, it appeared to be difficult to satisfactorily explain the 400-700 eV energy range.

The discovery of intermediate structure in the sub-threshold fission of Np-237 and Pu-240 by Paya et al. (8) and Migneco and Theobald (9) immediately suggested an alternative explanation because, as we have seen above, the s-wave fission in the 1^+ channel is sub-threshold. Correlation analyses of the type suggested by Egelstaff (57) of the fission cross-section of Pu-239 by Blons et al. (58) and Patrick and James (59) showed significant correlations which were interpreted as intermediate structure due to fission occurring through levels, with a spacing of ~460 eV, built on the second minimum in the fission potential as predicted by Strutinsky (60). Perez et al. (61), however, showed that the correlogram technique does not necessarily pick out the correct level spacings though it remains a useful method to detect the existence of intermediate structure. James and Patrick (62) subsequently analysed both the total and fission cross-section data and showed that above 700 eV the modulations present in the fission cross-section *were not present in the total* cross-section and they represented their average fission cross-section data by a series of Lorentzian terms on a smooth background. From this analysis it can be concluded that the modulations are due to variations of either $<\Gamma_\gamma>$ or $<\Gamma_f>$ of the 1^+ resonances (since $<\Gamma_f> >> <\Gamma_\gamma>$ for 0^+ resonances). A similar conclusion can be drawn from the data of Schomberg et al. shown in Fig. 6 where the values of $<\sigma_{n\gamma}>/<\sigma_{nf}>$ and $<\sigma_{nf}>\sqrt{E}$ are compared. These data also show that the fluctuations of $<\sigma_{n\gamma}>/<\sigma_{nf}>$ observed below 1 keV are repeated at higher energies and hence the fluctuations in alpha are unlikely to be due to statistical fluctuations and are more likely to be due to intermediate structure effects [the arrows on Fig. 6 show the positions where James and Patrick put the Lorentzian peaks in their fission cross-section analysis]. The final confirmation that the structure is due to variation of $<\Gamma_f>$ for the 1^+ resonances came from the work of the Saclay group who have measured the resonance parameters of Pu-239 up to an energy of 660 eV (63). Fig. 7 shows a comparison of $<\Gamma_f>$ for the 1^+ resonances given by Trochon et al. (64) compared with our evaluated $<\sigma_{n\gamma}>/<\sigma_{nf}>$ curve. The hatched areas give the limits in $<\Gamma_f>$ and the points on the $<\sigma_{n\gamma}>/<\sigma_{nf}>$ graph are the values calculated from the measured resonance parameters. It can be seen that where $<\sigma_{n\gamma}>/<\sigma_{nf}>$ is high $<\Gamma_f>$ is low particularly in the 400-700 eV range where the structure is most pronounced.

As a result of this discussion we can now understand how $<\sigma_{n\gamma}>/<\sigma_{nf}>$ can be higher in the keV energy range than in the resonance region. The value over an energy interval obviously depends upon the position and strength of the intermediate structure. At the present time no really satisfactory method has been found to determine the parameters of the intermediate structure modulations because of the strong fluctuations due to the fine compound nuclear resonances. Attempts at analysing the data are being made by a number of authors and we await their results with interest. However, an interesting conclusion can be drawn from some work being done by Sowerby and North (65). The aim of this is to provide a set of average resonance parameters which can be used with the RESP-GENEX system of computer codes (66) to produce a set of unresolved resonances and cross-sections. The parameters are chosen so that the calculated average cross-sections have the known structure in evaluated sets of data on total, fission and capture cross-sections. From this work it can be seen that the structure in $<\sigma_{n\gamma}>/<\sigma_{nf}>$ decreases as the neutron energy increases due to increase in the p-wave contribution to the cross-sections. This increase also probably explains most of the energy dependence in $<\sigma_{n\gamma}>/<\sigma_{nf}>$ in the 6-60 keV energy range. [The p-wave contribution to $<\sigma_{nF}>$ is approximately 7, 25, 38 and 63°/o at 1.5, 5.5, 9.5 and 25 keV respectively. The fluctuations in $<\sigma_{n\gamma}>/<\sigma_{nf}>$ reduce from $\sim \pm 50$°/o at ~1 keV to $\sim \pm 33$°/o at 4 keV and $\sim \pm 25$°/o at 7 keV]. At higher energies higher order partial waves become more important and the inelastic scattering cross-section becomes larger than the capture cross-section. Therefore many assumptions have to be made in order to calculate $<\sigma_{n\gamma}>/<\sigma_{nf}>$ and definitive conclusions on average resonance parameters cannot be made.

8. Comparison of the Evaluated α-values with Integral Data

Many integral measurements designed to test the differential data on Pu-239 alpha have been performed during the past few years. In order to do them all justice it would be necessary to write a long and detailed review which is beyond the scope of this paper. Our aim in this section is to see if the integral measurements are consistent with our evaluated curve and this can be done satisfactorily by considering a few of the more recent measurements which tend to be more accurate and agree with the earlier integral data. First of all, however, we will describe briefly the three main types of integral measurement.

(1) Irradiation Experiments

A sample of fissile material (Pu-239) is irradiated and the number of capture events is determined from a measurement of the amount of Pu-240 produced. The Pu-239 fission rate can be determined by a variety of techniques such as fission product yield measurements and measurements of the Pu-239(n,f) to U-235(n,f) or U-238(n,γ) ratio combined with absolute determinations of the number of these latter reactions by measurements of isotopic changes in samples of U-235 and U-238.

(2) The Reactivity Reaction Rate Method

The reactivity worth of a sample of Pu-239 and the Pu-239 fission rate are measured relative to the reactivity worth and reaction rate of an absorber (B-10 or Li-6) or relative to the reactivity worth and source strength of a calibrated Cf-252 neutron source. This experiment determines a spectrum averaged value of ($\bar{\nu}$ -1-α). Corrections are required for the reactivity effects of scattering and the variation of neutron importance with neutron energy.

(3) The PCTR Method

A zero leakage test zone consisting of fissile material, an absorber and a moderating material is built in a zero power critical assembly and the reaction rates in the absorber are measured relative to the fission rate in the fissile material. These reaction rates combined with a measurement of k_∞ for the test zone material enable a spectrum averaged value of ($\bar{\nu}$-1-α) to be determined. Corrections are required for the components of the neutron balance not measured directly.

These integral measurements of Pu-239 are usually combined with measurements of the neutron energy spectrum in the reactor: Differential spectra are often determined using time-of-flight or proportional counter techniques or spectral indicators such as reaction rate ratios are measured. The measured or calculated spectrum ($\phi(E)$) has then to be used to enable the spectrum average $\bar{\alpha}$ to be calculated so that the differential and integral data can be compared. $\bar{\alpha}$ is obtained from the formula

$$\bar{\alpha} = \frac{\int \sigma_{n\gamma}(E)\, \phi(E)\, dE}{\int \sigma_{nf}(E)\, \phi(E)\, dE} \qquad (14)$$

and hence in addition to the spectrum and alpha we also need to know the fission cross-section. Because the energy dependence of $\sigma_{n\gamma}$ and σ_{nf} are different the average energy of neutrons producing capture and fission events are different in a sodium cooled plutonium oxide fuelled fast power reactor (e.g. in Pu-239 ~40°/o of captures and ~15°/o of fissions are produced by neutrons with energies less than 10 keV and the energy spectra of capture and fission events peak at ~30 and ~200 keV respectively). Therefore, we must remember that when we compare the measured and calculated values of $\bar{\alpha}$ we are not directly testing alpha but a combination of alpha, the fission cross-section and the neutron spectrum in the reactor.

We have selected three sets of integral measurements for discussion; the measurements of Bouchard et al. (67), the measurements in ZPR-3 assembly 57 by Kato et al. (68) and Bretscher et al. (69) and the results analysed by Campbell and Rowlands (70).

Bouchard et al. reported three different sets of results. Measurements were made by the reactivity reaction rate method in the fast thermal critical assembly ERMINE and irradiation experiments were performed within a boron sleeve in the thermal reactor OSIRIS and in the fast reactor RAPSODIE. Measurements were made on both U-235 and Pu-239 and the results are given in Table 28 compared with values calculated using the Cadarache Version 2 data set and, for Pu-239, with data obtained primarily from our evaluation of alpha and the fission cross-section recommended by Sowerby et al. (40). In the Cadarache data set the Pu-239 alpha evaluation is based on the early results of Gwin et al. (71) at low energies but is 20°/o higher than the data of Lottin et al. (42) above 25 keV. The results given for the ERMINE experiment are for conditions under which more than 40°/o of the Pu-239 capture events occur at neutron energies of between 1 and 20 keV. For the OSIRIS data 51°/o of the Pu-239 captures occurred between 1 and 25 keV and 1°/o occurred below 100 eV. In the RAPSODIE experiments essentially all capture in Pu-239 was due to neutrons with energy greater than 20 keV.

It can be seen from the table that for both RAPSODIE and OSIRIS the values calculated using the present evaluation are in good agreement with the experimental data. The Cadarache data, however, gives calculated values that are respectively 13 and 6°/o higher than experiment. This shows that the 20°/o increase of the Lottin et al. data in the Cadarache evaluation is too great; our renormalisation by 5.3°/o appears to be more reasonable. The Cadarache calculated value for

ERMINE is a little high but since their evaluated alpha data above 25 keV is high we can assume that their evaluation below 25 keV (which agrees reasonably with our evaluation) is consistent with integral data. For U-235 the measured and calculated alpha values are in good agreement which confirms that there are no serious errors in the experimental methods used.

The measurement of Kato et al. in the ZPR-3 assembly 57 is the first experiment performed by the irradiation technique in a neutron spectrum similar to that in a large dilute fast power reactor. A sample of Pu-239 containing only 25 x 10^{-9} parts Pu-240 was specially prepared so that the experiment could be performed in a low power reactor. Spectrum measurements were made by the proton recoil technique and by building a similar core at the Gulf General Atomic sub-critical time-of-flight spectrum facility. The assembly was designed so that ~85°/o of the capture events and ~35°/o of the fission events were produced by neutrons with energies of less than 25 keV. The irradiation which lasted ~4 days increased the Pu-240 content of the sample to ~150 x 10^{-9} and the number of fission events was obtained by measuring the Ba-140 activity, this activity being related to mica track recorder fission measurements made in an earlier irradiation. Measurements were also made of central fission ratios and of alpha for U-233. The values of alpha obtained were 0.363±0.024 (Pu-239) and 0.10±0.04 (U-233).

Bretscher et al. used the reactivity reaction rate method in the same core and obtained alpha values of 0.383±0.026, 0.272±0.021 and 3.848±0.071 for Pu-239, U-235 and U-238 respectively. The results depend slightly on the neutron energy spectrum used in calculating the values of the corrections for the reactivity effects of scattering and the variation of neutron importance with neutron energy. The values for U-235 and U-233 (using the irradiation method) agree well with those calculated from ENDF/B data. The value for U-238 agrees with that measured by radiochemical techniques (3.715±0.129). The two measured values for Pu-239 in assembly 57 also agree well but it is difficult to draw conclusions by comparing these with calculated values as the calculations can vary significantly with the assumed neutron spectrum in the reactor. It does appear, however, as if our evaluated curve gives a reasonable value but there is some evidence that it could be too low below 30 keV, by up to 10°/o.

