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SECOND ADVISORY GROUP MEETING ON
TRANSACTINIUM ISOTOPE NUCLEAR DATA
ORGANIZED BY THE
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AND HELD IN
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Meeting Summary

The Second Advisory Group Meeting on Transactinium Isotope Nuclear Data was convened by the IAEA Nuclear Data Section at the CEA Centre d'Etudes Nucleaires at Cadarache, France, from 2-5 May 1979. The meeting was attended by 37 representatives from 10 Member States and 2 international organizations. The first meeting on this topic was held at the Kernforschungszentrum Karlsruhe in November 1975.

The main objectives of this meeting were to assess the transactinium nuclear data (TND) requirements for nuclear fission reactors and fuel cycles, with emphasis on new trends in nuclear technology, and to review the status of the required TND in the light of measurements, calculations and evaluations.

This report contains the text of all review papers prepared specifically for this meeting which address both the requirements for and the status of transactinium isotope nuclear data. The summary report of this meeting, including the recommendations for future activities, has been published in the IAEA Nuclear Data Section report INDC(NDS)-106/LNH.

CONTENTS

A. SURVEY OF TND REQUIREMENTS

COMPREHENSIVE REVIEW OF TND REQUIREMENTS FOR U AND U-Pu FUELED THERMAL AND FAST REACTORS, AND THEIR ASSOCIATED FUEL CYCLES

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Abstract

This paper reviews the major problems that have led to the need for transactinium nuclear data (TND), and summarizes the current status of TND requirements for uranium and uranium-plutonium fueled thermal and fast reactors in context of the recent developments and fuel cycle studies completed since the first IAEA TND meeting held in Karlsruhe in 1975.

- INTRODUCTION -

The first TND meeting in Karlsruhe in 1975 /1/ concluded by emphasizing that the extent of transactinium isotope nuclear data requirements could not be assessed in view of the rapid development of fuel cycle problems. It was nevertheless clear that for industrial reactors and in the fuel cycle processes at a similar development stage, the majority of the most compelling requirements were related to reactor core physics.

Although in the nearly four years since the Karlsruhe meeting no major problem has arisen in this area, it is worthwhile to re-examine the current status of TND requirements in view of recent developments in this field-especially fuel cycle studies completed in the interim.

The subject of this paper was covered at Karlsruhe by all or part of five documents (review papers A2, A3, A5, A6 & A8) and no attempt will therefore be made here to discuss in detail all of the problems which were presented and analyzed in 1975. However, the first section of this paper reviews the major problems whose existence has led to the need for transactinium nuclear data, and the third section summarizes the current status of TND requirements. Both of these sections therefore contain information which remains unchanged since 1975.

The second section of this document discusses a number of points concerning which new developments have occurred in the past few years, with particular attention to their repercussions on TND requirements. This section makes extensive use of works published in the interim, particularly at the recent Harwell Conference on nuclear data and at meetings of the NEACRP which has been very active in this area and will publish shortly a summary report on all the problems related to actinide buildup and decay.

1 - REVIEW OF THE SIGNIFICANCE OF THE ACTINIDES IN REACTORS AND THEIR FUEL CYCLES -

Three points should be made clear to specify the limits of the area covered by this paper.

a) The following discussion covers only uranium or uranium-plutonium fueled thermal and fast breeder reactors, together with the operations involved in the relevant fuel cycles.

b) The primary isotopes in the fuel cycle (^{235}U, ^{238}U and ^{239}Pu) are not discussed here with regard to their role and their principal nuclear data.

c) The buildup and decay processes for the transactinium isotopes have been described elsewhere and will not be discussed here, even though in some cases (e.g. ^{232}U) the full list of these processes is not fully self evident by virtue of their importance.

1-1 : Actinide Buildup

In recent years a large number of values have been advanced (cf/2/, /3/ and /4/) for all the isotopes of any importance either in the reactor core or in the remainder of the fuel cycle. A very wide dispersion exists for the isotopes which have only recently become the subject of serious interest. This dispersion might be interpreted as indicating that problem is not well understood, and that assessment of the results of "secondary" actinide buildup are subject to underestimations or even to omissions.

The reasons for this dispersion may, in fact, be distinguished :

a) The initial estimates were often made using highly simplified methods (burn-up codes with a single energy group using constant cross sections ; e.g. /5/) and on the basis of data not necessarily corresponding to present-day knowledge. If these calculations are repeated under better conditions, the results are very often appreciably different.

b) Isotopes with low concentrations generally result from a process of consecutive reactions, and their buildup varies with the 3rd or 4th power of the specific burn-up (this is true, for example, of ^{232}U, ^{238}Pu, ^{243}Am and all the curium isotopes from initial uranium fuel).Under these conditions, slight differences in the specific burn-up value considered lead to major discrepancies in concentration values for these isotopes.

c) The third - and probably the most important - reason is related to the fundamental calculation hypotheses, and principally to the detail of the relevant fuel cycle. A characteristic if not extreme example of this, involves the comparison of the values of actinide buildup for plutonium fuel recycling in light water reactors.The range of concentration values for the same isotope in the same type of reactor at the same specific burn-up often reaches factors of 5 or 10.This spread is easily explained by examining the various possible calculation hypotheses, as much as there is no single plutonium recycling process. The most common reactor calculation hypothesis involves partial refueling of existing reactors in order to achieve plutonium self-burnup and to avoid the need for any technological modifications to the reactors ;

the refueling fraction is then on the order of 20-30%. Depending on the reactor type, the fuel may be leaded either in mixed fuel assemblies or in "all-Pu" assemblies. Under these conditions, the secondary actinide buildup differs only slightly from the values obtained with uranium fuel (cf /2/ for example). If, however, it is assumed that special reactors are designed to burn recycled plutonium and that they are loaded with 'all-Pu" fuel, the resulting figures are obviously substantially different (cf /3/ & /4/ for example).

This, of course, is only an example. The discrepancies are scarcely less significant for fast breeder reactor fuel depending on whether the plutonium fraction comes from natural uranium reactors, light water reactors or from the fast breeder reactor itself in an equilibrium cycle (cf /4/).

The preceding paragraphs are intended primarily to prevent erroneous interpretations of the data in the Tables. It may be added that, although appreciable errors may still exist concerning very minor isotopes (as discussed in Section 2, the only way to detect such errors is by comparison with experimental findings), there is no longer any reason to suppose that major errors are still present for any significant isotopes in reactors which have reached or are nearing the industrial stage.

Finally, in order to avoid complicating the situation further with another table , this paper covers only selected concentration ranges capable of leading to a better overall assessment of the problem.

Table I shows the variations which may be expected for each of the causes mentioned above, while Table II summarizes the concentration ranges for the major fuel cycle options for light water reactors and fast breeder reactors.

1-2 : Reactor design and operation

Reactor core physics considerations have always motivated the most precise requirements in the areas of fission or capture cross sections. Although certain actinide isotopes have no significant effect except on the out-of-pile fuel cycle,this assertion may be considered accurate on the whole for the secondary actinides, as was clearly evident in the conclusions of the first meeting at Karlsruhe /1/.

The sources of the major nuclear data requirements are briefly reviewed below with reference to recent general works on this subject /6/ /7/.

The other design and operating problems are relatively unaffected by the secondary actinides with the exception of neutron emission, for shielding considerations, and after-power, for which the secondary actinide contribution is not at all negligible in certain cases.

1-2-1 : LWR Physics

The reactivity is pratically the only LWR core parameter affected by the presence of actinides other than the principal fissile and fertile isotopes. This was analyzed in detail at Karlsruhe /2/ and need not be referred to here except to

confirm the requirements stated at that time, as indicated in Table III. As will be discussed later, sensitivity studies since then on plutonium recycling have modified these requirements for certain isotopes, and it is now firmly established that this constitutes an exhaustive list of requirements related to current thermal neutron reactors.

Secondary actinide effects on reactor power, temperature coefficients and kinetics are in all cases negligible or result in less specific requirements than the reactivity modifications.

1-2-2 : FBR Physics

Here again, the 1975 conclusions were precise and are not disputed. The most specific requirements concern reactivity and, in particular, reactivity variations during the fuel cycle /2/, /7/. The heavier plutonium isotopes have a predominant effect on this parameter as well as on the breeding ratio and power level. Accurate orders of magnitude are sufficient for the other isotopes except for ^{241}Am which may become much more significant in the event of prolonged storage of fresh fuel or fuel in the process of irradiation.

Table IV summarizes the TND requirements for fast neutron reactors. It too may be considered an exhaustive list for U-Pu fueled FBRs. Contrary to a widespread opinion, consecutive plutonium cycles in this type of reactor do not result in larger amounts of secondary actinides : some ones are burned by the reactor faster than they are produced.

1-2-3 : Other Design or Operating Problems

Actinide shielding problems are attributable to the α and neutron emission of certain isotopes ; at this stage the γ emission is always negligible compared with that of the fission products.

These problems were reviewed in detail at Karlsruhe /8/ and were also discussed in papers at Harwell /9/ /10/.

Except for the effects of ^{239}Np on the residual power in the first few hours after shutdown, the other effects are almost exclusively attributable to ^{242}Cm and ^{244}Cm.

The transactinium isotopes are not involved in plant personnel contamination and irradiation hazards. They could result in strong α contamination only in the event of massive cladding failures ; under these conditions the curium isotopes would again predominate and numerous other uncertainty factors would be much more significant than those related to nuclear data.

In conclusion it may be affirmed that TND requirements relevant to reactor core physics are more important than those arising from any other design or operating problem.

1-3 : Out-of-Pile Fuel Cycle Problems

This vast field covers fuel element transport and storage, reprocessing, uranium enrichment, fuel fabrication from recycled materials and waste material management. Three major categories of problems arise with respect to the presence of secondary actinides :

- Isotopic composition data requirements for fuel cycle management
- Problems arising from the activity of certain isotopes
- Actinide effects on measurement and control problems.

Before considering each of these categories, two general observations are in order :

a) The relevant isotopes or their parent products are produced in the reactors. No attempt to optimize secondary actinide buildup is made in the design of the core or of the fuel elements ; that is, no effort is made to favorize the formation of certain isotopes or to limit the production of others. Rather, these products result from nuclear reactions considered secondary with respect to those involved in the basic design options. This accounts for the delated interest in these isotopes at a time when the reactors themselves and the major fuel cycle operations have already reached the industrial stage.

b) As mentioned in section 1-1, transactinium isotope buildup is in most cases highly variable depending on the operational hypotheses (fuel type and enrichment, storage time, specific burnup, origin of recycled material, etc?). The out-of-pile fuel cycle operations are designed to cover a wide range of possibilities, so that the uncertainty on isotope calculation is generally small compared with the variation limits accepted in the plant designing. For example, a LWR fuel reprocessing plant such as La Hague must be capable of reprocessing PWR or BWR fuels with varying initial enrichment values and within wide ranges of specific burnups and cooling times. This operational flexibility is ensured by providing specified safety margins with respect to the least favorable case conditions. Under these circumstances the uncertainty on the buildup of a particular americium or curium isotope, for example, is totally marginal. This explains the low accuracy levels required in most cases.

1-3-1 : Isotopic Composition Data

Irrespective of actinide activity problems, covered in the following paragraph, these data are important for fuel cycle management :

- re-utilization of fissile material
- radioactive waste disposal.

Such data may be obtained in two ways : by prior calculation or by subsequent analysis. This is relevant to core physics in that both calculated projections and examinations of the results of material recycling make use of reactor physics methods.

For the purposes of this review it will be assumed that only uranium and plutonium are recycled. The hypothesis of recycling other actinides is considered in another review paper at this meeting /11/.

Two problems arise in conjunction with recycling reprocessed uranium :
- the presence of ^{232}U
- the increased abundance of ^{236}U

The consequences and related TND requirements are discussed in Section 2-2 of this paper.

The conditions of plutonium recycling have already been examined since it is fundamental in fast breeder reactor fuel and since the use of recycled plutonium has also been considered for light water reactors.

Table V summarizes the TND requirements for accurate prediction of the final uranium and plutonium compositions in view of recycling. It must be emphasized that the exact compositions are measured in any case prior to re-utilization.