Campbell and Rowlands have considered a large number of accurate integral measurements and have adjusted group cross-sections so that there is good agreement between the calculated and measured integral data. This technique has been the subject of much discussion on whether or not the adjustments should be considered as significantly improving our knowledge of the cross-sections. The great value of the technique is that it considers a wide variety of integral measurements simultaneously and it is now agreed that at worst it is a sophisticated method of interpolating reactor properties (i.e. if measurements of a given reactor property are made over a range of compositions then if the method is used with these data the property will be accurately calculated for a new system with a composition within the range considered. If the composition is outside the range or if the property calculated is not included in the integral data used for adjustment then the prediction could well be in error). Campbell and Rowlands did not use integral measurements of alpha in their adjustment studies though data similar to that used in a PCTR measurement were included. Therefore their results are probably meaningful. They suggest that Pu-239 alpha values used in their calculations should be increased by $10 \pm 10^{o}/o$ over the whole energy range. They also note that these adjustments are consistent with the preliminary values of irradiation experiments. Our evaluated curve is slightly higher than theirs below 40 keV but at higher energies the two are consistent. This suggests that our evaluated curve is perhaps too low by up to $10^{o}/o$ at high energies. At energies below 30 keV it is probably reasonable although a slight increase cannot be ruled out.

From these comparisons with integral data it can be seen that our evaluated curve is consistent with the integral evidence. There are, however, some indications that better agreement would be obtained by increasing the evaluated data by up to $5^{o}/o$ over the whole energy range. We do not propose to alter our evaluated curve because this conclusion could be due to errors in the spectrum and the fission cross-section of Pu-239. However, it is obviously very important that additional measurements, preferably by a new technique, should be made at neutron energies above 30 keV where essentially only one type of measurement has been performed.

TABLE 28

Integral Measurements of Bouchard et al.

Reactor	U-235 alpha		Pu-239 alpha		
	Measured	Calculated (Cadarache version 2 data set)	Measured	Calculated (Cadarache version 2 data set)	Calculated (Present Evaluation)
ERMINE+	0.35±0.04	0.347	0.37±0.04	0.414	
OSIRIS	0.234±0.010	0.227	0.202±0.010	0.216	0.196
RAPSODIE	0.191±0.008	0.204	0.096±0.006	0.111	0.100

+ For ERMINE the result depends on sample size and the value given here is for a cylinder 4 mm in diameter and 50 mm long.

9. Conclusions

In this paper we have attempted to review the experiments which give significant results on the variation of $<\sigma_{n\gamma}>/<\sigma_{nf}>$ or alpha for Pu-239 in the energy range above 100 eV. We have considered the types of measurement that have been performed and conclude that no detector system used to date has been perfect. Ideally a detector system which detects 100°/o of the fission events is required otherwise the gamma-ray and fission detectors are sensitive to possible changes in the fission process as a function of neutron energy. Unless a very high efficiency fission detection system can be used it appears to us that highly accurate alpha measurements are not possible unless detailed measurements on fission gamma rays and fission fragment angular distributions are performed as a function of incident neutron energy.

We have reviewed the history of the measurements of plutonium alpha and feel the discovery that alpha is high (~1) in the keV energy range has some important lessons to tell us. First of all it warns us that calculations of cross-sections are no substitute for measurement and secondly it indicates that interpolation of values using what appears to be a reasonable theory can be seriously in error.

An evaluation of alpha has been performed and we estimate that alpha is known to approximately ±10°/o between 100 eV and 30 keV. At higher energies the error increases to ±30°/o at 1 MeV. The measurements show a wide spread around the evaluated curve below 30 keV but this is not considered to be too surprising because the values of the fission cross-sections of Pu-239 and the capture cross-sections of heavy elements such as U-238 and Au-197 are only known to ±4°/o or worse: A measurement of alpha is inherently more difficult than the measurement of these cross-sections. Though there is less spread in the data above 30 keV this may be due to the fact that the two significant measurements were made by an identical technique. It is obviously important that new measurements by another technique should be made in this energy range.

In performing the evaluation we have checked that the dispersion in the results of the various experiments is not due to differences in normalization or to variations of $\bar{\nu}$ with incident neutron energy. However, we could not rule out that $\bar{\nu}$ was varying significantly with neutron energy below 30 keV and consider that accurate $\bar{\nu}$ measurements are urgently required in this energy range. We feel that most of the differences between the alpha measurements are probably due to errors in background. In virtually all the experiments there is insufficient detail in the documentation to enable us to assess which experiments are less sensitive to background uncertainties and it appears to us that for important measurements it is vital that more details be published. At the present time the delayed gamma-rays produced by fission products are not limiting the accuracy of the measurements. However, they will become much more important as the experiments become more accurate.

Our evaluated curve is consistent with all the data on the total and partial cross-sections of Pu-239. We have also compared it with integral measurements of alpha made in various reactors. Within the errors of the measurements and the evaluation, the calculated and measured integral data are consistent though there is evidence that the evaluation may be low by up to 5°/o over the whole energy range. These conclusions could, however, be due to errors in the assumed neutron energy spectrum in the reactor and in the fission cross-section of Pu-239 and hence we consider that our evaluated curve should not be altered at the present time to take account of the integral data. The evaluated curve is not accurate enough to satisfy the requests of the reactor physicists and obviously more measurements are required. However, we feel that these should not be performed unless the techniques to be used are either new or have been significantly improved over those used in the measurements performed to date.

Table 29 summarises the principal conclusions of the review with regard to further measurements.

TABLE 29

Recommendations regarding further measurements

1. Unless high efficiency fission detectors can be used in the determination of alpha detailed measurements on fission gamma rays and fission fragment angular distributions are required for Pu-239 as a function of neutron energy.

2. Accurate measurements of $\bar{\nu}$ for Pu-239 are required between thermal energies and 30 keV.

3. Additional measurements of Pu-239 alpha are required both above and below 30 keV to achieve the accuracy required by the reactor physicists. These, however, should only be performed if the techniques to be used are either new or have been significantly improved.

10. Acknowledgements

We have received from the late Dr. E. R. Rae and Dr. J. J. Schmidt much invaluable support, encouragement and advice in the preparation of this review and this is gratefully acknowledged. We are particularly indebted to Dr. T. A. Byer, Dr. J. B. Czirr, Dr. J. A. Farrell, Dr. R. Gwin, Dr. V. N. Kononov, Dr. J. E. Lynn, Mr. D. S. Mather, Dr. B. H. Patrick, Mr. J. L. Rowlands, Dr. Yu. V. Ryabov, Dr. G. de Saussure, Mr. M. G. Schomberg, Dr. Yu. Ya. Stavisskii and Dr. S. I. Sukhoruchkin for the many helpful discussions we have held with them on the measurement and evaluation of Pu-239 cross-section data. There are a large number of other people who have helped us in many ways and we would like to express our thanks to them all, particularly those working in the Linac Group at AERE Harwell and in the Nuclear Data Section of the IAEA.

11. Appendix

Abstracts of direct alpha measurement works in the region from 0.1 to 20 keV

Abstract 1

Author:

R. Gwin, L. W. Weston, G. de Saussure, R. W. Ingle, J. H. Todd, F. E. Gillespie, R. W. Hockenbury and R. C. Block.

Reference:

Report ORNL-TM-2598, part 1, October 1969; Nucl. Sci. and Eng. 40 (1970) 306; Report ORNL 4707 (1971); Nucl. Sci. and Eng. 45 (1971) 25.

Establishment:

Oak Ridge National Laboratory and Rensselaer Polytechnic Institute, USA.

Quantities measured:

The neutron absorption and fission cross-sections for Pu-239 have been measured simultaneously over the neutron energy range from 0.02 eV to 30 keV and the ratio $<\sigma_{n\gamma}>/<\sigma_{nf}>$ was derived.

Accuracy:

The total error in the $<\sigma_{n\gamma}>/<\sigma_{nf}>$ ratio is 10-20 °/o for an 11-gram foil sample in the energy region 0.1 - 20 keV and 12.4-19.2 °/o for an ionization chamber at 0.1 - 2 keV.

Neutron Source:

Electron linear accelerator, time-of-flight method, the neutron flight path was 25.57 m. Nominal energy resolution was $\geq 7.1 \frac{\text{nsec}}{\text{m}}$.

Fission and Capture Detectors:

A large liquid scintillator was used to detect the gamma-rays resulting from the absorption of a neutron in the plutonium sample (both fission and capture events). Fission events were measured by using an ionization chamber or metallic Pu-239 foils and the high bias technique. Thus, with the chamber a fission was characterized by a pulse from the scintillator in coincidence with a pulse from the fission chamber, whereas a capture was characterized by a pulse from the scintillator alone. In the high bias technique pulses above the bias of ~11 MeV are produced by fission events while those between the low (~2.7 MeV) and high bias can be from both fission and capture. The fission chamber was used up to the energy of 4 keV to determine alpha and the high bias technique gave data up to 30 keV.

Sample Details:

Pu-239 metal foils used for the higher energy measurements have masses of 5.25, 11.2 and 21.3 g. The Pu in the ionization chamber (1.4 g Pu-239) was deposited on 0.005 in. Al plates. The chamber contained 21 plates. The Pu isotopic content was ~99°/o Pu-239 and 0.8°/o Pu-240. The content of Cm-244 gave ~30 spontaneous fissions per second. The chamber also contained a small amount of tungsten.

Flux Measurement:

The relative energy dependence of the neutron flux was measured using a parallel plate BF_3 ionization chamber. This was done assuming that the energy dependence of the reaction B-10(n,α)Li-7 is inversely proportional to the velocity of the incident neutron over the energy range from 0.02 eV to 30 keV.

Experimental Arrangement:

The neutron beam traversed a cylindrical tube extending through the scintillator and containing the fissile sample. The measurements of σ_{nA} and σ_{nf} were performed over the neutron energy region from 0.02 eV to 30 keV in two steps. The first step extended from 0.02 eV to about 45 eV and the second step extended from about 6 eV to 30 keV. The pulse repetition rate (30 pps) and the neutron pulse width were 2 μsec for the low-energy run and for the high-energy run the corresponding values were 240 pps and 0.1 μsec. In the low-energy runs the neutron filters used for background determination were Au(4.9 eV) and U-238 (6.67, 21, and 36.7 eV) and for the high-energy runs the filters were Co (132 eV), Mn (337 eV), Na (2.85 keV), and Al (35 keV). Measurements were made with the ionization chamber in the low energy runs and with both the ionization chamber and metal foils in the high energy runs.

Data Normalization:

The data were normalized at 0.0253 eV to values, recommended by Hanna et al. (1), of 271.3±2.6 barn for the neutron capture cross-section, $\sigma_{n\gamma}$, and to 741.6±3.1 barn for the neutron fission cross-section, σ_{nf}. The data obtained in the measurements extending from 6 eV to 30 keV were normalized to the low-energy run over the energy range from 7.3 to 37.5 eV, that is the energy integrals of the neutron capture cross-section from 7.3 to 37.5 eV were equated for the two runs as were the energy integrals for the neutron fission cross-sections.

The metal foil data (11-g Pu-239 sample) were normalized by equating the energy integrals of the neutron fission and capture cross-sections over the energy range from about 7 to 100 eV to the values derived from the measurements using the ionization chamber. The data obtained using the 11-g sample were more comprehensive than data obtained using a 5-g and 21-g sample. For this reason the data obtained with the 11-g sample of Pu-239 were chosen by Gwin et al. for a detailed analysis.