The other transactinium elements are at the present time considered as waste materials and their composition is generally not measured. It is therefore important to be able to estimate the amounts involved. Table VI compares for example the activities of various isotopes and their variation in time for each isotope and its decay products. Long-term waste storage does not call for any precise nuclear data requirements ; it is enough to be able to predict the amounts correctly and this is possible on the basis of data required for reactor calculations.

1-3-2 : Problem Related to Secondary Actinide Activity

These are the major problems involving transactinium isotopes in the fuel cycle today, and were reviewed in detail at Karlsruhe /12/ and at Harwell /10/.

Because of their strong α and neutron activity the curium isotopes are predeminant in the fuel cycle stages from the reactor to the reprocessing plant. Their activity must be correctly predicted, but high accuracy is not required in that the activity of the fission products is much more significant in these phases and substantial shielding measures are mandatory in any event.

The situation is different with regard to the use of recycled uranium and plutonium. In this case a number of secondary actinides are major activity sources - primarily ^{241}Am - ^{238}Pu and the ^{236}Pu - ^{232}U - ^{228}Th decay chains-.Only limited industrial experience is available in this area, but theoretical work shows that the activity of these isotopes may be a secondary limitation on a number of fuel cycle hypotheses or plant design features.

1-3-3 : Measurements and Controls

Radioactive emissions from the secondary actinides may be used to resolve a number of control problems or, on the contrary, may hinder other measurements.

Three measurement categories are involved :
- non-destructive examination of fresh or spent fuels
- fuel fabrication or plant process controls
- nuclear safeguards controls.

Some of these problems were covered in detail at Karlsruhe /13/, and the safeguards control requirements were thoroughly reviewed for the Harwell Conference /14/.

The reprocessing control problems will be discussed again in Section 2, below ; Table VII lists the TND requirements for these measurements and controls.

2 - RECENT TND STUDIES -

This section covers a number of recent studies which may help to obtain a precise assessment of transactinium nuclear data requirements for existing reactors and their fuel cycles. This is by no means an exhaustive review, and simply discusses a selection of studies familiar to the author. These studies are nevertheless sufficiently broad to show that at the present time the uncertainty on possible further requirements is less significant than the uncertainty on the actual accuracy levels achieved for the corresponding data.

2-1 : Sensitivity Studies

The value of sensitivity studies has often been demonstrated for suitable assessments of TND requirements for various applications.

Two such studies relevant to secondary actinides were presented at Karlsruhe /2/, /3/. Each of these papers covered both FBRs and uranium-fueled LWRs.

Since that time, other sensitivity studies have been carried out on transactinium isotopes in fast breeder reactors, notably by Japanese /15/ and Soviet /16/ groups. These studies have confirmed the requirements stated in 1975.

In the light water reactor field a sensibility study was run with various hypotheses concerning plutonium recycling in PWRs or BWRs. This work was completed in the scope of an EEC contract, and covered the cross sections of the heavier plutonium isotopes as well as of the americium and curium isotopes. Several hypotheses were investigated - particularly the case of two consecutive plutonium recycling campaigns with no intermediate blending, which may be considered as an extreme case. The effects of cross section variations were studied on the final actinide concentrations, the fuel α and neutron activities, the after power and the reactivity variations. The must significant results are shown in Table VIII /17/.It is interesting to note that the conclusions of this study modify only slightly the requirements stated in 1975 on the basis of much more cursory calculations.

2-2 : Uranium Recycling

The recycling of LWR waste uranium has always been considered as a standard application after reprocessing, although the consequences of this practice have never been analyzed in great detail.

The residual enrichment of such uranium is slightly less than 1% ^{235}U, but the ^{236}U abundance is relatively high (approx. 0.5%).

Re-enrichment and recycling of this uranium in light water reactors results a nearly 20% reduction in the amount of natural uranium required to fuel these reactors. Three difficulties inherent in this process, however, require re-examination of the problem of nuclear data.

a) The ^{232}U buildup during the first stage of uranium utilization cannot be disregarded with respect to radiation shielding in the enrichment facility and the fuel fabrication plant. This problem is much less pressing than in the thorium fuel cycle, but nevertheless requires a thorough and careful examination by virtue of the fact that the uranium input cycle in LWRs is a very low activity cycle. The ^{232}U buildup results from two formation processes : ^{236}Pu decay (which predominates in most cases) and neutron capture on ^{231}Pa (resulting from ^{235}U decay) or on ^{230}Th (resulting from ^{234}U decay) /18/. The latter process may not be negligible in uranium which has been in extented storage prior to irradiation. The major cross-sections involved in these formation processes are those for which TND requirements are stated in Table V.

b) Re-enrichment of uranium containing a significant amount of ^{236}U necessitates over-enrichment of the fuel to allow for the absorption effect due to this isotope. It is essential to be able to calculate the ^{236}U capture rate correctly in order to assess these effects properly. This does not change the order of magnitude stated in Table III for the TND requirements concerning this isotope for core physics purposes.

c) The third point involves the plutonium formed from this recycled uranium. As a result of the high ^{236}U content there is greater buildup of ^{237}Np under irradiation, and therefore higher concentrations of ^{236}Pu and ^{238}Pu in the final plutonium amount. This increases the difficulties in using this plutonium, especially at the fuel fabrication stage. An example of this problem may be found in table IX, which compares the plutonium breakdown obtained from enriched natural and recycled uranium. These considerations confirm the TND requirements stated in table V for the ^{236}Pu and ^{238}Pu formation processes.

2-3 : Reprocessing Plant Control

The transactinium isotopes may be involved in the input material balance accountability or for nuclear controls in the head-end of the facilities.

a) Input controls

The material balance covers only the principal elements, uranium and plutonium. The balance is obtained by direct chemical analysis methods and therefore requires no prior knowledge of nuclear data. Correlation and interpretation techniques are nevertheless under development to simplify or verify these measurements. An effort is then made to calculate the relation between the isotopic compositions and the element concentration values /19/. The required accuracy level

for such relations are very stringent and can only be achieved with adjusted formula sets. The requirements in this area thus approach those already expressed for core calculation methods.
Moreover, the relevant isotopes are generally the major uranium and plutonium isotopes and primary effort should be concentrated on the data for which the highest accuracy is already required.

b) Nuclear controls

Certain process of safety controls are based on neutron emission from the fuel or the plutonium after fission product separation.
The overall fuel neutron emission is primarily attributable to the curium isotopes ; too many other uncertainty factor (fuel identification, irradiation history, specific burnup, etc...) are involved to achieve reasonable accuracy levels based on calculated projections of this emission. It is thus necessary to fall back on relative measurements, in which case the projected orders of magnitude are adequate.
In the case of plutonium, the principal neutron emission generally results from 238 Pu and 240 Pu. Here again, concentration calculations are not feasible, and the measurement accuracy is determined only by the radioactive decay constants.

2-4 : Comparison of experimental and calculated results

The integral experiments - and especially spent fuel analyses and fission chamber measurements - constitue the basis for evaluating the uncertainties on cross section data. Significant examples were presented at KARLSRUHE /2/ /3/, and other findings have been published in the interim /4/.

In most cases these results confirm that the stated uncertainty bounds for the major isotope cross sections are realistic, although this does not imply that the situation is satisfactory since these uncertainties may exceed the requirements stated in WRENDA.

The situation is not so clear for the secondary isotopes, and a few examples are in order here.

2-4-1 : 244 Cm buildup in LWRs

Detailed analyses on spent fuel from the Ardennes Nuclear Plant /18/ revealed discrepancies reaching 50 % between the amount of this isotope measured in fuel samples and the values calculated from APOLLO library data /20/. Similar findings had already been reported, in particular for the SAXTON fuel analyses /3/. A number of remarks may be made concerning the interpretation of these results.

a) Calculated results for the same samples gave very accurate values for the primary actinide isotopes (uranium 235, 236, 238 and plutonium 239, 240, 241). It may thus be assumed that the irradiation spectrum is well calculated.

b) In this case, 99 % of the 244 Cm buildup results by neutron capture :

$$^{242}Pu + n \longrightarrow {}^{243}Am + n \longrightarrow {}^{244}Cm.$$

c) Neutron capture on 244 Cm is slight, and sensitivity studies confirm that for the relevant fuels (PWR, initial uranium fuel, specific burnup ranging from 15000 to 35000 MWj/MT) uncertainty bounds of ± 50 % on this capture produce at most a 5 % variation in the final 244 Cm concentration.

d) The only relevant cross-sections are the 242 Pu and 243 Am capture cross sections, for which the sensitivity coefficients - ratio of the concentration variation to the cross section variation-for the final 244 Cm concentration are on the order of 0.8 and 0.9 respectively .

e) The values for these cross sections as used in the calculation discussed here are relatively recent estimates (ENDF/B4 library).

f) The stated uncertainties for these cross sections /21/ are as follows

	$\sigma_{2200}(n,\gamma)$	$I_{res}(n,\gamma)$
242 Pu	4 %	4 %
243 Am	5 %	3 %

g) Finally, in these irradiation spectra, ^{242}Pu and ^{243}Am capture occurs mainly with resonance neutrons.

The need to increase the calculated 244 Cm concentration values is clearly incoherent with the stated uncertainty bounds on the cross sections, the combination of which should result in errors of less than 10 % on these concentrations.

If the analysis is carried further by allowing for the deviations between calculated and measured results of the 242 Pu and 243 Am concentrations (the analysis results are less complete and less accurate for the latter, however) this leads to an upward adjustment of more than 20 % on the 242Pu capture cross section and 243 Am capture cross section /18/. The necessity of these adjustments has not yet been satisfactorily explained.

2-4-2 : 238 Pu buildup in LWRs

Although the mean deviations are only about 20 % , this situation is analogous to the preceding one. The 238 Pu formation processes are as follows in uranium-fueled LWRs (Specific burnup 32000 MWd/MT ; post irradiation concentration

values) :

235 U + n ⟶ 236 U + n	⟶	237 Np + n	⟶ 238 Pu	: 73 %
238 U(n,2n)	⟶	237 Np + n	⟶ 238 Pu	: 18 %
		242 Cm (α)	⟶ 238 Pu	: 9 %
		239 Pu(n,2n)	⟶ 238 Pu	: < 0.1 %

Allowing for the error range on 237 Np concentration and based on the findings of sensitivity studies, the following adjustments are required /18/.

$\sigma(n,\gamma)$ for 236 U : - 5 %

$\sigma(n,\gamma)$ for 237 Np : + 20 %

It should be emphasized that, as there is no single solution, these adjustments are not necessarily optimum.

The following uncertainty values are announced for these capture cross sections/21/.

	$\sigma_{2200}(n,\gamma)$	$I(n,\gamma)$
236 U	6 %	6 %
237 Np	2 %	8 %

It is evident in this case that only the 237 Np adjustment is well outside the expected limits. This is particularly surprising in that 237 Np capture primarily involves thermal neutrons.

2-4-3 : 241 Am Fission in FBRs

Fission chamber measurements in critical experiments have shown that the calculated fission estimates for this isotope were 25 to 50 % too high depending on the spectrum ranges /3/ , /4/. These measurements are accurate enough to permit fully satisfatory adjustments for fast reactor calculations. Nevertheless, it is interesting to note that a recent evaluation /22/ considerably reduces these errors and increases the adjustment accuracy.

3 - SUMMARY OF TND REQUIREMENTS -

The required accuracy limits for transactinium isotope cross sections are summarized in Table X together with the requirements for the half-lives and the mean number of neutrons emitted per fission.

The cross section requirements are expressed in terms of the accuracy of the mean cross sections for LWR or FBR spectra. The "50 %" entries correspond to the requirement of a valid order of magnitude.

A number of remarks may be made concerning the more precise requirements.

234 U : No problems seem to arise with this isotope, and the LWR capture accuracy stated here is already achieved.

236 U : Because of the low thermal capture rate of this isotope, improved accuracy levels will be obtained by work on resonance neutron capture. No major disagreements were noted with spent fuel analysis results.