Corrections and Errors:

A major source of uncertainties for the measurement of the neutron capture cross-sections above 100 eV arises from errors in estimating the time-dependent background of the liquid scintillator counts not identified as fission events (this error was equivalent to about 0.2 barns over the neutron energy range from 100 eV to about 2 keV, and decreased monotonically to about 0.1 b from 2 keV to 30 keV); the background from delayed γ-rays (<1°/o); uncertainty in the relative neutron flux for energies less than 2 keV due to "off-energy" neutrons (about 1.5°/o); the effect of neutrons which are scattered by the sample and absorbed in the sample (less than 1°/o); uncertainty in $\sigma_{n\gamma}$ due to fissions missed by the ionization chamber (less than 0.6°/o of σ_{nf} (Pu-239)); normalization errors (about 2°/o in the ratio σ_{nf}/σ_{nA}); uncertainties in the response of the large liquid scintillator to changes in the prompt gamma-ray cascade resulting from neutron absorption in the sample (measurements of the pulse-height response of the large liquid scintillator for a few resonances in Pu-239, for both fission and capture, have not indicated any measurable differences in the pulse-height distribution within the statistics of the measurements).

For the 11-g sample the corrections due to multiple scattering were estimated by a Monte Carlo method. The calculation showed that over the neutron energy range from 7 to 76 eV about 2.5°/o of the neutrons absorbed were scattered at least once. The effects of resonance scattering are estimated to have a small effect (~2°/o) in the average cross-sections in the resonance energy region.

No correction for the neutron absorption cross-section of the impurities in the ionization chamber or in the 11-g sample has been made.

Authors' Comments:

The time-dependent background in the experiments with a Pu-239 metal foil was interpreted differently in the final report (34) than in the earlier report (17). Experiments performed at RPI (by R. W. Hockenbury) and at ORNL indicated that there was a background in the ORNL-RPI measurements which was correlated with the fissions in the Pu-239 sample. An allowance for this background was made and the error analysis incorporates uncertainties introduced by this correlated background. This re-evaluation of the background resulted in an increase in the α-values above 3 keV of 0.06 to 0.1 over those previously reported (17).

In the prior report (17) the normalization of the data for the metal foils was made to values of the ratio of the neutron fission to neutron absorption cross-sections about the peak of isolated resonances. In the latest analysis the normalization of the metal foil data was made by equating the energy integrals of the neutron fission and capture cross-sections over the energy range from 7.3 to 100 eV obtained using the ionization chamber. This procedure takes advantage of all the data rather than utilizing only that data about the peaks of the resonances.

Abstractors' Comments:

The values of $<\sigma_{n\gamma}>/<\sigma_{nf}>$ obtained are not dependent on a knowledge of $\bar{\nu}$.

The final normalization procedure used appears to be more satisfactory and precise than in the earlier report. The results obtained by two different techniques (metal foils and ionization chamber) agree with each other within experimental uncertainties. The use of the large liquid scintillator minimizes the effects of possible changes in the gamma-ray spectra from resonance to resonance. The authors say that they measured this effect for a few resonances, but not for high-energies where p-waves become important.

Abstract 2

Author:

M. G. Schomberg, M. G. Sowerby, D. A. Boyce, K. J. Murray and (Miss) D. L. Sutton.

Reference:

IAEA Conference on Nuclear Data for Reactors, Helsinki, 15-19 June 1970, paper CN-26/33, Vol. 1, p.315 (1970).

Establishment:

Harwell, Didcot, Berks., United Kingdom.

Quantities Measured:

The ratio $<\sigma_{n\gamma}>/<\sigma_{nf}>$ and $<\sigma_{nf}>$ were measured in the energy range from 0.1 to 30 keV.

Accuracy:

The total accuracy is between ±5 and 8°/o in $<\sigma_{nf}>/<\sigma_{nA}>$ which corresponds to 10 to 16°/o in $<\sigma_{n\gamma}>/<\sigma_{nf}>$.

Neutron Source:

Electron linear accelerator, time-of-flight spectrometer, flight path length was 34.86 m, nominal resolution was 7.2 ns/m.

Fission and Capture Detectors:

Two detector systems, which basically consist of fast neutron detectors and gamma-ray detectors, were used. The gamma-ray detector was of the "Moxon-Rae" type and the neutron detector was a recoil proton detector, which by use of pulse shape discrimination had zero efficiency for capture events. It was found with the first system (2) that the ratio of the efficiencies of the gamma-ray detector for fission and capture events was ~2.5 rather than 1.0 - 1.3 as expected from the Moxon-Rae characteristic and the known total energy of prompt fission (~7 MeV) and capture (~6.4 MeV) gamma-rays. This was due to the high gamma-ray and fission neutron multiplicity of fission events causing accidental coincidences. The effect has been investigated by rebuilding the detector system and increasing the number of detectors. The results obtained with the modified detector system showed that the efficiency ratio was 1.5 ± 0.2. The count to background ratio for the modified system was, on an average, about 1.5 higher than that for the original system.

Sample Details:

Three samples 5.08 cms diameter, containing 1.07°/o Al, 0.7°/o Pu-240, canned in 0.0127 cm Al and with sample thicknesses of 0.0012. 0.000579 and 0.00029 atoms per barn; 1 sample 7.4 cm diameter, containing 1.8°/o Pu-240, thickness 0.0044 atoms per barn, canned in 30 cm long Al cylinder with 0.092 cm end windows.

Flux Measurement:

The energy spectrum of the incident neutron flux was measured by a 0.32 cm thick Li-6 glass scintillator. 6.35 cms in diameter and mounted 5.25 cms from the photomultiplier.

Experimental Arrangement:

The detector system was assembled on one of the flight paths of the Harwell time-of-flight neutron spectrometer based on the 45 MeV Electron Linear Accelerator with its neutron 'Booster' target. The measurement covered the incident neutron energy range from 10 eV to 30 keV. A total of nine sets of experimental data were obtained with the two detector systems. The resonance filters used for background measurements were: Mn (337 eV, 1.10, 2.38, 7.17 and 8.87 keV), Mo (45, 131 eV), Ta (10.34 eV), Na (2.85 keV), Al (35 keV). B-10, Al and Na were used as permanent "black" filters.

Data Normalization:

The data were normalized to the α-values on the peaks of well resolved low energy resonances where the values of α are known from other experiments measuring η and alpha. The set of resonance α-values used for normalization purposes was obtained by evaluation of the following four experiments:

(a) η -experiment of Bollinger et al. (28) (the results were neglected because of disagreement in shape with other data in the thermal region).

(b) α-experiment of Czirr and Lindsey (36) (the results have also been largely ignored because the experiment was only partially made in the thermal region).

(c) α-experiment of Gwin et al. (17) (the evaluation made by Schomberg et al. (35) depends heavily on these results, because as only one cross-normalization is required in the experiment of Gwin, accurate flux measurements are not needed, and Gwin's results are supported by the data of Czirr and Lindsey).

(d) η -experiment of Patrick et al. (72) (the results were originally normalized to the data of Brooks et al. (73) which had been normalized to η = 2.0 at 0.08 eV, and Sowerby made a reappraisal of the cross-normalizations within the Brooks experiment and between it and the Patrick experiment).

The Patrick et al. results renormalized through η = 2.034 at 0.057 eV are about 20 °/o higher than those of Gwin et al. in the alpha region of 0.1 - 1.6. The authors renormalized for the second time the Patrick et al. data by combining the normalization through η with a normalization based on Gwin results at 10.9, 14.3, 15.5, 22.3 and 32.3 eV resonances, and combined the values obtained with the values of Gwin et al. to obtain the following weighted α-values which were used for normalization:

Resonance Energy eV	α
7.83	0.86 ± 0.04
10.93	0.33 ± 0.03
11.93	1.52 ± 0.07
14.30	0.56 ± 0.04
14.70	1.18 ± 0.05
15.50	0.11 ± 0.05
17.60	1.13 ± 0.05
22.30	0.66 ± 0.04
26.30	0.90 ± 0.05
44.60	8.94 ± 0.60
50.20	2.27 ± 0.20
52.70	4.92 ± 0.29
65.90	0.91 ± 0.05
91.00	4.08 ± 0.27

Corrections and Errors:

The total error quoted was typically about 15 % in α and mainly consists of: error due to statistics and background fitting (about 10 to 15 %), error due to uncertainties in determining the resonance α-values (thought to be 2.5 % of 1 + α for α-values in the range 0 to 1.5 which means 5 to 7 % in α), and error due to a 2 % uncertainty in $\bar{\nu}$ -value in the energy region above 100 eV (which leads to 5 to 7 % uncertainty in α). A correction for self-screening effects was made.

It has been assumed that multiple scattering effects are negligible; no corrections have been made for the effect of Pu-240 in the sample. It has also been assumed that the efficiencies of the detectors for fission and capture events are independent of neutron energy. The effect of delayed gamma-rays from fission was found to be negligible.

Authors' Comments:

The present data set for alpha supersedes all the previous data of the same authors. The main differences between the two data sets (the present and the previous one (2)) are in the experimental conditions and experimental technique used and in the resonance alpha values, which were used for normalization of experimental results.

The correction for multiple scattering is negligible if (a) the sample is "thin"; (b) α does not vary with neutron energy; (c) the ratio of the scattering and total cross-sections is small. The experiment was normalized or results only given when at least one of these conditions was true.

Abstractors' Comments:

The measurements of Schomberg et al. show the same structure in alpha as the measurements of Gwin. They agree reasonably well with the results of other authors while, in the region 0.8 to 5 keV, the results tend to be systematically lower than the others. In this energy region the results may not be as accurate as others because of large background errors.

The α-values obtained depend strongly on the resonance α-parameters used for normalization. Comparison of the resonance α-values obtained in other α measurements with those evaluated by Schomberg et al. shows that these evaluated parameters are quite good and in good agreement with the parameters of Belyaev et al. (37) for $\alpha < 1$, but for $\alpha \gg 1$, namely at the 44.5 eV resonance, they are about 8-10 % lower than the results of other measurements.

The results of Weston et al. (13) give little evidence for the spin-dependence of $\bar{\nu}$ -values and thus the error estimate in α for this effect appears to be slightly "overgenerous" or, at least, not too small.

Abstract 3

Author:

J. B. Czirr and J. S. Lindsey.

Reference:

IAEA Conference on Nuclear Data for Reactors, Helsinki, 15-19 June 1970, paper CN-26/47, Vol. 1, p. 331 (1970).

Establishment:

Lawrence Radiation Lab., University of California, Livermore, California 94550, USA.

Quantities Measured:

The ratio $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ has been measured over the neutron energy region from 100 eV to 30 keV.

Accuracy:

The total uncertainty in the $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ ratio, as quoted by the authors, is 6.3°/o to 12.2°/o in the energy region from 0.1 to 30 keV.

Neutron Source:

The Livermore 33 MeV electron linear accelerator, time-of-flight method with a resolution of 50 nsec/m, the neutron flight path was 11 m.

Fission and Capture Detectors:

Capture and fission gamma rays and fission neutrons were detected in a 1 litre liquid scintillator, using pulse shape discrimination to identify the particle type. Since the gamma data consist of both capture and fission events, it was necessary to subtract a quantity proportional to the fission cross-section in order to obtain the capture cross-section. The fraction to be subtracted was determined by normalizing the fission data at an energy corresponding to a low α-value - from 15.5 to 16.0 eV.

The ratio of the efficiencies of the capture detector for fission and gamma events was found to be 0.86.

Sample details:

20-g metallic plutonium foil of 4.3×10^{-4} atoms/barn thickness was used. The composition of plutonium was: 99.11°/o Pu-239 and 0.875°/o Pu-240.

Flux Measurement:

The incident neutron flux was measured with a single BF_3 tube inserted into the beam pipe during separate runs.

Experimental Arrangement:

The metallic Pu foil was placed 11 m from the neutron source and viewed by a

1 litre liquid scintillation detector. The gamma events were pulse-height weighted on-line to provide data which are essentially independent of variations in the capture-gamma de-excitation spectrum. This linear weighting assures spectral independence for capture events if the fraction of the capture-gamma energy spectrum below the threshold level is not a function of the incident neutron energy. The gamma threshold was set at about 0.75 MeV. The background induced by out-of-time neutrons was measured at 4, 10, 120 and 2800 eV by inserting the resonance filters of Na, Co and Ta during a separate background run.

Data Normalization:

The measured alpha-values were normalized at 0.07 - 0.09 eV and 15.5 - 16.0 eV. Using a thermal value for $\alpha = 0.3653 \pm 0.0036$ (74) and the ENDF/B file data on η (E) from thermal energy to 0.09 eV (4) the value of $\bar{\alpha} = 0.460 \pm 0.009$ was obtained from 0.07-0.09 eV.

For 15.5-16.0 eV the α-value was obtained by combining calculated $\sigma_{n\gamma}$ values (using available resonance parameters for nearby resonances) with measured σ_{nf} data (33) taking into account the contributions from nearby resonances. This α-value equals $0.092^{+0.02}_{-0.03}$, which includes a 50°/o error increase for this effect. In order to determine the effect of the quoted uncertainty $\binom{+0.02}{-0.03}$ upon α, the data were renormalized using α at 15 eV of 0.112 and 0.062. The average value of α over 0.1 to 10 keV changed by ±3°/o upon doing so.

Corrections and Errors:

The errors of the experiment mainly consist of: treatment of out-of-time background for the neutron and gamma data (about 5°/o), uncertainties in the other background components (±2°/o), fission-gamma subtraction errors of 3°/o, uncertainty caused by the sensitivity of the liquid scintillation detector to the changes in the capture γ-de-excitation spectra of 5°/o, and the error due to primary alpha-normalization of 2°/o.

The data have been corrected for the effect of the 0.875°/o Pu-240 concentration upon the normalization at 0.08 eV (the correction was 0.7°/o). No correction for the effect of self-shielding was made for the energies above 100 eV. The effects of multiple collisions were neglected in the analysis of the data, because of the small energy loss combined with the small probability for elastic scattering.

Authors' Comments:

The major source of uncertainty in the background treatment arises from the assumption of equal out-of-time background for the neutron and gamma data. For the determination of the gamma background α(E) was assumed to be a constant throughout the energy range of interest, and it then follows that the fractional background due to absorption of out-of-time neutrons in the foil would be the same for the fission and gamma signals. Due to a systematic trend in $\bar{\alpha}$ above 7 keV, the above approximation introduces a 5°/o uncertainty in $\alpha(E)$ in the 7-30 keV energy region.

The error due to the uncertainty in the energy dependence of the $\bar{\nu}$ -values in the energy region above 100 eV has not been applied to the α-values, because of the large relative error in this correction.

Abstractors' Comments:

It is assumed in the normalization of the experiment that the efficiency of the gamma-ray detector for fission events is constant. At the present time it seems to be very difficult to assess the error in this assumption because of a lack of necessary information. We can say that this systematic uncertainty may be less than 10°/o and incline to agree to the authors that it is 5°/o.

The error due to uncertainty in the spin-dependence effect of the $\bar{\nu}$ -values, leading to ~5°/o uncertainty in α, should be added to the α-value error.

The normalization point at 15.5-16.0 eV is potentially subject to a large absolute error. The early data of Bollinger (26) yielded $\alpha \approx 0.300$ at 15.5 eV, Farrell (75) gives $\alpha = 0.066$; according to Stehn (76) this α-value is equal to 0.05 ± 0.01; Gwin (77) gives $\alpha = 0.14 \pm 0.06$, and $\Gamma_\gamma / \Gamma'_f = 0.035$. The α-values for the 15.5 eV resonance of Farrell and of Stehn are really $\Gamma_\gamma / \Gamma'_f$ and do not include contributions from nearby resonces to $\sigma_{n\gamma}$. The value $\bar{\alpha} = 0.092^{+0.020}_{-0.030}$ was obtained without taking into account the results of Farrell, Stehn and Gwin, although it agrees with them within the assigned uncertainties. We have adopted that the uncertainty in α caused by the normalization procedure used would be 5°/o.

The normalization point at 0.07-0.09 eV is based upon data at thermal energies. The thermal value for α(Pu-239) was recently evaluated by Hanna et al. (1) as 0.3659 ± 0.0039. This recommended value is based heavily on the experimental value of Lounsbury et al. (74) which Czirr and Lindsey used for normalization purposes and therefore the difference between the evaluated and experimental values is very small (less than 0.2°/o) and may be neglected. Czirr and Lindsey used the Greebler data (4) on η (E) from thermal energy to 0.09 eV. Greebler indicated in his evaluation that the curve given by Leonard was the best, but it might be improved by using a least-squares fitting procedure. We carried out analyses of the shape of the curve for $\sigma_{nf}\sqrt{E}$ and α in the region 0.01-0.2 eV and came to the conclusion that the curve for σ_{nf} coincides with the curve of Greebler within 1°/o, and the curve for $\sigma_{n\gamma}$ is systematically 3-5°/o higher than the curve of Greebler, especially in the region higher than 0.1 eV and lower than 0.03 eV. The respective α-values equal 0.442 (at 0.07 eV), 0.465 (at 0.08 eV), 0.490 (at 0.09 eV), and the mean α-value over the energy region 0.07-0.09 eV is 0.466. Czirr and Lindsey used for normalization the α-value 0.460 ± 0.009, which can be considered as adequate (the difference is 1°/o). Hence, the error of 2°/o due to primary alpha-normalization looks reasonable.

Three more comments on the experiment are appropriate. The background induced by out-of-time neutrons was not measured at the energies higher than 2.8 keV (that means that the α-values are less accurate at these energies); the ratio of the detector efficiency for fission and gamma events was found to be 0.86 which appears to be a little too small.

The errors in α-values given by the authors seem to be a little too low. For the time being we have added, for evaluation purposes, the uncertainty caused by the $\bar{\nu}$ -values (5°/o) and taken a 5°/o error for fission subtraction rather than 3°/o.

Abstract 4

Author:

F. N. Belyaev, K. G. Ignat'ev, S. I. Sukhoruchkin, S. P. Borovlev, V. V. Pavlov, M. V. Polozov, A. N. Soldatov.

Reference:

IAEA Conference on Nuclear Data for Reactors, Helsinki, 15-19 June 1970, paper CN-26/89, Vol. 1, p.339 (1970).

Establishment:

Institute of Theoretical and Experimental Physics, Moscow, USSR.

Quantities Measured:

The α-values for Pu-239 have been measured from thermal energy up to 10 keV. The α-values were determined from the ratio of experimental counts due to capture and fission events.

Accuracy:

The total error in the α-value is from 7 to 20°/o (with an average of 13°/o) in the energy region from 0.1 to 10 keV.

Neutron Source:

The cyclotron of ITEP, time-of-flight spectrometer, the neutron flight path was 14.56 m, nominal energy resolution was $\geqslant 217 \frac{\text{nsec}}{\text{m}}$.

Fission and Capture Detectors:

Two kinds of detectors were used - ZnS detector for detection of neutrons and NaI-crystal for registration of capture and fission gamma-rays in one case, and a stilbene crystal with pulse shape discrimination in a second case. The insensitivity of both fission detectors to gamma-rays has been checked by the absence of the 1 eV capture resonance for Pu-240 on the measured fission curves.

Sample Details:

Metallic Pu-239 sample with thickness of $2.2 \cdot 10^{-3}$ atoms per barn, containing 1.8°/o of Pu-240.

Flux Measurement:

Two BF_3-counters were used for relative measurement of neutron flux.

Experimental Arrangement:

The measurements of α-values were made in two steps. The first step extended from 0.3 eV to 10 keV, and the second one extended from 0.025 eV to 10 eV. The measurements in the second step were carried out with the same flight path and the same detectors, as was done in the first step, but the pulse repetition rate was decreased (the repetition period was 17000 μsec instead of 2300 μsec) and the neutron pulse width was 8 μsec instead of 3 μsec. In the second step measurements of the neutron transmission were also made using a ZnS (Ag) with B_2O_3 detector.

The neutron filters used for background determination were Mn, Na and Ag; "out-of-time" neutrons were monitored with Cd. For capture events a constant component of background due to natural radioactivity of a sample was about 30°/o in the resonance energy region and a time-dependent background component determined by resonance Mn, Na and Ag filters was about 40-50°/o at 5-10 keV and was equal to zero in the resonance energy region. In the case of fission events only a constant background component due to spontaneous fission of Pu-240 was present (about 20°/o in the resonance region).

Data Normalization:

The measured α-values were normalized at thermal energy and at the energy 0.30 eV. For these purposes the measurements of the values of α and η/ν were carried out from thermal energy up to 10 eV. The values of η obtained in these measurements were 2.11 at thermal energy and 1.728±0.026 at 0.3 eV. Using these η-values and the $\bar{\nu}$-value in the thermal energy ($\bar{\nu}$ = 2.88 from (1)) the authors obtained the following α-values: 0.36 at thermal energy and $0.66^{+0.03}_{-0.02}$ at 0.3 eV, which were used for normalization.

Corrections and Errors:

The total error quoted by the authors was typically about 13°/o in α and mainly consists of: error due to statistics and background fitting (from 3 to 12°/o), error due to normalization (about 5°/o for α = 0.6 - 1.1).

It was assumed that the sensitivity of the detector to the possible changes of the capture gamma-ray spectra was low. This assumption had been checked by special measurements of gamma-ray spectra due to capture of resonance neutrons, both for U-235 and Pu-239.

Authors' Comments:

Gamma-rays from capture and fission events were detected in the 1-2 MeV energy range only. It was done, in this energy range, because firstly, the best ratio of gamma ray yields from capture and fission events was observed (about 1:1), and secondly, the background due to scattered neutrons was lower in this case, for there is no transition with great intensity in capture gamma-ray spectra in I (the detector used was NaI).

For comparison purposes only the resonance α-values were obtained in this experiment for five fully resolved resonances at the energies of 7.85, 17.7, 22.3, 26.3 and 44.5 eV. The values obtained are in good agreement with those of Gwin et al.

and those of Schomberg et al. (except the resonance at 44.5 eV).

Abstractors' Comments:

The α-results obtained with the two different detector systems agree with each other within their experimental uncertainties. This allows the authors to reduce the statistical errors considerably.

An uncertainty in the α-values due to uncertainty in the energy dependence of the $\bar{\nu}$ -values (about 5°/o in α) should be added to the total α-error.

In the experiment only gamma-rays in the 1-2 MeV range were detected. The authors say they checked in the resonance region that their results were not sensitive to changes in the capture gamma-ray spectra, but presumably they could be in error at high energies where p-waves become important.

No uncertainties caused by the sensitivity of the gamma detector to the possible changes in the capture gamma spectra are included into the errors.

The data have not been corrected for the effect of the 1.8°/o Pu-240 concentration upon the normalization at thermal energy. This correction presumably would be about 1.5°/o.

The correction for multiple scattering was not introduced, but it is negligible for their sample.

Abstract 5

Author:

J. A. Farrell, G. F. Auchampaugh, M. S. Moore and P. A. Seeger.

Reference:

IAEA Conference on Nuclear Data for Reactors, Helsinki, 15-19 June 1970, paper CN-26/46. Vol. 1, p.543 (1970).

Establishment:

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87544, USA.