237 Np : The required LWR capture accuracy values do not appear to be actually attained. The thermal and resonance capture rates are of the same order of magnitude, but the disagreement on the integral values may be attributable to the interpretation of the 0.5 eV resonance. A current evaluation /23/ confirms this analysis and can bring material for an answer.
The FBR requirements are less demanding, and recent estimates completed by a few integral experiment results should be adequate in this case.

238 Pu : The high thermal capture cross section for this isotope seems to be sufficiently well determined, although this has been confirmed by only a very limited number of integral experiments to date.
The accuracy values required for fast reactors are relatively high, and integral experiments have shown discrepancies well above the values stated here.

240 Pu, 241 Pu : Very precise requirements have been formulated for these two isotopes for a long time, and these have been discussed elsewhere in much greater detail than is possible here. It may simply be pointed out that, at the present time, the reactor calculations in which these isotopes have a significant contribution are run under satisfactory conditions with frequent adjustments based on integral experiments.
The half-life of 241 Pu remains something of a problem.
The current accuracy is adequate for core or fuel composition calculations, but not fully satisfactory for certain measurement techniques (241 Am formation).

242 Pu : The status of this isotope is similar to that of the two preceding isotopes with regard to the FBR requirements.
For thermal reactors, the incoherence observed regarding 244 Cm buildup in spent fuel analyses was mentioned in section 2.4.
The thermal capture rate is slight, and once again the reasons for this uncertainty lie in the area of resonance captures, involving either insufficient parameter data or inadequate interpretation of the low-energy resonances.

241 Am : This isotope is covered by a separate paper at this meeting /22/.

242 Am : The fission data for this isotope seems to be adequately defined despite the complete absence of integral measurements.
The need for capture measurements was emphasized at KARLSRUHE.

243 Am : Here again, with the exception of the unaccountable disagreement on 244 Cm buildup in LWR spent fuel, the capture cross section (with a low thermal neutron component) seems to be sufficiently well defined for resonance neutrons.
With regard to fast reactor conditions, the currently available integral measurement results are inadequate to confirm the stated fission accuracy. Capture measurements were also requested at KARLSRUHE.

- CONCLUSION -

This review of transactinium nuclear data requirements for existing thermal and fast breeder reactors and the associated U-Pu fuel cycle does not reflect any major changes since 1975, and this is not surprising.

As the out-of-pile fuel cycle reaches the industrial stage, the relevant problems are better defined, but they are generally not resolved by more accurate data on the secondary actinides. For the reactors themselves the development work continues with computer formula sets subject to varying degrees of adjustment. Reactor physicists systematically attempt to weed out these adjustments as more accurate information on differential data becomes available.

Nevertheless the work in this area has been extremely limited for a number of reasons :

- Recent evaluations are not always available.
- When available, they require substantial adaptation to enter the data in the reactor formula sets.
- After this step the result must be requalified on the basis of integral measurement findings.
- Finally, and above all, the anticipated advantages are limited in any event. Apart from the resulting intellectual satisfaction - which it would be dangerous to underestimate - those advantages generally concern very long term developments which cannot be considered as taking precedence over the immediate industrial needs.

This is a long range effort, and it is clear from this discussion that the top priority will remain with the principal isotopes (including those not mentioned at this meeting), and that secondary isotope requirements can generally be met by theoretical work supported by a minimum of experimental research.

A C K N O W L E D G M E N T S
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TABLE I : LWR 1000 MWe - URANIUM FUEL

Transactinium concentration variation with burn-up, cooling time and initial enrichment.

ISOTOPE	CONCENTRATION Reference (1) (g/ton)	MULTIPLICATIVE FACTOR		
		Burn-up 36000 MWJ/T	Cooling time 2 years	Initial enrichment 4.2 %
232 U	$6,4\ 10^{-4}$	1.37	2.00	0.94
237 Np	422	1.15	1.00	1.05
236 Pu	$1.7\ 10^{-3}$	1.32	0.60	0.93
238 Pu	135	1.32	1.00	0.90
241 Am	44	1.15	4.20	0.95
242 Am	0,5	1.18	1.00	1.00
243 Am	70	1.49	1.00	0.61
242 Cm	7.3	1.30	0.045	0.77
243 Cm	0.37	1.44	1.00	0.70
244 Cm	15	1.74	0.93	0.73
245 Cm	0.63	1.89	1.00	0.47
246 Cm	0.07	2.26	1.00	0.41

(1) Reference case : Initial enrichment 3.2 % Burn-up 32000 MWJ/T
Cooling Time 3 months

TABLE II: SECONDARY ACTINIDE CONCENTRATION RANGES FOR LWR AND FBR (concentrations at the end of irradiation in g/ton of fuel)

Range (g/ton)	L W R Uranium	L W R Plutonium	F B R Pu(LWR)	F B R Pu "equilibrium"
> 1000	236U, 240Pu 241Pu	236U, 240Pu, 241Pu, 242Pu	238Pu, 240Pu, 241Pu, 242Pu, 241Am	240Pu, 241Pu, 242Pu
100 à 1000	234U, 237Np 238Pu, 242Pu	234U, 237Np, 238Pu, 241Am, 243Am, 244Cm	237Np, 242Am, 243Am, 242Cm, 244Cm	237Np, 238Pu, 241Am, 243Am 244Cm
10 à 100	241Am, 243Am 242Cm, 244Cm	242Am, 242Cm, 245Cm	243Cm, 245Cm	241Am; 242Cm
1 à 10		243Cm, 246Cm	246Cm	243Cm, 245Cm
0,1 à 1	242Am, 243Cm	247Cm	247Cm	246Cm
10^{-2} à 10^{-1}	245Cm		232U, 236Pu	236Pu, 247Cm
10^{-3} à 10^{-2}	233U, 236Pu, 246Cm	232U, 236Pu		232U
10^{-4} à 10^{-3}	232U, 247Cm			

TABLE III: THERMAL REACTORS - NEEDS FOR REACTIVITY CALCULATIONS (%)

ISOTOPE	σ(n,γ)	σ(n,f)	ν
236 U	4	-	-
237 Np	10	-	-
238 Pu	10 *	-	-
240 Pu	1	-	-
241 Pu	3	1	0,5
242 Pu	5	-	-
241 Am	10	-	-
242 Am	20 *	10 *	10
243 Am	10 *	-	-
242 Cm	20 *	-	-
244 Cm	20 *	-	-

* Those values have been modified compared to the 1975 ones in order to take into account the limit cases in the plutonium recycling in LWR.

TABLE IV : FAST REACTORS : NEEDS FOR REACTIVITY CALCULATIONS (%)

ISOTOPE	σ(n,γ)	σ(n,f)	ν
237 Np	30	50	50
239 Np	20	50	50
238 Pu	20	7	4
240 Pu	5	2	1
241 Pu	8	1.5	0.5
242 Pu	8	4	4
241 Am	5	15	10
242 Am	50	15	10
243 Am	10	30	25
242 Cm	50	25	15
244 Cm	50	50	50

TABLE V : NEEDS ASSOCIATED TO THE FISSILE MATERIALS RE-USING (%).

ISOTOPE	L W R			F B R		
	σ(n,γ)	σ(n,f)	σ(n,2n)	σ(n,γ)	σ(n,f)	σ(n,2n)
230 Th	50	-	-	-	-	-
231 Pa	50	-	-	-	-	-
232 U	50	-	-	-	-	-
236 Pu	50	-	-	50	50	-
237 Np	10	-	50	50	-	50
238 Pu	20	-	-	20	20	-
239 Pu	-	-	-	-	-	50

TABLE VI : SECONDARY ACTINIDE ACTIVITY EVOLUTION DURING THE LONG TERM WASTE STORAGE.

ISOTOPE	ACTIVITY (Curies/ton of initial fuel)			
	1 year	100 years	1000 years	10000 years
237 Np	0.3	0.3	0.3	0.3
241 Am	278	230	56	0.1
242 Am	5	3	0.2	-
243 Am	14	14	13	5.6
243 Cm	17	2	1	0.5
244 Cm	1190	20	3	1
245 Cm	0.1	0.1	0.1	0.005
246 Cm	0.02	0.02	0.02	0.01

(The indicated activities corresponds to the isotope and its radioactive daugter products)

TABLE VII : NEEDS ASSOCIATED TO MEASUREMENTS AND CONTROLS

1°/ Cross Sections - The correspondant needs are covered by requests concerning reactor physics

2°/ Radioactive half lives

ISOTOPES	REQUIRED PRECISION
238Pu, 239Pu	0,5 %
240Pu, 241Pu, 241Am	1 %
242Cm, 244Cm	2 %
228Th, 232U, 236Pu	5 %

TABLE VIII / EXAMPLE OF RESULTS OF THE SENSIVITY STUDY CONCERNING PLUTONIUM RECYCLING IN LWR (PWR, 2nd plutonium recycling without intermediary mixing)

CROSS SECTION	SENSITIVITY TO A 1% CROSS SECTION VARIATION (*)					REQUIRED ACCURACY (%)
	Initial reactivity (10^{-5})	Reactivity evolution (10^{-5})	Alpha activity (%)	Neutron emission (%)	After power (%)	
(n,γ) 240 Pu	± 132	±150	±0.03	± 0.07	± 0.01	± 1 %
(n,γ) 241 Pu	± 28	± 36	±0.07	± 0.22	± 0.03	± 3 %
(n,f) 241 Pu	± 156	± 40	±0.24	± 0.35	± 0.08	± 1 %
(n,γ) 242 Pu	± 18	± 4	±0,27	± 0,80	± 0.10	± 5 %
(n,γ) 241 Am	± 10	± 7	±0,15	± 0.03	± 0,06	± 10 %
(n,γ) 242 Am	-	± 7	±0.01	± 0.05	-	± 20 %
(n,γ) 243 Am	-	± 12	±0,24	±0,66	± 0,10	± 10 %
(n,γ) 244 Cm	-	± 3	±0,05	±0,14	± 0,02	± 20 %

* The variations are relative to the average cross sections for a caracteristic LWR spectrum..

TABLE IX: PLUTONIUM QUALITY OBTAINED FOR THE URANIUM RECYCLING IN LWR

ISOTOPES	CONCENTRATIONS	
	STANDARD URANIUM *	RECYCLED URANIUM **
236 Pu	1.7 10^{-7}	6. 10^{-7}
238 Pu	1,4 %	4,8 %
239 Pu	57,96 %	58,5 %
240 Pu	21,9 %	19,8 %
241 Pu	13,6 %	12,7 %
242 Pu	5,2 %	4,2 %
Emission neutronique Pu (n/g/s)	600	1200

* Uranium enriched from natural uranium, i.e. without initial U 236.

** Uranium enriched from recycled uranium,containing a supposed 1% of initial U 236.

TABLE IX : RECAPITULATION OF TRANSACTINIUM NUCLEAR DATA NEEDS FOR THERMAL AND FAST REACTORS AND THE ASSOCIATED U-Pu CYCLES.

ISOTOPE	$\sigma_{n\gamma}$ (1)		σ_{nf} (1)		ν	$\sigma n,2n$	Half life
	LWR	FBR	LWR	FBR			
228 Th	-	-	-	-	-	-	5 %
230 Th	50 %	-	-	-	-	-	-
231 Pa	50 %	-	-	-	-	-	-
232 U	50 %	-	-	-	-	-	5 %
234 U	5 %	-	-	-	-	-	-
236 U	6 %	-	-	-	-	-	-
237 Np	10 %	30 %	-	50 %	50 %	50 %	-
239 Np	-	20 %	-	50 %	50 %	-	-
236 Pu	50 %	50 %	-	50 %	-	-	5 %
238 Pu	10 %	20 %	-	7 %	4 %	-	0,5 %
239 Pu	x	x	x	x	x	50 %	0,5 %
240 Pu	1 %	5 %	-	2 %	1 %	-	1 %
241 Pu	3 %	8 %	1 %	1,5 %	0,5 %	-	1 %
242 Pu	5 %	8 %	-	4 %	4 %	-	-
241 Am	10 %	5 %	-	15 %	10 %	-	1 %
242 Am	20 %	50 %	10 %	15 %	10 %	-	-
243 Am	10 %	10 %	-	30 %	25 %	-	-
242 Cm	20 %	50 %	-	25 %	15 %	-	2 %
244 Cm	20 %	50 %	-	50 %	50 %	-	2 %

(1) The required precisions correspond to the average cross sections for reactor spectra.

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TND REQUIREMENTS FOR ALTERNATE FUEL CYCLES

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ABSTRACT

A review is given of recent developments in alternate fuel cycle studies, with emphasis given to those studies having a possible impact on requirements for data on transactinium nuclei. These include extended burnup in LWR's, the use of thorium to supplement the use of uranium, the use of accelerators to produce fissile material, and the Fast Mixed Spectrum Reactor. The new features introduced by these concepts are longer burnup of fuel, and hard neutron spectra in breeders. Similar trends appear in studies of transmutation of nuclear waste, where a new feature is the possibility of recycling actinides in LSR fuel which has not undergone full fuel reprocessing but has been treated by the Airox process. Such recycle in thermal reactors would lead to generating large amounts of higher transactinide nuclei.

The concepts that depend on extended burnup do not lead to new requirements for data on transactinide nuclei, but they do strengthen the requirements that have been stated in the past. Among the requirements for data for the hard spectrum breeder, the need for measurements of capture cross-sections of transactinides above a few hundred keV is most important. Requirements also exist for (n, Nn) cross-sections.

We shall use as our starting point the excellent papers presented at the IAEA's November, 1975, Advisory Group meeting on Transactinium Nuclear Data. These reviewed the needs for such data in light of the concepts being developed by the nuclear industry at that time, and the state of data to satisfy these needs.

Subsequent developments have led to some change in emphasis and direction of nuclear development, which will be discussed here. The greatest force behind this change has been increasing anxiety over the possibility and consequences of a growth in number of nations possessing nuclear weapons. This concern has been particularly strong in the United States. There has been a heightened official recognition of a possible relationship between reprocessing spent nuclear fuel to extract the plutonium for further use in producing nuclear power, and the more ready availability of that plutonium for use in weapons. This has led the United States to institute a moratorium on reprocessing of spent nuclear fuel, and to the Administration's decision to cancel construction of the Clinch River Breeder Reactor. Measures of this kind are in part designed to make it clear that the United States is willing to join on an even basis with other countries in a world in which there is no commercial traffic in plutonium, if this kind of operation of the nuclear fuel cycle is found to be technically feasible and generally acceptable.

The question of technical feasibility of these objectives is still not settled. The principal problem that it raises is how, at the same time, to

ensure a long-term supply of fuel for nuclear power, to achieve the same objective as breeding.

Among the technical measures being explored are means of extending the burnup of uranium in the LWR once-through fuel cycle, the use of thorium as a supplement to uranium, and the use of accelerators in the nuclear fuel cycle. Some aspects of these fuel cycles would lead to changed requirements for transactinium cross-sections, and some would not lead to changes.

One further concept has been receiving increased attention in the United States. This is a once-through fast breeder, called the Fast Mixed Spectrum Reactor (FMSR). The FMSR has unique characteristics that lead to heightened requirements for transactinium nuclear data.

EXTENDED BURNUP IN LWR's

Steps to improve the resource efficiency of LWR's would lead to the most immediate improvement in the amount of energy available from fissioning uranium. Some measures that would increase the number of megawatt days per ton of mined uranium could be introduced relatively soon. The most promising of these is an increase in enrichment of the fresh fuel loaded into the reactor. Increase in enrichment would permit fuel to be burned longer before the reactor runs out of reactivity. Since the residual U-235 content of spent fuel is not highly sensitive to the initial enrichment, a greater fraction of the U-235 available in mined uranium can be burned this way, and the fuel utilization is accordingly more efficient. It has been estimated that an increase in uranium efficiency of about 15% can result from increasing the enrichment of fresh fuel for PWR's to about 6%. Fuel burnup at discharge would be about 45,000 MWd/tonne, compared to the present 30,000 MWd/tonne.

Another improvement of about 15% in uranium utilization could be achieved by reducing the period of time between fuel reloading from 12 months to 6 months. This would reduce the fissile content in fuel being discharged, and so it would increase the burnup that had occurred. Reduction of time between loadings would inevitably reduce the fraction of time the power plant is being used, and this would increase the cost of electricity. The trend in the nuclear power industry is opposite to this; the time between fuel reloads is being gradually increased, and the effect is that efficiency in using fuel is being reduced.

Other and somewhat less effective methods of extending burnup in LWR's have also been proposed. One of the more interesting suggestions is to use hollow cylindrical pellets of fuel in place of solid pellets. The flux disadvantage factor in fuel leads to lower burnup in the center than in the outer region of the pellet, and a more uniform burnup of fuel would be achieved with pellets in which the center is missing.

To summarize, several ways have been proposed to improve the efficiency of burning uranium in light water reactors. The United States is devoting an increasing amount of attention to this objective.

These proposed methods do not significantly change the neutron spectrum of the reactors, nor do they introduce new materials. Cross-section requirements for the reactors are not greatly affected, and in particular no new requirements for cross-sections of transactinium isotopes arise specifically for analysis of higher burnup in LWR's. There is, however, added urgency to the requirement for TND. Transactinium isotopic production will be increased by this strategy. The effects of actinides on reactivity, reactivity coefficients, and activity of spent fuel will be greater than with current modes of operation of PWR's.

THORIUM CYCLE IN THERMAL REACTORS

Almost all power reactors now use the uranium-plutonium cycle. Interest has been rekindled in the use of thorium to supplement use of uranium in

thermal reactors. Two concepts that have been proposed have somewhat greater interest than others. The first is the light water breeder reactor, which in the steady state would generate ^{233}U at essentially the same rate as it is consumed. The second is use of the denatured fuel cycle in light water reactors or advanced converters.

A light water breeder core has been installed in the Shippingport Reactor. This is a seed and blanket core, in the same general class as the seed and blanket design of the ^{235}U-^{238}U cores previously in Shippingport. The ^{233}U and the thorium are initially in separate fuel assemblies, both moderated and cooled by ordinary water. The ^{233}U is removed periodically and recycled in the seed elements. The light water breeder reactor operates on a well thermalized neutron spectrum.

The denatured fuel cycles are based on use of a fuel in which the ^{233}U is produced by neutron capture in thorium mixed in with uranium. This uranium when reprocessed will contain ^{233}U at a concentration lower than is suitable for use in a nuclear weapon. The fertile material is predominantly thorium rather than ^{238}U, and ^{233}U production from thorium is neutronically more favorable than ^{239}Pu production using ^{238}U. The uranium is used to denature the ^{233}U and to provide only the ^{235}U required to make up for the deficiency in ^{233}U production to continue the cycle. For these reasons, the requirements for uranium per megawatt of heat are substantially reduced. Of course, thorium is needed in place of uranium, but the thorium can be recycled.

The ^{233}U-Th cycle continues to be attractive in connection with high temperature gas cooled reactors. These reactors can be operated on either the straight-forward ^{233}U-Th cycle or on a denatured cycle.

FAST REACTOR PRODUCTION OF ^{233}U

Analysis has been made of fuel cycles based on symbiosis between fast breeder reactors and thermal reactors burning ^{233}U. The breeder reactors would burn plutonium in the central core region, and would generate ^{233}U in the blanket. No designs exist, though a number of options have been contemplated. In one option, the makeup feed of plutonium to the central core would be supplied by a combination of internal breeding in the fast breeder, and plutonium from some light water reactors. The fissile material produced in excess of fissile needs of the fast reactor operation would be provided as denatured ^{233}U fuel to other light water reactors.

These studies reflect the recognition that thorium based fuels are not well suited to use in the central region of fast reactors, because of the low fission cross-section of thorium. Although ^{233}U is a fine fast reactor fuel, the low value of the fast fission factor of the parent ^{232}Th more than makes up for this.

FUEL PRODUCTION BY ACCELERATORS

The use of accelerators to produce fissile material by neutron irradiation of fertile material is an old concept, which has been traced back to ideas of Bennett Lewis during the Manhattan Project. In the late 1940's and the early 1950's, a project of substantial size was underway in the United States, to develop a means of using accelerators to produce plutonium for military purposes. This was the so-called Materials Testing Accelerator Project (MTA), which was directed by Ernest O. Lawrence. The MTA Project was abandoned in about 1954, when it was ascertained through mineral exploration that enough uranium ore existed in the United States to meet the foreseen military demands even if the less resource-efficient course were adopted of plutonium generation through operation of production reactors. At the close of the MTA project, however, substantial progress had been made, and design and construction were underway to build an accelerator which would be about 50% efficient in transforming an input of electrical energy into a proton beam to be incident on a target.

Interest in this concept has been maintained over the years in Canada, where the basic principle has also been investigated as a means of generating an intense source of neutrons for research purposes. In the past few

years, as interest has grown in the United States in extending the use of fissile resources through other means than plutonium breeders, there has been a revival of attention given to the possibilities of electro-nuclear production of fissile material.{1} Studies have been conducted at Oak Ridge on rates of production of fissile material in several targets bombarded by an intensive beam of protons from an accelerator.{2} Conceptual design studies have been conducted at Los Alamos on a sodium-cooled target of thorium rods, producing ^{233}U extracted through periodic chemical processing.{3}

In all of these conceptual studies, the accelerator is assumed to embody current technology for proton linear accelerators. Modern accelerator designs based on combining features of several existing machines would be capable of generating beams of protons of 1 GeV or greater energy, in steady state beam currents of several hundred milliamperes. A nominal design point of 1 GeV, 300 mA, would impact 300 MW of protons on the target. It has been established that through spallation and evaporation from excited nuclei, about 40 neutrons are generated by the average 1 GeV proton incident on a large heavy metal target (somewhat more if the target is fissile), The number of neutrons per incident proton is found to be directly proportional to the energy of the proton at proton energies greater than about 600 MeV. Capture of the neutrons in a blanket of fertile material would lead to production of about 600 kg of fissile material per year, for operation of the nominal 1 GeV, 300 mA accelerator on a duty cycle of 80%.

The neutronic properties of the blanket are functions of the design layout and especially the means of cooling. Most of the neutrons from the target would be products of evaporation from heated nuclei, and would have the typical boil-off spectrum averaging several MeV. Targets cooled by light or heavy water would contain neutron spectra typical of or reminiscent of thermal neutron reactors. The Los Alamos design study leads to a target with a neutron spectrum resembling that in a fast breeder reactor.

The cost of fissile material produced by this method is quite high - typically about $400/gm of fissile material. The process is not attractive in competition with fissile material produced through isotope separation, where the cost is now about $50/gm of ^{235}U.

LINEAR ACCELERATOR DRIVEN REACTORS

A Brookhaven group has studied the possibility of driving subcritical systems of nuclear fuel and moderator, through injection of a neutron source from a linear accelerator.{4} Principal attention was given to subcritical assemblies of uranium oxide or thorium oxide rods cooled by light or heavy water. Calculations were extended to burnup of as much as 100,000 MWd/tonne, as a function of lattice geometry, to determine the average power that could be generated using a given beam power of accelerator.

The neutronics of the system is fully determined by the choice of fuel and coolant, and their geometry. All such systems analyzed had reasonably well moderated neutron spectra, though in some very close-packed geometries the thermal neutron group was largely suppressed through incomplete neutron slowing down. In these assemblies, resonance cross-sections assumed greater than usual importance. The analysis of burnup to 100,000 MWd/tonne also is of unusual interest in this case. We shall discuss the significance of extended burnup in the context of the subject of this meeting, in a later section of this report.

All cases that were investigated in this Brookhaven survey were characterized by excessive energy consumption. That is, in no case was the energy consumed by the accelerator less than one-third the electrical energy produced by the driven reactor.