Quantities Measured:

The fission, capture, scattering and total cross-sections of Pu-239 have been measured simultaneously over the neutron energy range from 20 eV to 1 MeV, and the ratio $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ was derived.

Accuracy:

The total error in the average value of alpha was from 10 to 19°/o in the energy region from 0.1 to 30 keV.

Neutron Source:

As a pulsed neutron source an underground nuclear explosion was used. The resolution in the thermal region was about 20 nsec/m and above 300 eV the resolution improved to less than 1 nsec/m, but was limited to about 4 nsec/m by the data recording system.

Fission and Capture Detectors:

The plutonium samples used for the fission event detection were viewed by Si solid state detectors at 55° and 90° to the beam. The foils used for the capture cross-section measurements were viewed by two solid state Moxon-Rae type detectors, the efficiency of which was determined absolutely with an accuracy of 5°/o.

Sample Details:

There were three Pu-239 samples, a thin foil, $1.4 \cdot 10^{-6}$ atoms/barn, for the fission cross-section measurement and two thicker foils, 0.00083 atoms/barn and 0.0058 atoms/barn, for the capture, scattering and transmission measurements. The Pu-samples used were 94.41°/o Pu-239, 5.27°/o Pu-240 and 0.3°/o Pu-241.

Flux Measurement:

The neutron flux consisted of two parts, a thermal Maxwellian spectrum peaking at 80 eV and extending to 300 eV, and a 1/E spectrum at higher energies. The neutron flux was determined from the Li-6 and U-235 foils. There was a 10-15°/o discrepancy at the higher energies between the two flux monitors which is probably due to errors in the cross-sections used for Li-6 and U-235. The U-235 evaluation of Davey (77) was used as reference cross-section.

Experimental Arrangement:

The neutron beam was brought to the surface of the ground in an evacuated pipe and collimated to a circle of 1.74 cm diameter before passing through the stack of samples. Background for the flux monitors and the fission cross-section were measured with the blank foil. A bismuth sample provided a measurement of the scattered neutron background in the capture detectors. Transmission through the Pu-samples was measured by Li-6 foils located above each sample.

Data Normalization:

To obtain the capture cross-section the fission contribution was subtracted from the raw capture plus fission signal. The fission gamma efficiency was determined from eight broad 0^+ resonances to be 1.27±0.08 times the capture efficiency. The efficiency of the capture detector was determined by a separate experiment on the same event by activation of a ribbon of gold.

Corrections and Errors:

The predominant errors in the capture cross-section and consequently in alpha are due to the subtraction of the large fission background, especially at high energies. The estimated error in the capture detector efficiency determination is 5°/o, and the determination of the efficiency was dependent on the assumption that the efficiency is independent of the gamma-ray spectrum. The total error in the α-value measured includes statistical errors, errors in fission gamma subtraction and estimates of systematic errors due to target density, detector efficiency and solid angle etc. Not included are possible systematic errors due to uncertainty in the zero level of the amplifiers used and the background from the aluminium sample container, which are expected to be small below 30 keV.

The capture plus fission data were corrected for self-absorption using the signals recorded from the Li-foils positioned on each side of the capture samples. No multiple scattering correction has been made (the correction is estimated to be 5-10°/o on the highest peaks).

Authors' Comments:

In the present experiment, the energy dependence of alpha for Pu-239 is determined rather accurately below 10 keV. Above 10 keV, where the capture cross-section is small, the error due to the subtraction of the large fission background (about 85°/o of the signal at 30 keV) is large. Besides, above 30 keV there was an additional background due to the aluminium sample container. Therefore in the energy region from 10 to 30 keV α-values were determined with an accuracy of about 30°/o, which is less than the accuracy achievable in the Van de Graaff measurements.

Abstractors' Comments:

No corrections for the content of Pu-240 and Pu-241 in the samples were incorporated. There is no need to introduce the correction for the spin-energy dependence of $\bar{\nu}$ -values into the results of this experiment.

Abstract 6

Author:

V. N. Kononov, M. A. Kurov, E. D. Poletayev, Yu. S. Prokopets, Yu. V. Ryabov, So Don Sik, Yu. Ya. Stavisskii and N. Chikov.

Reference:

Dubna Preprint P3-5112 (1970); also Nuclear Data for Reactors, Vol. 1, IAEA Vienna (1970) 345 and Atomnaya Energiya 30, (1971) 362. These measurements are referred to in this abstract as the JINR-FEI data.

Establishment:

Joint Institute for Nuclear Research, Dubna, and Institute of Physics and Power Engineering, Obninsk, USSR.

Quantities Measured:

The quantity $\alpha(E) = \sigma_{n\gamma}(E)/\sigma_{nf}(E)$ has been measured in the energy region 0.1 to 29.5 keV.

Accuracy:

The total error in the α-value is 7 to 30°/o in the energy region from 0.1 to 30 keV.

Neutron Source:

As a source of neutrons in one case a pulsed fast reactor with the resolution of 220 nsec/m, and in the second case a pulsed fast reactor with an electron injector-microtron with a resolution of 15 nsec/m have been used. Time-of-flight method with a flight path of 250 m was used.

Fission and Capture Detectors:

Fission events were measured by using a high-efficiency ionization fission chamber containing 120 mg of Pu-239. A large liquid scintillator with a volume of 500 litres was used for recording capture and fission gamma-rays. The detector was divided into two halves connected in coincidence, and it had an important characteristic, namely the low sensitivity to any minor changes in the capture gamma spectrum.

Sample Details:

"Thin" layers of Pu-239 were used in an ionization chamber (120 mg of Pu-239). A "thick" sample used in a liquid scintillator was about 7 grams (7×10^{-4} atoms/barn) with the content of 1.5°/o Pu-240.

Flux Measurement:

The energy dependence ne on flux has not been measured in this experiment, and the shape of the flux was assumed to be $E^{-0.81}$, as had been obtained by other authors with a flight path of 250 m.

Experimental Arrangement:

The neutron beam passed through the central channel of the scintillation detector where a sample was placed in nearly 4 π-geometry. The neutron filters used were Na (2.85 keV), Mn (0.337 keV), Co (0.132 keV), Ag (5.2 eV). For microtron operation three series of measurements were carried out using a sample, and one series of measurements using the fission chamber. For reactor operation one series of measurements was performed using the chamber and one series using a sample.

Data Normalization:

For calibration purposes the authors used the resonance alpha-values for 12 well-resolved resonances obtained in the other works, namely in the work of Derrien et al. (75), Stehn et al. (76), Bollinger et al. ([illegible]), Gwin et al. (77), the first set of alpha resonance parameters of Schomberg et al. (78) and Ryabov et al. (79). These data were not simply averaged, but were used to obtain the normalization constants by a least squares method which took into account both the errors in each set of α-values and the errors in the experimental values of N_γ and N_F obtained in the experiment.

Corrections and Errors:

The total error in the α-value measured (about 15-20°/o) mainly consists of statistical errors in the measurement of N_γ/N_F, statistical errors in the background determination, and the normalization errors.

The results for microtron operation were obtained by averaging for the three series of measurements and the errors given characterize the mean square spread of the data in these series. The error in α is due to statistical error in the measurement of the ratio N_γ/N_F and to allowance for the background for each series (20-50°/o). In the case of reactor operation the accuracy of the α-values measured is ±15-20°/o.

Authors' Comments:

The fission cross-section values measured in this experiment with an accuracy of 15°/o are of illustrative nature only, as σ_{nf} and alpha have been obtained with different normalization. There is good agreement over the entire energy range with the JINR-2 measurements (40) using a resolution of 60 nsec/m. The measurement of both capture and fission events was carried out with a thick sample, and fission events with a thin one. To obtain the normalization constants (A and B) the areas under resonances have been corrected for the thickness, using an area analysis method with taking into account the resonance parameters and Doppler widths. So the constants A and B effectively belong to a thin sample and all the samples used were considered to be thin in the energy region higher than 0.1 keV.

Abstractors' Comments:

As the measurement of fission events was made by an ionization chamber, and capture and fission events were measured with a thick sample, the latter results (capture plus fission) will require a correction for resonance self-shielding. Such a correction was not made in the JINR-FEI measurement in the region of unresolved resonances.

No correction was made for the content of Pu-240 in the sample.

The JINR-FEI and JINR-2 measurements of Ryabov et al. (40) do not agree with each other in the region around 600 eV where the structure exists.

The reasons for rejecting this experiment or considering it with less weight are the following:

(1) The data do not show the structure expected around 600 eV. It is surprising that in the energy region 0.65 keV there is a great difference between the JINR-FEI measurement which gives the α-value less than 1, and the results of other measurements where α varies from 1.44 to 1.89. Such absence of the structure which has been reliably determined in the other measurements gives evidence of the weak sensitivity of the experiment used to genuine α-variation.

(2) The difference between α-values obtained in microtron and reactor conditions is rather significant in some energy intervals, such as 0.2 - 0.3, 0.3 - 0.4, 0.7 - 0.8, 4 - 5, 5 - 6, 6 - 7 keV, lying outside the experimental errors given by the authors. The data of both series differ greatly in some energy intervals from the mean values of other measurements.

Because of poor accuracy in σ_{nf} obtained in the present work (about 15°/o) it is difficult to make detailed comparison between the data of the present experiment and the other experiments. Rough comparison shows that the data of the present experiment are systematically higher, particularly in the energy region 0.3 - 1 keV (about 20-30°/o). We agree with the remarks of the authors that $<\sigma_{nf}>$ values are not always sufficient criteria of the quality of the experiment, because background for the detection of fission events is, as a rule, quite low and can be treated very well, but the absolute value of σ_{nf} depends upon both normalization of σ_{nf} and the energy dependence of neutron flux, which do not affect the α-values measured. The energy dependence of neutron flux has not been measured in the present work, thus the σ_{nf} values obtained are to be mainly considered as illustrative only.

(3) The reactor series of measurements were carried out with poor energy resolution and therefore comparisons with other experiments are difficult because of the structure in the cross-sections of Pu-239.

Abstract 7

Authors:

Yu. V. Ryabov, So Don Sik, N. Chikov and M. A. Kurov.

Reference:

Preprint of the Joint Institute of Nuclear Research P3-5113, 1970; IAEA Conference on Nuclear Data for Reactors, Helsinki, 15-19 June 1970, paper CN-26/124, part I, Vol. 1, p. 345 (1970) and Atomnaya Energiya 30, (1971) 258. The second series of measurements referred here as the JINR-2 measurement and in the text as Ryabov et al. measurement.

Establishment:

Joint Institute for Nuclear Research, Dubna, USSR.

Quantities Measured:

The quantity $\alpha(E) = \sigma_{n\gamma}(E)/\sigma_{nf}(E)$ has been measured in the energy region 0.1 to 20 keV.

Accuracy:

The total error in $\alpha(E)$ is 7 to 25°/o in the energy region from 0.1 to 20 keV.

Neutron Source:

A pulsed fast reactor, time-of-flight method, the neutron flight path was 1010 m, and the resolution 60 nsec/m.

Fission and Capture Detectors:

A 500 litre liquid scintillation detector in which cadmium had been added to the solution, so that the ratio of the nuclei Cd to H was 0.004. The fission events were recorded by double delayed coincidences in the liquid scintillator, and capture events were detected in the same scintillator without coincidences.

Sample Details:

Five different samples of Pu-239 were used: $2.85.10^{-4}$, $5.8.10^{-4}$, $8.7.10^{-4}$, $1.42.10^{-3}$, $2.7.10^{-3}$ atoms/barn with the content of 1.5°/o Pu-240.

Flux Measurement:

The relative energy dependence of the neutron flux was measured by 10 BF_3 counters.

Experimental Arrangement:

Time spectra for fission and radiative capture in samples of Pu-239 were measured. The threshold for gamma-ray detection from fission was 0.3 MeV, and for gamma-ray from capture - 0.7 MeV, and for neutrons - 0.8-1.5 MeV. For experimental determination of the background level the neutron filters used were Ag, Co, Mn, Na and Ti.

Data Normalization:

For normalization purposes the authors used the same resonance alpha-values taken from the same works as in the JINR-FEI measurements.

Corrections and Errors:

The total error in the α-value measured is mainly determined by systematic errors due to the variable background component, scattered neutrons, and normalization errors. No correction for the Pu-240 content in the samples was introduced. The detector efficiences were considered to be constant in the energy region measured. The final results for α have been obtained by averaging over all the sets of measurements, while the errors shown describe the mean square spread of α for individual series of measurements.

Authors' Comments:

The measurement of α have been made with a view to further refining previously published results (80). Two modifications have been made since the first experiment had been carried out:

(a) the total background has been reduced from 70°/o to 40°/o in the case of capture events, and in the case of fission the total background was reduced to 30°/o;

(b) in order to avoid the problem of incorporating multiple scattering corrections, the alpha measurements were carried out with several plutonium samples of different thicknesses from $2.85.10^{-4}$ to $2.7.10^{-3}$ nuclei/barn.

It is necessary to point out that in the present work the major part of fission gamma-rays has been subtracted using the anti-coincidence technique ($\varepsilon_{cf}/\varepsilon_{cc}$ was equal to 0.3). Therefore the method used in the experiment is little sensitive to "σ_{nf}-criteria", but sensitive to a certain degree to scattered neutrons.

The σ_{nf} values which are given in the report, do not represent the 'best' cross-section, but they are just one of a series obtained with the sample of thickness 5.10^{-4} atoms/barn.

Abstractors' Comments:

(1) At the energies 0.45, 0.75, 0.85 and 0.95 keV the α-values obtained by Ryabov et al. look very high, higher than the results of other six laboratories. It looks like there is the same tendency towards the high α-values in the region 0.4 - 1 keV as in the earlier work by Ryabov (80). Earlier this effect was explained by correlation with the low σ_{nf} values. In the present measurement the σ_{nf} values are very low in the region 0.3 - 0.4 and 0.4 - 0.5 keV (5.8 and 3.7 barns instead of 8.8 and 9.5 barns), and in the energy region 0.5 - 1.0 keV they are slightly higher than those of other laboratories, coinciding with them within error limits.

The sensitivity of the method used for scattered neutrons can lead to higher α-values in the regions where $\sigma_{n\gamma}$ is small.

The question which seems to require careful checking in this experiment, as well as in the JINR-FEI measurements (39), is the role of "tails" in the resolution function of the neutron spectrometer. Indeed, if the strong fluctuations in the energy α-dependence are due to maxima and minima in cross-sections, then the tails in the resolution function will add to the small cross-section values a considerable part from the nearest maximum, so the real fluctuation of the α-value would be artificially smoothed.

The authors have carried out the α-measurements for five different sample thicknesses and have not discovered the dependence of α on the sample thickness. The effect of resonance self-shielding might in principle lead to such dependence. The resonance self-shielding will be different for σ_{nf} and $\sigma_{n\gamma}$, because broader fission resonances are less affected by this effect than the narrow resonances with high α. The errors quoted do not include the systematic errors. We propose to add in quadrature to the quoted error the larger of $\pm 7^{o}/o$ and ± 0.04 to correct for this deficiency.

An uncertainty in the α values due to uncertainty in the energy dependence of the $\bar{\nu}$ -values (about $5^{o}/o$ in α) should be added to the total α-error.

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FIGURE CAPTIONS

1) Early measurements and evaluations of Pu-239 alpha.

2) Measurements of $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ for Pu-239 between 100eV and 30keV.

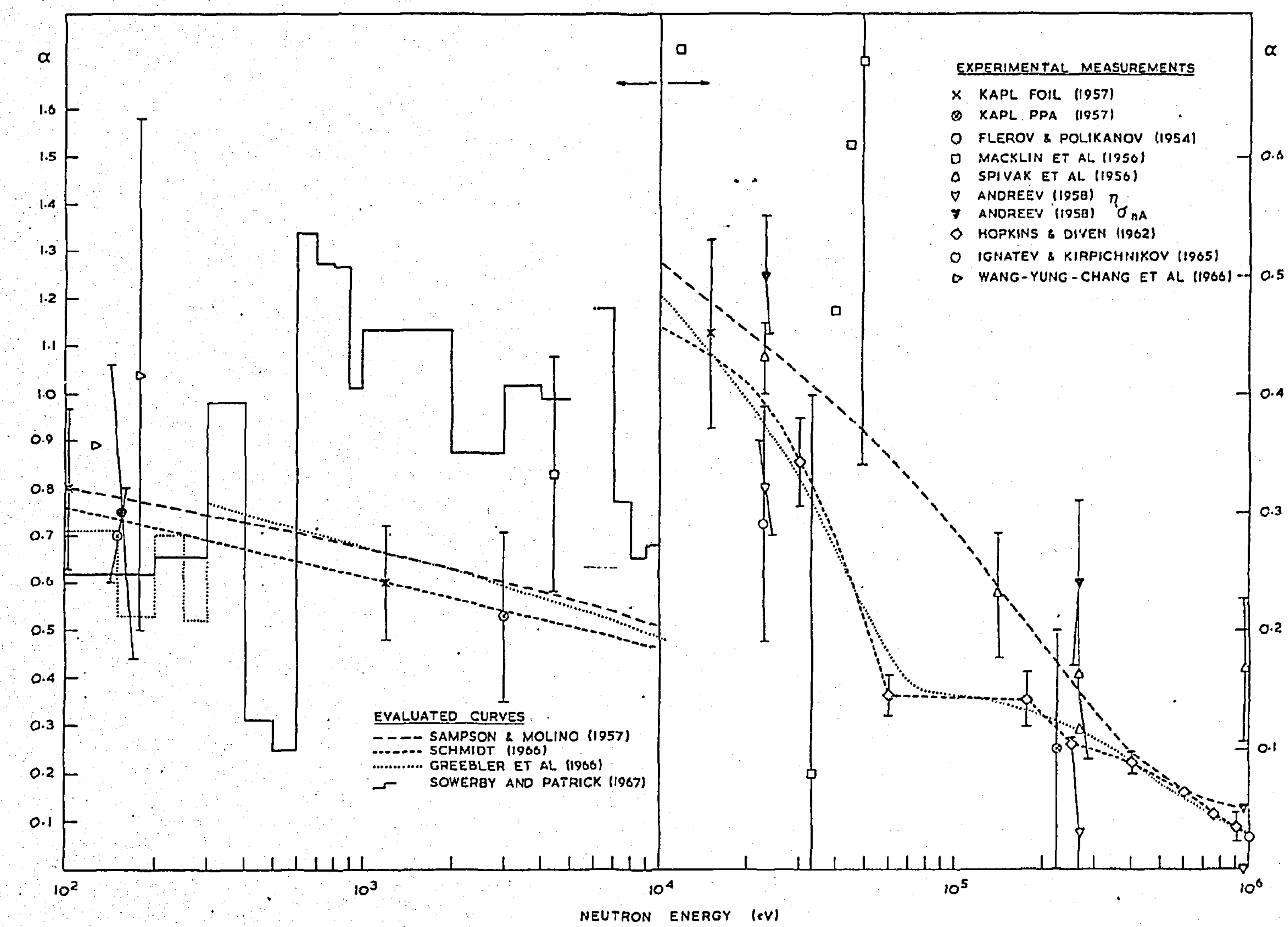
3) Measurements of Pu-239 alpha between 10 and 100keV.

4) Measurements of Pu-239 alpha between 100keV and 1MeV.

5) Comparison of the present evaluation with recent measurements.

6) Structure in $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ and $\langle\sigma_{nf}\rangle$ between 0.1 and 4keV observed by Schomberg et al(35).

7) Comparison of $\langle\Gamma_f\rangle$ for 1^+ resonances with $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$. The hatched areas give the limits in $\langle\Gamma_f\rangle$ and the points on the $\langle\sigma_{n\gamma}\rangle/\langle\sigma_{nf}\rangle$ graph are the values calculated from resonance parameters.



α
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
α
0.6
0.5
0.4
0.3
0.2
0.1
EXPERIMENTAL MEASUREMENTS
× KAPL FOIL (1957)
⊗ KAPL PPA (1957)
○ FLEROV & POLIKANOV (1954)
□ MACKLIN ET AL (1956)
△ SPIVAK ET AL (1956)
▽ ANDREEV (1958) η
▼ ANDREEV (1958) σ nA
◇ HOPKINS & DIVEN (1962)
○ IGNATEV & KIRPICHNIKOV (1965)
▷ WANG-YUNG-CHANG ET AL (1966)
EVALUATED CURVES
SAMPSON & MOLINO (1957)
SCHMIDT (1966)
GREEBLER ET AL (1966)
SOWERBY AND PATRICK (1967)
10^2
10^3
10^4
10^5
10^6
NEUTRON ENERGY (eV)