LINEAR ACCELERATOR FUEL REGENERATOR (LAFR)

A second scheme based on applying linear accelerators in the fuel cycle has been studied at Brookhaven.{5} This would use a linear accelerator to produce neutrons that would in turn be absorbed in ^{238}U nuclei of fuel fabricated for a power reactor, accomplishing the same purpose as prior en-

richment of the fuel. Fuel subassemblies that have for instance been fabricated in geometry suitable for a light water reactor could have their fissile content increased from an initially inadequate level to a value suited for loading as fresh fuel into the light water reactor they are designed for. In the Brookhaven scheme, an assembly would first be fabricated of uranium of nominal enrichment 2%. Irradiation in the LAFR could then increase the fissile content to about 3%, suitable for the reactor. The fuel could then be burned down to about 2% total fissile content in irradiation to about 30,000 MWd/tonne. Reirradiation could restore the fissile content to the original reactivity, and a second burnup in the reactor could then take place. The process could be repeated in principle until some physical limitation is reached; at present this is seen as degradation of properties of the zircaloy cladding to a point prohibiting further use. The properties of zircaloy under irradiation seem at present to assure the ability to use the fuel through at least two of these cycles, to a total of 60,000 MWd/tonne, without excessive fuel cladding failure. At this exposure and with this strategy, fuel efficiency would be about a factor of 3.6 better than in the LWR once-through cycle now in general use. On the other hand, the cost of electrical power produced using this scheme would be higher by about thirty percent over the next ten to fifteen years than with the LWR once-through cycle.

Advocates of the LAFR point out that success of the concept is assured, since proof of principle is not required. The required accelerator is in the range of current technology, though combining features of existing machines to provide the intense service required for LAFR leads to a step-function increase in some operational problems.

The target of the accelerator beam is contemplated as a spatial distribution of liquid lead jets, falling from a header to a collecting trough, collected there for recirculation through a heat exchanger. The blanket consists of pressure tubes containing individual fuel subassemblies cooled by (one option) heavy water. With an accelerator of 1.5 GeV beam energy and 300 mA beam current, the absorption of spallation and evaporation neutrons would enrich and rejuvenate fuel subassemblies at a rate suited to the fuel requirements of three light water power reactors in a two-pass strategy for fuel use (60,000 MWd/tonne at 30,000 MWd/tonne per pass).

Irradiation in the fuel regenerator requires tailoring the neutron spectrum in this region to favor plutonium production over fissioning of plutonium. This objective is necessary to keep the heat load in the fuel low during irradiation, and to ensure that plutonium produced in the LAFR is not prematurely burned in the LAFR, but is available for subsequent burning in the LWR. Accomplishment of the objective is attained through undermoderation of the neutrons in the blanket to provide a neutron spectrum in which the ratio of ^{238}U capture to ^{239}Pu fission is more favorable than it is at thermal energies.

The neutronics of LAFR resembles that of a LWR, in that the same range of neutron energies is of interest. There is, however, some difference in emphasis in nuclear data requirements. There are the result of the harder neutron spectrum of the LAFR, and the extended burnup of fuel.

FAST MIXED SPECTRUM REACTOR (FMSR)

The FMSR is a novel concept in fast reactors for electrical power production, that has also originated at Brookhaven, and that is receiving growing attention as a fast breeder alternative.{6} It has as its objective a substantial increase in the amount of energy available from a given amount of mined uranium, while at the same time avoiding the need for reprocessing of spent fuel, at least for a very long period of time. FMSR is sometimes called the "once-through fast breeder". The neutronics of FMSR is unusual, and the neutron data needs are somewhat different from those for the related fast breeder reactors. Because of the newness of the FMSR concept, its description is not readily available in the published literature. For these reasons of unfamiliarity and differing data needs, a more extended description of the concept will be given here.

FMSR is a fast reactor with two regions in which the neutron energy spectra are substantially different. The fuel is metallic uranium in steel cladding, in conventional shapes of fast breeder subassemblies, and this permits achieving a high density of fissile and fertile nuclei in the subassembly. A central region of the reactor contains only fueled subassemblies. Because of the high concentration of fuel in this region, the spectrum is very hard, and the breeding gain is very high. Surrounding the hard spectrum core is a region in which fueled subassemblies are interspersed with graphite or beryllium blocks of the same hexagonal shapes and sizes as fueled subassemblies. The moderator softens the spectrum in the outer region. Figure 1 shows the appearance of the reactor with its two zones. Figure 2 shows a comparison of spectra typical of the two regions.

The reactor in its steady state fuel cycle would be supplied fresh fuel only as natural uranium or depleted uranium (clad metal rods in standard subassemblies, as stated above). The overall breeding ratio is very high (1.6-1.7), and operation would be sustained on burning of the plutonium generated in-situ in the fuel. Fuel shuffling would be necessary, with many possible fuel shuffling options being possible, only a few of which have been explored.

The presently preferred fuel shuffling strategy is based on loading fresh fuel into the outer fuel positions in the moderated region of the reactor. Fuel would reside there over several fuel reshuffling periods, absorbing leakage neutrons to augment its plutonium concentration (it must be kept in mind that no plutonium was present in fuel as initially loaded). This fuel would then be moved to inner fuel positions of the moderated zone, where plutonium generation would be more rapid. After a period of sustained residence in this second zone, the fuel would be moved to the first of four sequential locations in the hard spectrum region. Residence in the four inner zones would be accompanied by continued growth in plutonium concentration, until a near-asymptotic value is reached. Total residence time in the reactor must be long, typically about 15 years, of which about 10 years are required in the hard spectrum inner core. The long residence time leads to problems whose solution will require substantial research and development, because demands on materials are extended into regions well beyond present experience.

The plutonium concentration in fuel as a function of time and location in the inner hard spectrum region is shown in Figure 3. At the time fuel enters the hard spectrum region, the plutonium concentration has built up to a value of about 3%. At the end of residence in the first zone of the hard spectrum region, the plutonium concentration has increased to above 4%. After residence in the second zone of the hard spectrum region, the plutonium concentration has increased to about 5%. In the fourth zone, the plutonium is near its equilibrium concentration, and at discharge has an axially averaged value a little above 7%.

Fuel on its removal would have experienced a burnup of 14% average, 18% peak, of the initial heavy metal. It would therefore be heavily loaded with fission products, so that parasitic capture by fission products becomes important even in the very hard neutron spectrum.

From the start, the central neutron physics question has been whether the cross-sections lead to plutonium concentrations high enough for criticality in the equilibrium cycle. In fact, it is found that criticality in the equilibrium cycle seems achievable with helium-cooling and also with sodium-cooling. Most of the analysis performed so far has been done on the gas-cooled version of the reactor.

It is well-known that uranium metal undergoes large dimensional changes at burnups above about one atom percent. Design and testing to achieve higher burnup has continued since the severe radiation damage was first observed many years ago. The most significant improvement has been achieved through use of the Mark II sodium bonded fuel design in EBR-II irradiations, where burnup of about 13.5% weight of heavy metal has been reached.{7} Failure of cladding eventually occurred at a dimple in the cladding which concentrated the stresses.

The success of the Mark II fuel is attributable to the space left on purpose between fuel and cladding, to allow for fuel expansion. This space is filled with sodium. As the metal fuel expands radically under radiation damage, it expels the sodium, until the uranium and cladding are in contact. At this point, further growth is small. The gaseous fission products are then released from the fuel almost as fast as they are formed through an interconnected porosity of the metal fuel. The Mark II fuel has been selected as the reference fuel for the sodium-cooled version of FMSR. This fuel may also be acceptable for the gas-cooled version of FMSR, though it is thought necessary also to investigate spherepack metal fuel for the gas-cooled reactor.

Tables I and II provide information pertinent to the gas-cooled version of FMSR. Tables III and IV give the corresponding data for the sodium-cooled version.

The hard spectrum of the inner region is the cause of the very high breeding ratio. It also has other consequences; almost one-third of the power is the result of fast fission in ^{238}U. The spectrum is so hard that even ^{240}Pu becomes a reasonably good reactor fuel. Therefore, the isotopic composition of plutonium in discharged fuel is very different from that in fuel from light water reactors.

FMSR is a relatively new program in the United States. It is currently being carried at a low level, but tentative plans envision a substantial growth in program in the near future. The program is being conducted on a cooperative basis with contributions from a number of laboratories including Brookhaven National Laboratory, Argonne National Laboratory, Oak Ridge National Laboratory, the General Atomic Corporation, the Hanford Engineering Development Laboratory, and the Massachusetts Institute of Technology. Attention is concentrated for the present on the technical problems on which feasibility depends. These are particularly: development of metallic fuel capable of extended burnup, development and testing of cladding materials that can withstand high fluence without excessive degradation of properties, design of duct walls that can endure long in-reactor use without excessive dilation, development of optimum fuel shuffling strategies, exploration of aspects of design and operation that bear on safety, and preparation for critical experiments to check out the neutron physics. A number of these activities are already pursued under the fast breeder development program, and require at most a change in emphasis to be adapted to FMSR.

For a number of years, development programs in the fast breeder field have been formulated with mixed oxide fuel in mind. The neutron physics of hard spectrum systems has been relatively neglected. As will be discussed, important requirements exist for neutron physics data for these systems with hard neutron spectra.

TRANSMUTATION OF NUCLEAR WASTE

Little has been added to the analysis of possibilities for transmutation of nuclear waste since the IAEA's last meeting on Transactinium Isotope Nuclear Data. The moratorium on spent fuel reprocessing postponed consideration of such activity in the United States, since nuclear waste is being indefinitely retained in the spent fuel assemblies.

Two new possibilities have been added to the methods available for use in transmutation. The first of these is the intriguing recognition that it may be possible to reconstitute spent fuel into reload fuel without full chemical reprocessing. This can be done through use of the Airox process, developed by the Rockwell Corporation. Airox works as follows. A spent uranium oxide fuel rod first has holes drilled through the cladding into the fuel, along a line from one end to the other. It is then exposed to hot oxygen. Rapid conversion of the UO_2 to U_3O_8 is accompanied by volume expansion which breaks open the cladding along the line of holes in a kind of zipper action. The U_3O_8 is formed as a powder which can be shaken out of the open cladding. Volatile gases are completely released by the transform-

ation. Non-volatile fission products remain in an oxidized state. Reduction by hot hydrogen gas then follows, to restore the uranium to the lower valence state. Repelletization can then take place. The reconstituted fuel contains all of the plutonium and non-volatile fission products that were in it before Airox treatment, and this is the chief advantage offered by this concept for transmuting. The process would avoid the need for highly effective removal of plutonium and fission products from chemical waste, an unsolved problem which must be overcome if any of the conventional approaches to packaging and transmuting nuclear waste were to be realized.

Airox technology could be used in several strategies. Spent fuel from an LWR could be mixed with fresh slightly enriched uranium for reconstituting and reuse in place of normal LWR fuel. If a Linear Accelerator Fuel Enricher were used, spent fuel could be reirradiated and then used again in an LWR after submission to Airox and reconstitution.

The second new consideration in transmutation of waste is the possibility that fission products might be irradiated and transmuted in the high neutron flux near the target of a powerful linear accelerator, such as has been visualized for some of the concepts discussed earlier. These neutron sources can have the high intensity ($>>10^{16}$n/cm^{2}sec) necessary for transmutation to be important relative to natural radioactive decay.

Finally, it must be noted that hard spectrum breeders such as FMSR would generate far fewer transactinide nuclei than thermal reactors and appreciably fewer than conventional oxide fueled fast reactors. Reactor concepts that depend on longer fuel residence in the reactor core will also generate a lower inventory of fission products outside the reactor.

CURRENT CROSS SECTION NEEDS

A new edition of BNL-50444 (Compilation of Requests for Nuclear Data) is about to be issued. Table V is an extract from this request list, giving the Priority I requests from U.S. sources.

These cross-section requests reflect requirements for the more conventional thermal reactors, the main line fast breeder program, and the use of thorium in thermal reactors, such as for the Light Water Breeder. They do not reflect requirements for concepts using extended burnup, and for hard spectrum fast reactors.

REQUIREMENTS RESULTING FROM EXTENDED BURNUP

In extended burnup of fuel, the transactinides that are formed continue to be exposed to the neutron flux, and to undergo nuclear processes. Meanwhile, the fission products have been undergoing decay and also have been transmuted to a degree. The effect on transactinide content can be seen in Table VI, which gives the isotopic composition of plutonium from a typical LWR as a function of burnup, according to a strategy whereby, at intervals of 30,000 MWd/tonne, the burned fuel is restored through mixing with fresh slightly enriched uranium, is then reconstituted, and reburned in the same LWR.