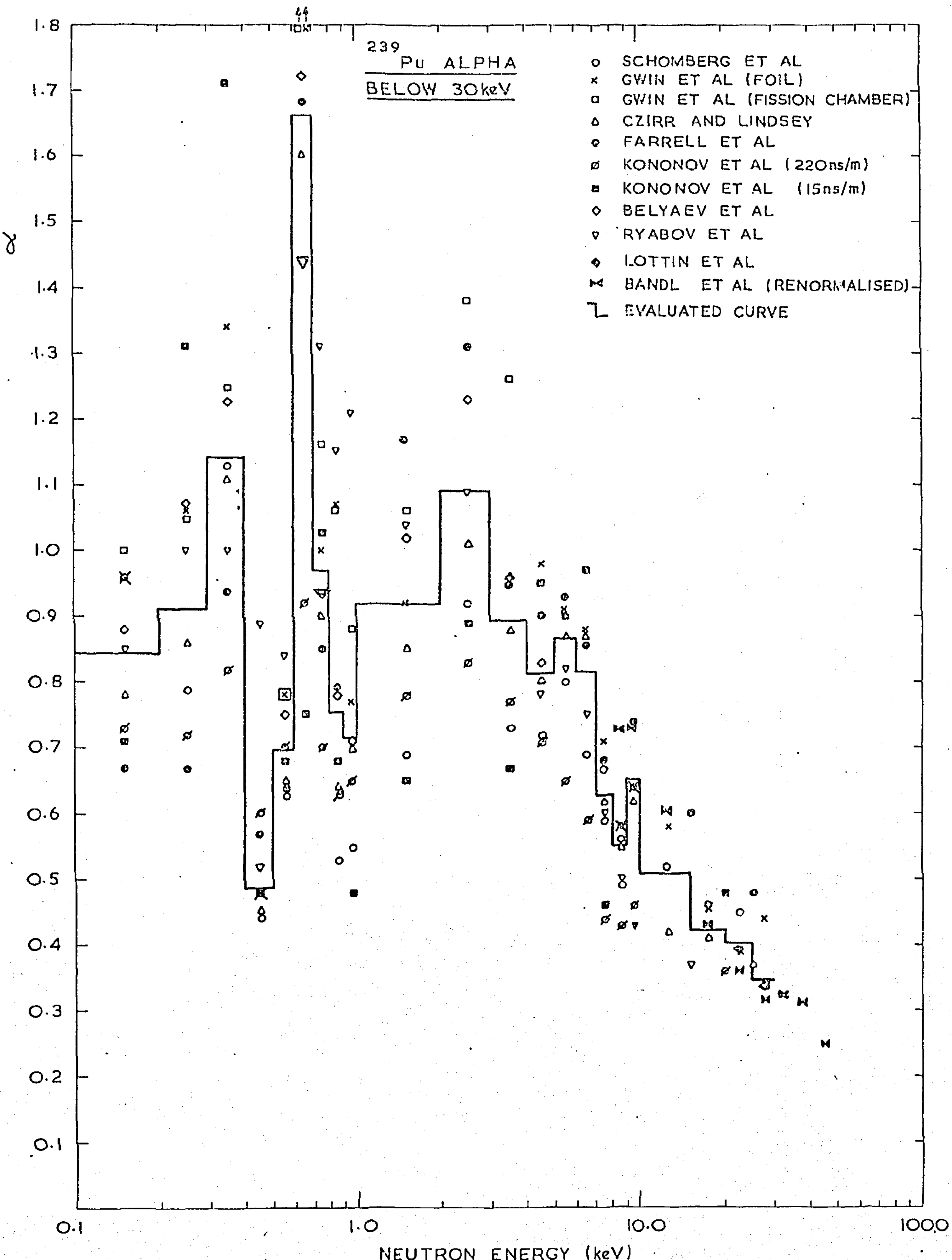

239 Pu ALPHA
BELOW 30keV
SCHOMBERG ET AL
GWIN ET AL (FOIL)
GWIN ET AL (FISSION CHAMBER)
CZIRR AND LINDSEY
FARRELL ET AL
KONONOV ET AL (220ns/m)
KONONOV ET AL (15ns/m)
BELYAEV ET AL
RYABOV ET AL
LOTTIN ET AL
BANDL ET AL (RENORMALISED)
EVALUATED CURVE
α
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.1
1.0
10.0
100.0
NEUTRON ENERGY (keV)

Fig. 2

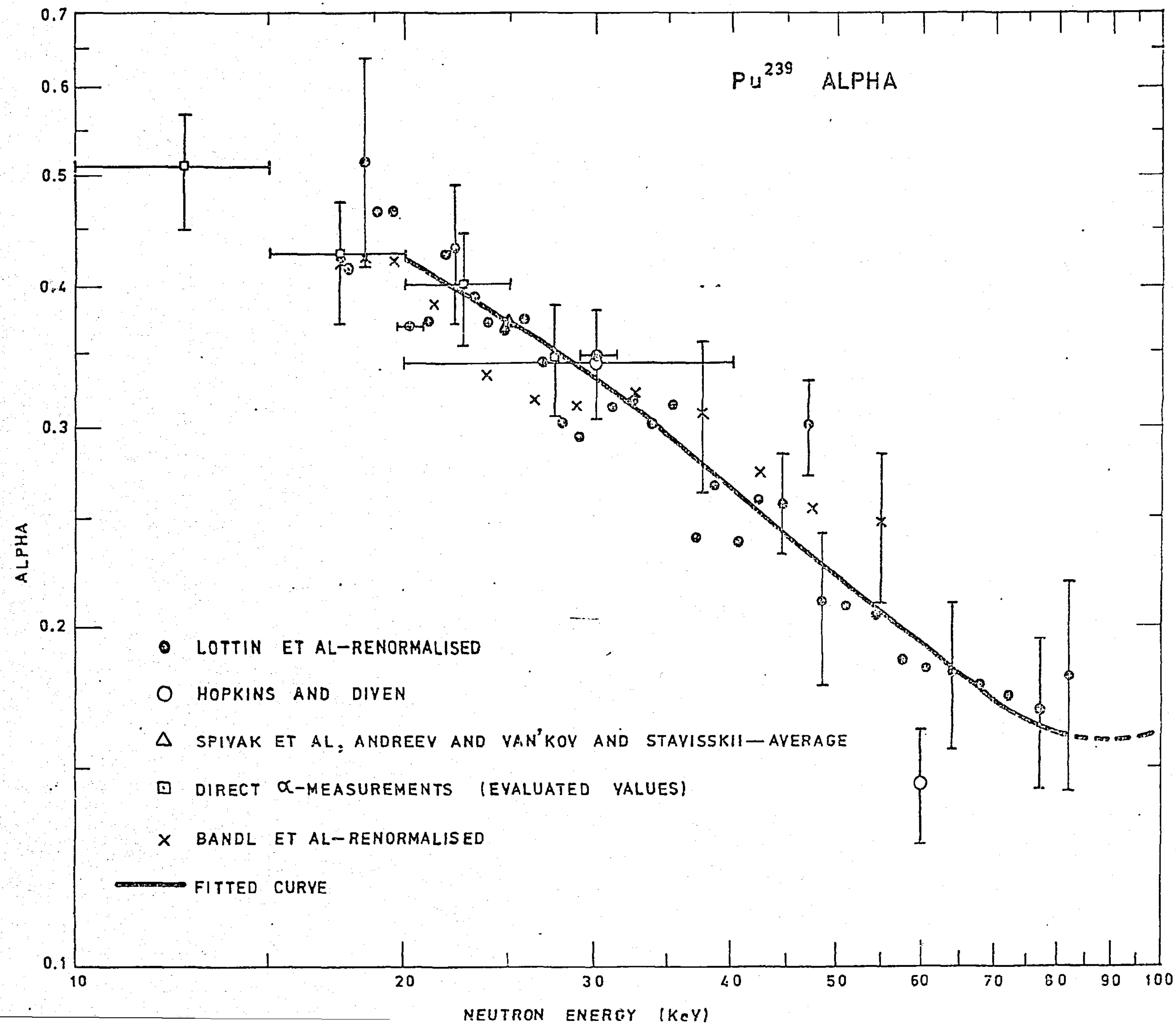
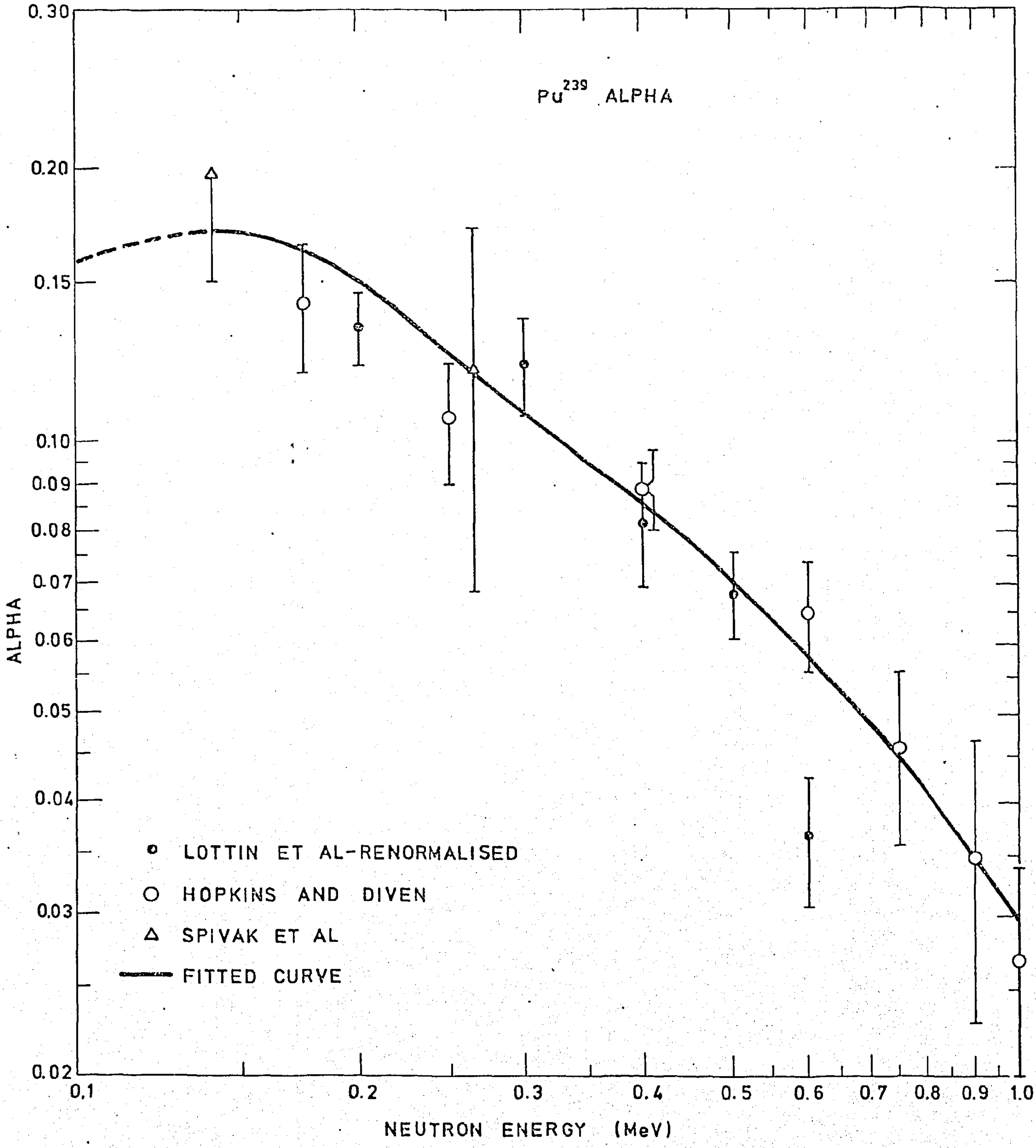
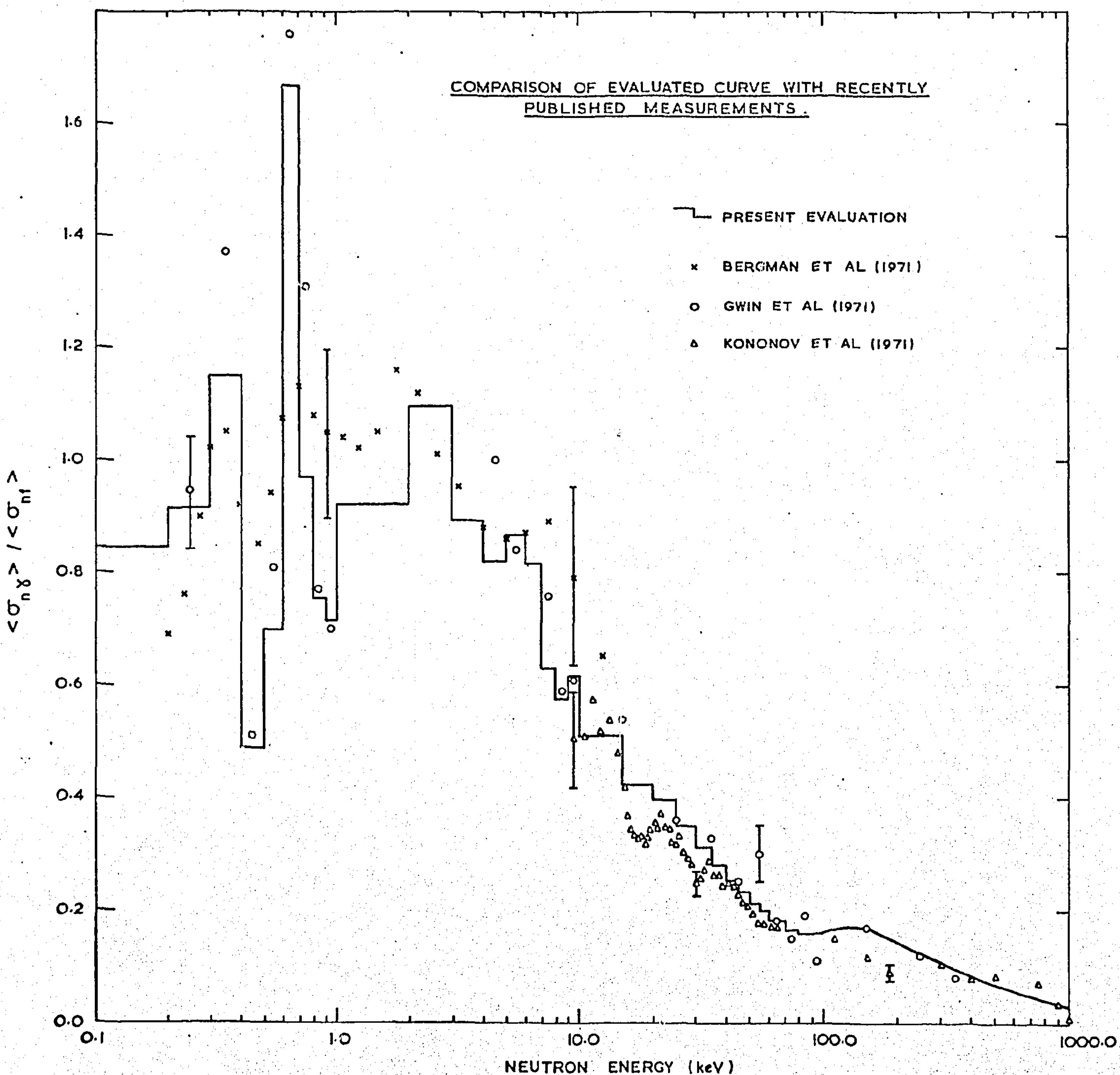