These analyses are made for a typical thermal reactor spectrum. The cross section sets used are those of ENDF-V, and the requirements for improvements in knowledge of the cross-sections are already reflected in the cross section request list. Corresponding calculations for the higher transactinide species are underway. It is expected that the requirementss for cross sections that were expressed as a result of past interest in production of ^{252}Cf would also serve the needs for analysis of actinide recycle according to this and similar schemes.

REQUIREMENTS RESULTING FROM HARD SPECTRA

There is a pervasive lack of direct measurements of neutron capture cross sections above a few hundred keV. At these higher energies, the cap-

ture cross sections of these nuclei become small, and the associated difficulty of measurement has discouraged filling the long-existent gap. The lack of direct experimental data is especially unfortunate, however, for calculation of the neutronics of hard spectrum fast reactors such as FMSR.

Tables VII, VIII, and IX list spectrum-averaged cross sections for the CRBR and for two regions of FMSR. In one of these two regions the spectrum is softened by nearby moderator. In the other, the spectrum is very hard. The differences are striking, with the most important spectral effects being seen in average capture cross-sections. In most respects the CRBR cross sections fall between those of the hard and soft-spectrum regions of FMSR, though there are some anomalous effects from energy dependence of cross-section curves and of spectrum details.

Tables X through XIV give relative isotopic concentrations of plutonium, for uranium exposed in the three spectra to different burnup levels. These are not meant to represent isotopic compositions of plutonium generated by any particular design of reactor, because fuel is commonly exposed at different locations for different lengths of time, and over the course of time sees a succession of spectra. However, in FMSR the fuel would actually reside the longest period of time in hard spectrum regions, and would, in fact, according to current strategy end its residence in the hard spectrum. Thus the composition for the hard spectrum FMSR at 150,000 MWd/T is reasonably representative of discharged fuel.

The isotopic compositions are seen to differ markedly, even at low exposure levels. The differences are extremely important for the neutronic behavior, particularly for calculation of reactivity. Since successive plutonium isotopes are the result of successive neutron capture in nuclei that were oroginally ^{238}U, the precise values of capture cross sections of these transactinides is of great importance. It is urged that steps be taken to provide the measurements that are still lacking.

The cross sections used to generate these data have been simplified by the neglect of all absorption except fission and capture. In refined reactor analysis it will be necessary to include (n, 2n), (n, 3n) etc. reactions which enter at a few MeV. These reactions will contribute some additional reactivity particularly in FMSR where the integrated neutron flux and the neutron importance are greatest in hard spectrum regions. Mostly because of difficulty of measurement against a background of fission events, the (n, Nn) cross sections are poorly known. Improvement in their knowledge is required as a lower priority matter.

Because of the early stage in FMSR development, attention has not yet been given to the content of higher transactinides that would accompany use of the hard spectrum. The tables make it clear, however, that the higher transactinides will not be generated at as high a rate as would be found from use of an oxide-fueled breeder. Even at 150,000 MWd/T, far fewer higher transactinides would be found in spent FMSR fuel than are normally present in LWR fuel at 30,000 MWd/T. This point has profound implications for spent fuel storage, which still must be explored.

The needs for cross sections of the higher transactinides in light of these considerations will be developed in further analysis.

Table I

HELIUM-COOLED FMSR SELECTED REACTOR PARAMETERS

TOTAL NUMBER OF FUEL SUBASSEMBLIES = 374

NUMBER OF FUEL S.A/ZONE SHUFFLED PER CYCLE = 11

CYCLE DURATION = 160 FPD

ΔK DURING CYCLE = 2.2%

ZONAL CONVERSION RATIOS:

ZONE 1 = 5.9
ZONE 2 = 3.4
ZONE 3 = 2.15
ZONE 4 = 1.40
ZONE 5 = 1.17
ZONE 6 = 1.04

OVERALL BREEDING RATIO = 1.67

Table II

HELIUM-COOLED FMSR MATERIAL INVENTORIES

	Pu (TONNES)	HEAVY METAL (TONNES)
CORE INVENTORY: (BOC)	5.04	115.5
DISCHARGE/YR*	0.59	8.1

AVERAGE DISCHARGE ENRICHMENT = 7.2%

DISCHARGE Pu COMPOSITION (%)
(239/240/241/242) : : (82.4/15.3/2.0/0.3)

CORE BURNUP (MWD/T):

AVERAGE = 130,000
PEAK = 160,000

PEAK FLUENCE (E > 0.1 MEV) = 7.56×10^{23})

*80% LOAD FACTOR

Table III

SODIUM-COOLED FMSR SELECTED REACTOR PARAMETERS

TOTAL NUMBER OF FUEL SUBASSEMBLIES = 374

NUMBER OF FUEL S.A/ZONE SHUFFLED PER CYCLE = 11

CYCLE DURATION = 185 FPD

ΔK DURING CYCLE = 2.7%

ZONAL CONVERSION RATIOS:

ZONE 1 = 4.8
ZONE 2 = 3.0
ZONE 3 = 2.7
ZONE 4 = 1.7
ZONE 5 = 1.22
ZONE 6 = 1.12

OVERALL BREEDING RATIO = 1.69

Table IV

SODIUM-COOLED FMSR MATERIAL INVENTORIES

	Pu (TONNES)	HEAVY METAL (TONNES)
CORE INVENTORY: (BOC)	5.90	159.0
DISCHARGE/YR*	0.68	9.69

AVERAGE DISCHARGE ENRICHMENT = 7.0%

DISCHARGE Pu COMPOSITION (%)
(239/240/241/242) : (83.8/14.4/1.6/0.2)

CORE BURNUP (MWD/T):

AVERAGE = 114,000
PEAK = 137,000

PEAK FLUENCE ($E > 0.1$ MEV) = 7.56×10^{23}

*80% LOAD FACTOR

TABLE V

PRIORITY I REQUESTS FOR THE Th CYCLE

ISOTOPE	QUANTITY	ENERGY RANGE	ACCURACY	REQUESTED BY
^{232}Th	$\sigma_{n,\text{tot}}$ (E)	60 eV to 100 keV	2%	ORNL
	$*\sigma_{n,\gamma}$ (E)	1 eV to 20 eV	2%	Bettis
		20 eV to 5 keV	5%	Bettis
	$*\sigma_{n,x\gamma}$ (E,E_γ)	0.1 MeV to 10 MeV	5%,10%	ORNL
	$*\sigma_{n,2n}$ (E)	Thresh to 10 MeV	10%	GE
	$*N_{n,f}$ (E, E_n)(delayed), yield and spectra		2%	Bettis
^{231}Pa	$*N_{n,f}$ (E, E_n)(delayed), yield and spectra		5%	Bettis
^{233}U	Half-life		0.5%	Bettis
	$*\sigma_{n,\gamma}$ (E)	1 mV to 0.5 eV	1%	Bettis
		0.5 eV to 2 eV	2%	Bettis
		0.1 keV to 1.5 MeV	5-10%	ORNL
	$*\sigma_{n,f}$ (E)	1 mV to 1 keV	10%	GA
		1 mV to 20 MeV	1% below 100eV	Bettis
		Ratio, 1 keV to 10 MeV	5% above 100eV	DOE
		(Ratio to U-235 fission, accuracy 2-3%, 1% energy accuracy)		
	*Alpha	1 eV to 1 keV	2%-8%	GA
	*eta	1 mV to 1 eV	0.4%	Bettis
	*ν(E)	1 eV to 30 eV	0.25%	GA
		30 eV to 1 keV	1%	
		1 keV to 30 keV	2%	GA, Bettis
	*ν(E)(delayed)	Thermal	5%	Bettis
	$*N_{n,f}$ (E, E_n)	Thermal	1%	Bettis
	$*\gamma_{n,f}$ (E, nuclides)	Thermal	1%	Bettis, KAPL
^{234}U	Half-life		0.3%	NBS
	$*N_{n,f}$ (E, E_n)(delayed)		5%	Bettis

PRIORITY I REQUESTS FOR THE Pu CYCLE

ISOTOPE	QUANTITY	ENERGY RANGE	ACCCURACY	REQUESTED BY
^{236}U	$*\sigma_{n,\gamma}$ (E)	Thermal to 1 keV	10%	GE
	$*N_{n,f}$ (E,En)(Delayed)		5%	Bettis
^{237}Np	$\sigma_{n,f}$ (E)	50 keV to 7 MeV	2%	NBS
	Half-life		0.5%	NBS
	$*\sigma_{n,\gamma}$ (E)	1 mV to 1 keV	3-10%	GE
^{240}Pu	Half life		1%	NBS
	$*\sigma_{n,\gamma}$ (E)	Thermal to 0.1 keV	3%	GE
		0.5 keV to 0.15 MeV	5%	ANL
		0.15 MeV to 1 MeV	10%	DOE, GE
	$N_{n,\gamma}$ (E, E_γ)	Thermal	20%	LASL

TABLE V (Continued)

PRIORITY I REQUESTS FOR THE Pu CYCLE (Continued)

ISOTOPE	QUANTITY	ENERGY RANGE	ACCURACY	REQUESTED BY
^{241}Pu	$*\sigma_{n,\ tot}$ (E)	10 mV to 3 eV	1%	OR
	$*\sigma_{n,\gamma}$ (E)	Thermal to 30 keV	3%	GE
	$N_{n,\gamma}$ (E, E_γ)	Thermal	20%	LASL
	$*\sigma_{n,f}$ (E)	10 eV to 30 keV	10%	West.
		1 eV to 3 eV	1%	BNWL
	$*\sigma_{n,f}$ (E) (Ratio to ^{235}U, ^{249}Pu)	Thermal to 10 eV	3%	ANL, GE
	$*\sigma_{nf}$ (E) (Ratio to ^{235}U)	20 keV to 400 keV	3%	DOE
	*Alpha	1 keV to 2 MeV	10%	GE, DOE
	*ν(E)	1 keV to 1 MeV	2%	DOE
	*Resonance Parameters	1 eV	1%	ORNL
^{242}Pu	$*\sigma_{n,\gamma}$ (E)	1 keV to 7 MeV	15-20%	DOE
		Thermal to 100 eV	3%	GE
		100 eV to 1 keV	10%	GE
		1 keV to 10 MeV	15-20%	GE
	$N_{n,\gamma}$ (E,E_γ)	Thermal	20%	LASL
^{241}Am	$*\sigma_{n,\gamma}$ (E)	Thermal to 1 keV	10%	SRL
		1 keV to 2 MeV	20%	DOE
^{243}Am	$*\sigma_{n,\gamma}$ (E)	Thermal to 10 MeV	10%	GE, CE
		1 keV to 200 keV	30%	DOE
^{245}Cm	$\sigma_{n,\gamma}$ (E)	Thermal to 10 keV	10%	SRL
	$\sigma_{n,f}$ (E)	Thermal to 10 keV	10%	SRL
^{246}Cm	$\sigma_{n,\gamma}$ (E)	Thermal to 10 keV	10%	SRL
^{247}Cm	$\sigma_{n,\gamma}$ (E)	Thermal to 10 keV	5-10%	SRL
	$\sigma_{n,f}$ (E)	Thermal to 10 keV	10%	SRL
	Resonance Parameters	Thermal to 10 keV	20%	SRL
^{249}Bk	$\sigma_{n,\gamma}$ (E)	Thermal to 10 keV	10%	SRL
^{250}Cf	$\sigma_{n,\gamma}$ (E)	Thermal to 10 keV	10%	SRL
	$\sigma_{n,f}$ (E)	Thermal to 10 keV	10%	SRL
	Resonance Parameters	Thermal to 10 keV	20%	SRL
^{251}Cf	$\sigma_{n,\ }$ (E)	Thermal to 10 keV	10%	SRL
	$\sigma_{n,f}$ (E)	Thermal to 10 keV	10%	SRL
	Resonance Parameters	Thermal to 10 keV	10%	SRL
^{252}Cf	Spon ν		25%	NBS, DOE, Bettis
	$N_{spon\ f}$ (E_n)		1%	KAPL, Bettis
	$\sigma_{n,\gamma}$ (E)	Thermal to 10 keV	10%	SRL
	σ_{nf} (E)	Thermal to 10 keV	10%	SRL

TABLE VI

PLUTONIUM COMPOSITION OF FUEL REBURNED IN LWR (Atom Percent)

ISOTOPE	MWd/tonne				
	30,000	60,000	90,000	120,000	150,000
239	0.65	0.51	0.44	0.41	0.38
240	0.26	0.32	0.33	0.31	0.30
241	0.07	0.10	0.11	0.11	0.10
242	0.02	0.07	0.12	0.17	0.22

TABLE VII

SPECTRUM AVERAGED FISSION CROSS-SECTIONS (barns)

ISOTOPE	CRBR	FMSR(Soft)	FMSR(Hard)
U-235	2.01	3.06	1.50
U-238	0.0446	0.043	0.050
Pu-239	1.87	2.59	1.65
Pu-240	0.363	0.394	0.446
Pu-241	2.52	4.67	1.97
Pu-242	0.290	0.296	0.350

TABLE VIII

SPECTRUM AVERAGED ABSORPTION* CROSS-SECTIONS (barns)

ISOTOPE	CRBR	FMSR(Soft)	FMSR(Hard)
U-235	2.59	4.26	1.85
U-238	0.345	0.378	0.230
Pu-239	2.387	3.70	1.90
Pu-240	0.784	2.14	0.728
Pu-241	2.96	5.70	2.25
Pu-242	0.644	0.414	0.518

* Only fission and capture.