Pu239 ALPHA
ALPHA
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10
20
30
40
50
60
70
80
90
100
NEUTRON ENERGY (KeV)
LOTTIN ET AL-RENORMALISED
HOPKINS AND DIVEN
SPIVAK ET AL, ANDREEV AND VAN'KOV AND STAVISSKII—AVERAGE
DIRECT α-MEASUREMENTS (EVALUATED VALUES)
BANDL ET AL-RENORMALISED
FITTED CURVE

Fig. 3



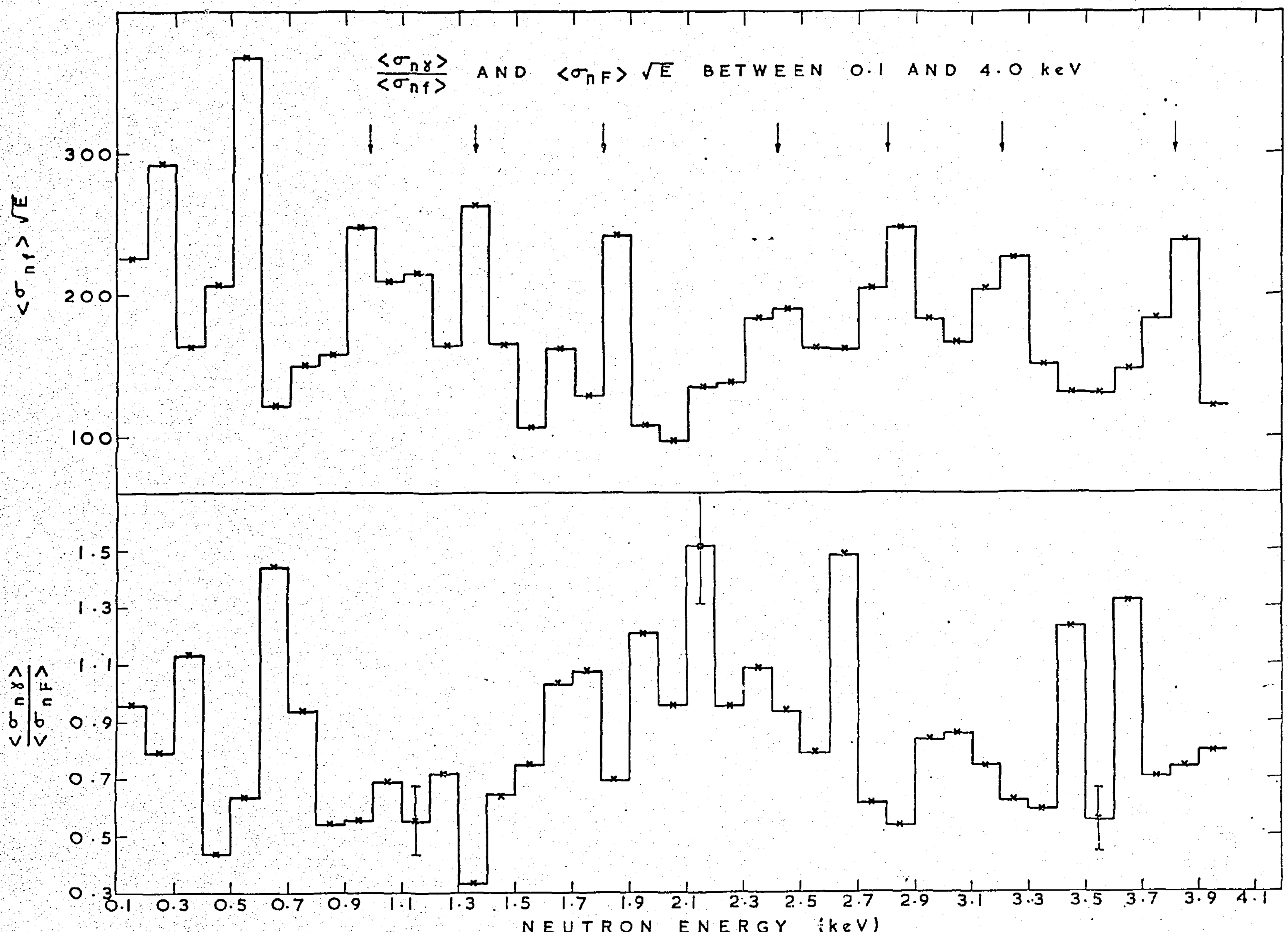
Pu^{239} ALPHA
ALPHA
0.30
0.20
0.15
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
NEUTRON ENERGY (MeV)
LOTTIN ET AL-RENORMALISED
HOPKINS AND DIVEN
SPIVAK ET AL
FITTED CURVE

Fig. 4



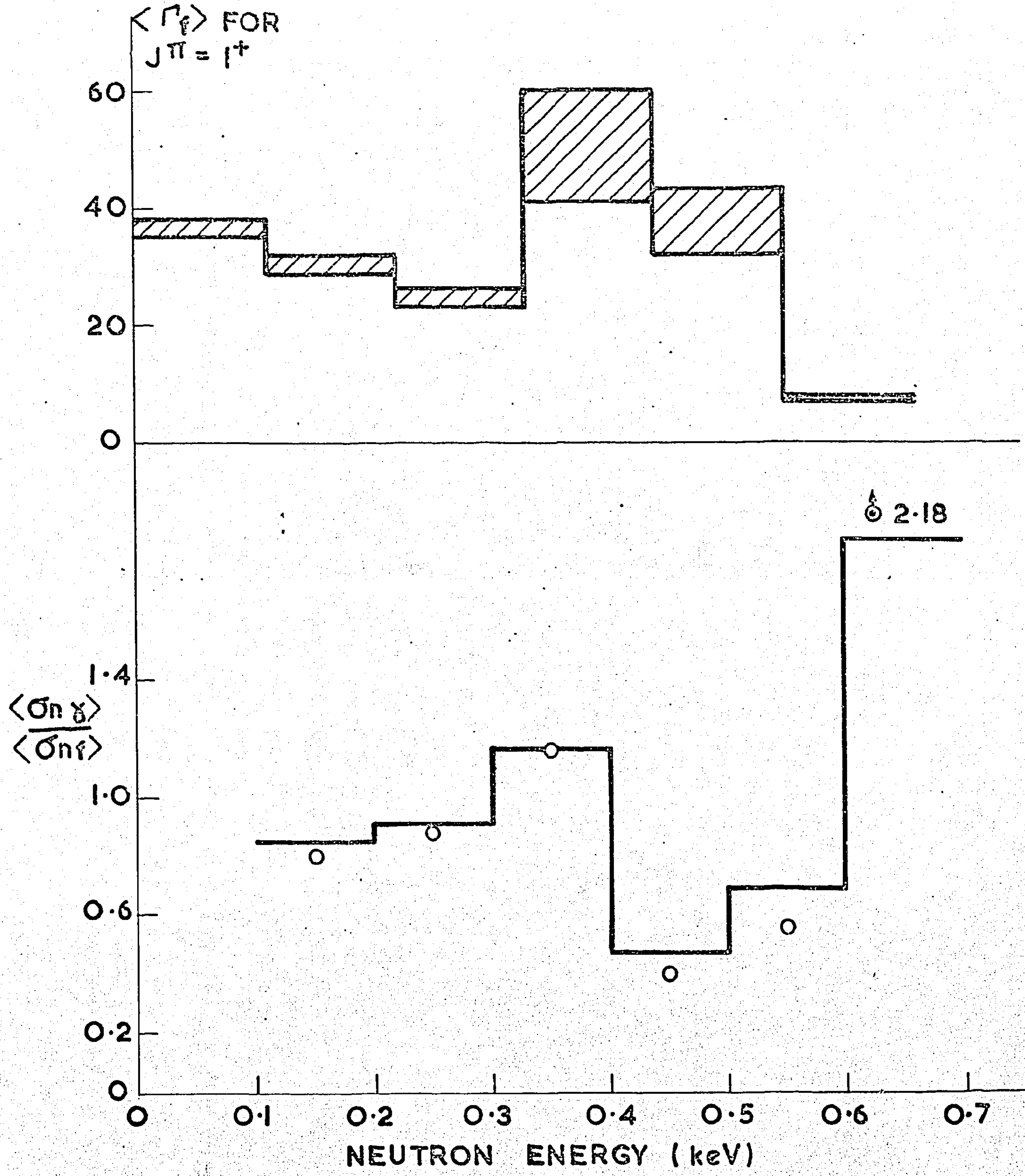
COMPARISON OF EVALUATED CURVE WITH RECENTLY PUBLISHED MEASUREMENTS.
PRESENT EVALUATION
BERGMAN ET AL (1971)
GWIN ET AL (1971)
KONONOV ET AL (1971)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.1
1.0
10.0
100.0
1000.0
$<\sigma_{n\gamma}> / <\sigma_{nf}>$
NEUTRON ENERGY (keV)

Fig 5.



<σnγ>/<σnf> AND <σnF> √E BETWEEN 0·1 AND 4·0 keV
<σnf> √E
300
200
100
<σnγ>/<σnF>
1·5
1·3
1·1
0·9
0·7
0·5
0·3
0·1 0·3 0·5 0·7 0·9 1·1 1·3 1·5 1·7 1·9 2·1 2·3 2·5 2·7 2·9 3·1 3·3 3·5 3·7 3·9 4·1
NEUTRON ENERGY (keV)

Fig 6



CAMPARISON OF $\langle \Gamma_f \rangle$ FOR $J^{\pi} = 1^+$ WITH EVALUATED $\langle \sigma_{n\gamma} \rangle / \langle \sigma_{nf} \rangle$

Fig 7