TABLE IX

SPECTRUM AVERAGED CAPTURE CROSS-SECTIONS (barns)

ISOTOPE	CRBR	FMSR(Soft)	FMSR(Hard)
U-235	0.58	1.20	0.35
U-238	0.300	0.335	0.180
Pu-239	0.517	1.11	0.25
Pu-240	0.421	1.74	0.282
Pu-241	0.44	1.03	0.28
Pu-242	0.354	0.118	0.208

TABLE X

ISOTOPIC COMPOSITION OF PLUTONIUM AT 30,000 MWD/T

ISOTOPE	CRBR	FMSR(Soft)	FMSR(Hard)
Pu-239	0.924	0.871	0.957
Pu-240	0.072	0.114	0.043
Pu-241	0.003	0.014	0.000
Pu-242	0.000	0.001	0.000

TABLE XI

ISOTOPIC COMPOSITION OF PLUTONIUM AT 60,000 MWD/T

ISOTOPE	CRBR	FMSR(Soft)	FMSR(Hard)
Pu-239	0.879	0.807	0.924
Pu-240	0.115	0.162	0.072
Pu-241	0.006	0.027	0.004
Pu-242	0.000	0.003	0.000

TABLE XII

ISOTOPIC COMPOSITION OF PLUTONIUM AT 90,000 MWD/T

ISOTOPE	CRBR	FMSR(Soft)	FMSR(Hard)
Pu-239	0.841	0.757	0.899
Pu-240	0.148	0.196	0.093
Pu-241	0.010	0.039	0.008
Pu-242	0.001	0.007	0.000

TABLE XIII

ISOTOPIC COMPOSITION OF PLUTONIUM AT 120,000 MWD/T

ISOTOPE	CRBR	FMSR(Soft)	FMSR(Hard)
Pu-239	0.809	0.720	0.874
Pu-240	0.176	0.221	0.112
Pu-241	0.014	0.049	0.012
Pu-242	0.001	0.010	0.001

TABLE XIV

ISOTOPIC COMPOSITION OF PLUTONIUM AT 150,000 MWD/T

ISOTOPE	CRBR	FMSR(Soft)	FMSR(Hard)
Pu-239	0.778	0.685	0.851
Pu-240	0.202	0.241	0.130
Pu-241	0.018	0.057	0.017
Pu-242	0.002	0.015	0.001

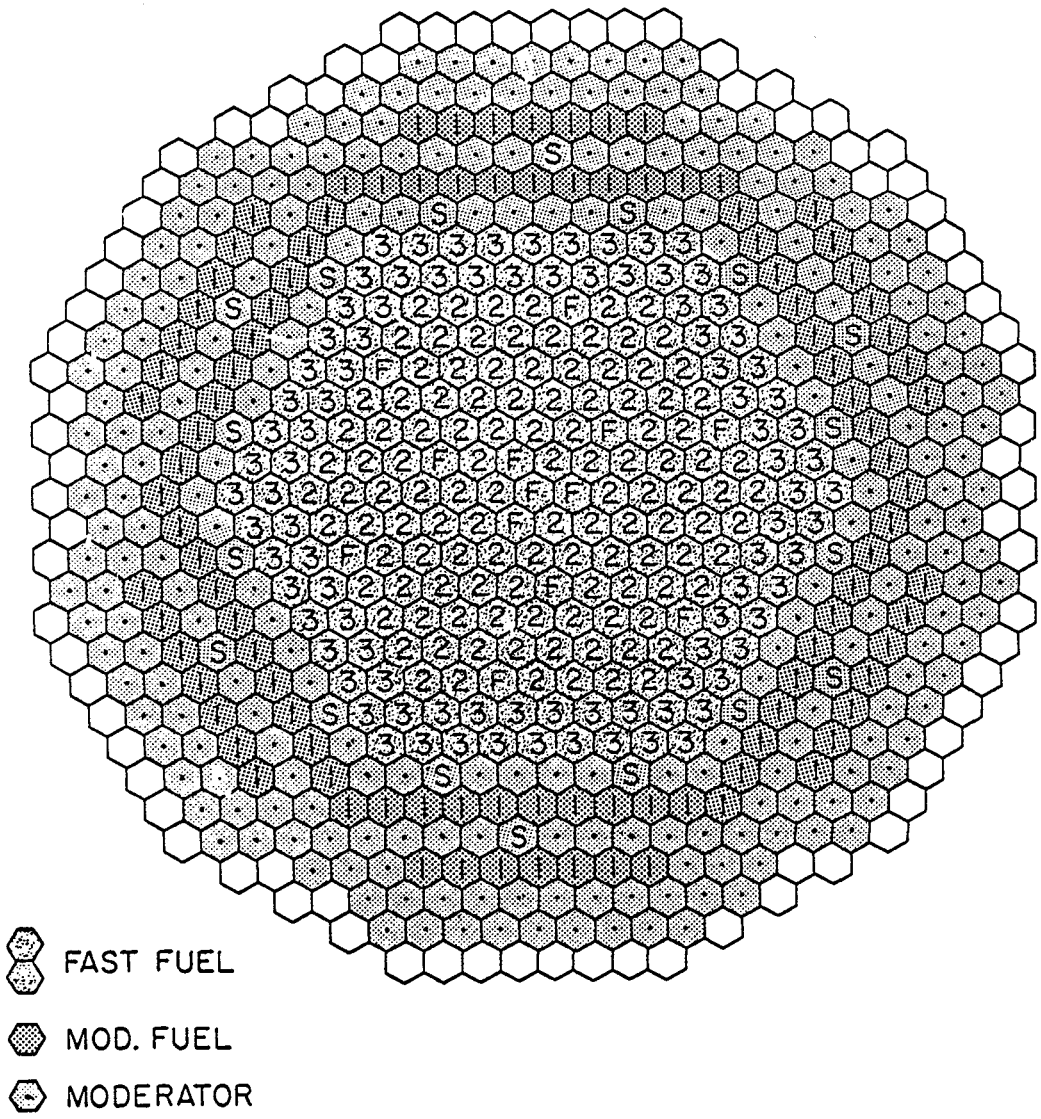

Figure 1 Fast-Mixed Spectrum Reactor Concept
Cross-Sectional View of the FMSR

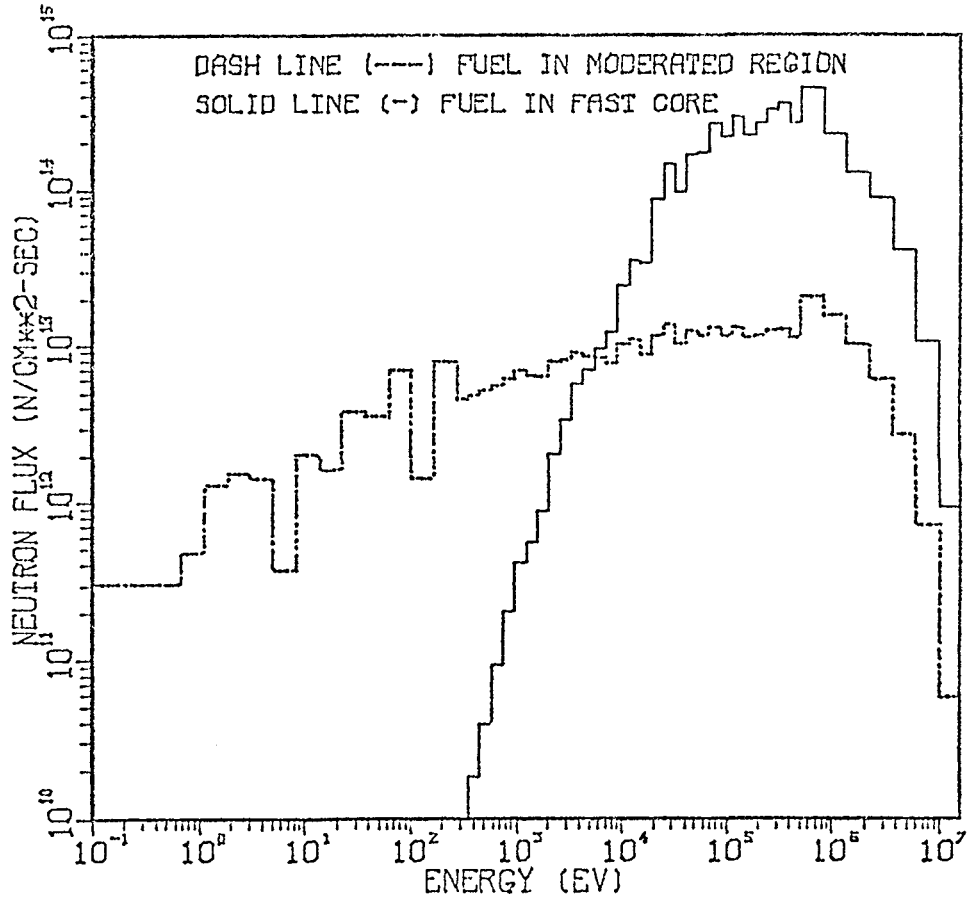

Figure 2 Neutron Spectrum

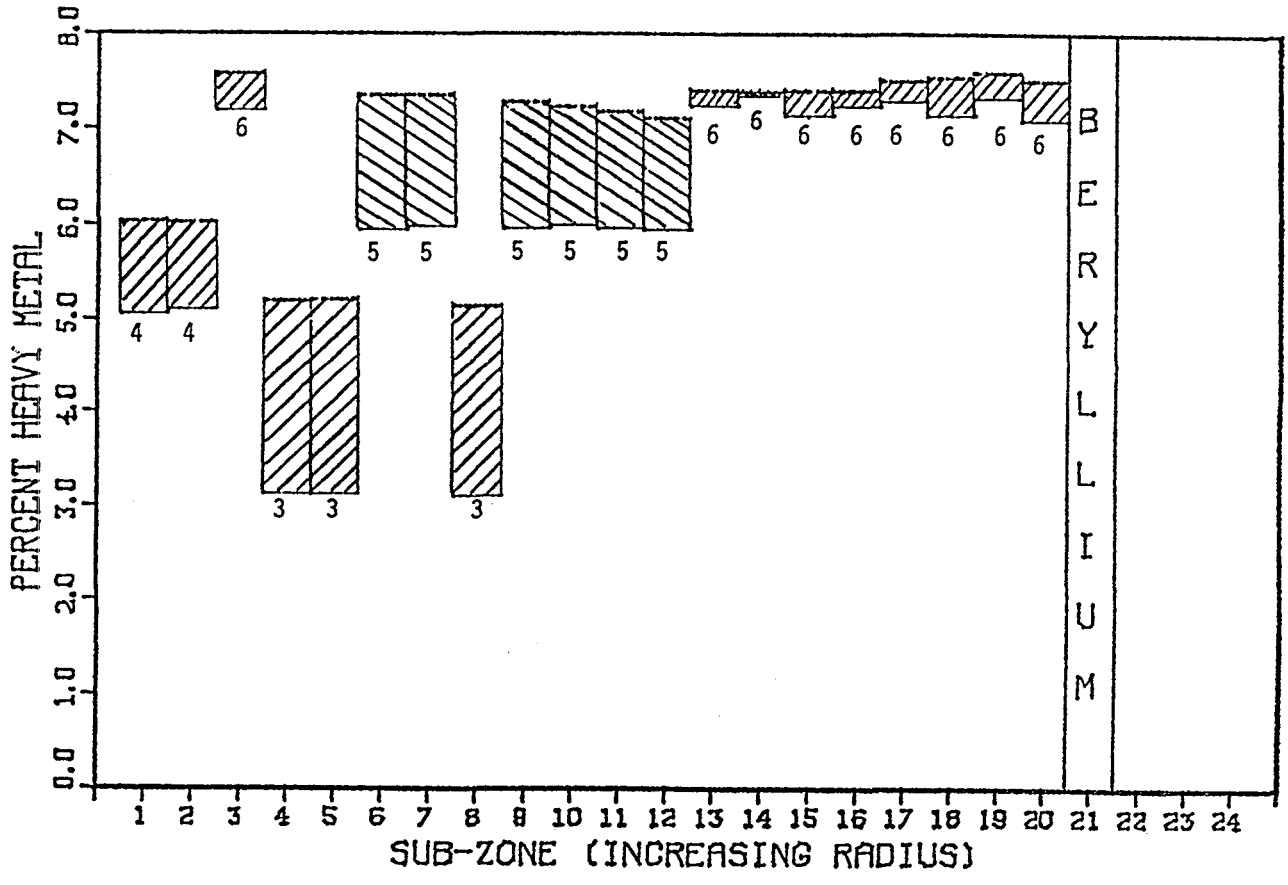

Figure 3 Pu-239 Concentration Variation over Fuel Residence in Sub-Zones, He-Cooled FMSR

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B. STATUS OF TRANSACTINIUM ISOTOPE NUCLEAR DATA

REPORT ON THE IAEA COORDINATED RESEARCH PROGRAMME ON THE MEASUREMENT AND EVALUATION OF TRANSACTINIUM ISOTOPE NUCLEAR DECAY DATA†

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ABSTRACT

As one result of the First IAEA Advisory Group Meeting on Transactinium Isotope Nuclear Data, held in November 1975 at Karlsruhe, an IAEA Coordinated Research Program was set up to address certain identified actinide-isotope decay-data needs in reactor technology. At present, laboratories from five nations are involved in this effort. In this paper, we give an overview of this program, including its origin and the present status of the measurements being carried out. The current status of the actinide-nuclide half-life, spontaneous-fission branching-ratio, α-intensity and γ-intensity data of concern to the Coordinated Research Program is presented and briefly discussed.

1. INTRODUCTION

At the first IAEA Advisory Group Meeting on Transactinium Isotope Nuclear Data [1], held in November, 1975, at Karlsruhe, one of the problem areas addressed was the status of the decay data (half-lives, α and γ intensities) for the transactinium ($Z \geq 90$) nuclides. It was pointed out that the accuracy of many of these data was not adequate to satisfy a number of needs in such areas of reactor technology as safeguards, fuel assay, sample-mass determination and standards preparation. At that meeting, a list of these important transactinium isotopes and the accuracy requirements for their decay data was drawn up. Further, it was recommended that an internationally coordinated research program of decay-data measurement and evaluation be initiated to meet these identified data needs. Subsequently, the IAEA Nuclear Data Section set up a Coordinated Research Program (CRP) on the measurement and evaluation of transactinium-isotope nuclear decay data, with groups from six nations agreeing to participate. The first meeting of the national representatives for this program was held in Vienna, April 20-21, 1978; and a summary report of this meeting was subsequently issued [2]. The second meeting of this group was held on the two days (April 30-May 1, 1979) immediately preceding this conference (the Second IAEA Advisory Group Meeting on TND).

† Work performed under the auspices of the U.S. Department of Energy.

In this paper, the present status and future plans of the Coordinated Research Program are discussed. In addition, a brief summary is given of the current status of those decay data with which this program is primarily concerned. Finally, attention is called to a recent precise measurement of the absolute intensities of the γ rays from the ^{233}Pa decay and to the implications which this result carries for certain aspects of nuclear decay-data evaluation.

2. THE COORDINATED RESEARCH PROGRAM: PARTICIPANTS AND PLANS

2.1 Participating Research Groups

At the first meeting of the national representatives for the Coordinated Research Program, the following participating laboratories were represented.

Laboratory (Nation)	National Representative
Central Bureau for Nuclear Measurements (CEC)	R. Vaninbroukx
Laboratoire de Métrologie des Rayonnements Ionisants (France)	J. Legrand
Bhabha Atomic Research Center (India)	H. C. Jain
Japan Atomic Energy Research Institute (Japan)	H. Umezawa
Atomic Energy Research Establishment Harwell (United Kingdom)	A. J. Fudge
Idaho National Engineering Laboratory (United States of America)	C. W. Reich

Within the U.S., work at a number of laboratories is relevant to the objectives of the CRP. Absolute α-particle intensity measurements are being carried out at Argonne National Laboratory by I. Ahmad. At INEL, we are involved in the carrying out of absolute γ-ray intensity measurements. The Half-Life Evaluation Committee is involved in measurement and evaluation of half-life values for selected Pu isotopes. This latter group, representing individuals from six laboratories, was formed several years ago to address the then-current poor status of half-life data on the more common Pu isotopes. The following laboratories (and representatives) make up this Committee: Mound Laboratory (W. Strohm, Chairman); Argonne National Laboratory (A. Jaffey); Los Alamos Scientific Laboratory (J. E. Rein); Lawrence Livermore Laboratory (A. Prindle); National Bureau of Standards (L. Lucas); and Rocky Flats Laboratory (R. Carpenter).

2.2 Measurement Goals of the CRP

Prior to the first meeting of the participants in the Coordinated Research Program, the status of the measurement activities and the plans for future measurements at the participating laboratories were assessed.

A summary of this information was prepared [3] and formed a basis for some of the discussions at that meeting. This summary, slightly modified, is presented in Table I. It reflects the presently defined overall measurement goals of the CRP and, as such, forms the basis for much of our subsequent discussion.

TABLE I. STATUS AND PLANS OF TND DECAY DATA MEASUREMENT. (Adapted from A. Lorenz, private communication, April 1978)

Required Accuracy: listed are those supplied by Harwell, values recommended at the 1975 Karlsruhe meeting are given in parentheses if different.

Participating Laboratory: Measurement Status:
Plan = measurement is planned to be performed; parentheses imply that plans are not firm; (U) indicates urgency.
Prog = measurement in progress
Finished = measurement completed; parentheses mean that data are being processed.

Priorities: priorities given by each participating group are given as a number in parentheses to the right of measurement status.

Isotope and Quantity		Required Accuracy	Participating Laboratory (or organization)						
			INEL	$T_{1/2}$ Comm.	ANL	Harwell	CBNM	LMRI	JAERI
^{233}Pa	I_γ		Plan(1)						
^{233}U	I_γ		Plan(2)						
^{234}U	I_α	1%			Plan	Plan(1)			(3)
	I_γ	5%				Plan(2)			(3)
^{235}U	$T_{1/2}(\alpha)$	1%				Plan(2)			(3)
	I_α^2	1%			(Plan)	Plan(2)			(3)
	I_γ	1%	Plan(1)			Plan(1)			(3)
^{236}U	$T_{1/2}(\alpha)$	1%				Plan(2)			(3)
^{237}U	I_γ						Plan		
^{238}U	I_α	1%			(Plan)	Plan(2)			(3)
^{237}Np	I_α	1%			Plan	Plan(2)			(3)
^{238}Pu	$T_{1/2}(\alpha)$	0.5%[a]				Plan(1)	Prog.		(2)
	I_α^2	0.5%(0.1%)			Plan	Plan(1)			(2)
	I_γ	1%	Plan(1)			Plan(1)		Plan	(1)
	I_{LX}						Plan		
^{239}Pu	$T_{1/2}(\alpha)$	0.5%[a]		Prog.		Plan(1)	(finished)		(2)
	I_α^2	1%[a]			Plan	Plan(1)			
	I_γ^α	1%	Plan(1)			Plan(1)		finished	(1)
^{240}Pu	$T_{1/2}(\alpha)$	1%		Plan		Plan(1)	Prog.		(2)
	I_α^2	1%			Plan	Plan(1)			
	I_γ^α	1%(0.2%)	Plan(1)			Plan(1)		Plan	(1)

TABLE I. STATUS AND PLANS OF TND DECAY DATA MEASUREMENT (Cont.)

Isotope and Quantity	Required Accuracy	Participating Laboratory (or organization)						
		INEL	$T_{1/2}$ Comm.	ANL	Harwell	CBNM	LMRI	JAERI
^{241}Pu $T_{1/2}(\alpha)$	1%		Plan		Plan(U)	(finished)		(1)
I_γ	1%	Plan(1)			Plan(1)	Plan	Plan	(1)
^{242}Pu $T_{1/2}(\alpha)$	1%[a]		(Plan)		Plan(2)			(3)
I_α	4%			Plan	Plan(2)			(2)
^{241}Am $T_{1/2}(\alpha)$	1%				Plan(2)			(2)
I_γ	1%				Plan(1)	Plan	Finished	(2)
^{242}Cm $T_{1/2}(\alpha)$	0.5%(0.1%)[a]				Plan(1)			Plan(1)
$T_{1/2}$(S.F.)	1%(3%)				Plan(1)			Plan(1)
^{244}Cm $T_{1/2}$(S.F.)	2%(0.3%)[a]				Plan(1)			(1)
^{252}Cf $T_{1/2}(\alpha)$	0.5%(0.2%)				Plan(2)			(3)

a) Required accuracy achieved by a known recent measurement.

3. CURRENT STATUS OF DECAY DATA RELEVANT TO THE CRP

Before discussing the progress to date of the measurement activities related to the goals of the Coordinated Research Program, it is helpful to consider the present status of the decay data. Since the 1975 Karlsruhe meeting, several data evaluations relevant to the transactinium isotopes have appeared. The most comprehensive of these are the Nuclear Data Sheets [4] and the Seventh Edition of the Table of Isotopes [5]. In addition, an Evaluated Nuclear Structure Data File, ENSDF, based on the data evaluations contained in the Nuclear Data Sheets, is being produced by the Nuclear Data Project at ORNL and updated on a periodic basis. A description of this file, in the context of Transactinium Isotope Nuclear Data, is being given as a Review Paper [6] presented at this meeting.

3.1 Half-life data

In Table II, we summarize the status of the half-life data, as contained in several recent evaluations, on those nuclides that were discussed at the first meeting of the participants in the Coordinated Research Program. The data in the third column of Table II are those in the most recent version of ENSDF, dated 1 October 1978, as summarized in Ref. [7]. The values associated with the Table of Isotopes are those "adopted" for the Seventh Edition [5]. No uncertainties have been associated with these values since the authors of Ref. [5] have chosen not to quote "adopted" uncertainties for them. Rather, it is intended that the precision quoted for a given value convey an estimate of its associated uncertainty [9]. For example, the listed half-life for ^{238}Np, 2.117 d,

indicates that the associated uncertainty is to be taken to be < 0.005 d; if the uncertainty to be associated with this value were > 0.005 d (but less than 0.05 d), then the value would have been written as 2.12 d. The ENDF/B values, column 5, are those prepared at INEL [10] for inclusion in the Actinide File of ENDF/B-V. These data were, in general, prepared prior to the appearance the other two evaluations and in some cases (e.g., ^{237}Pu and ^{240}Pu) do not incorporate measured values which were published subsequently. The values listed in the sixth column of Table II

TABLE II. SUMMARY OF HALF-LIFE VALUES OF SELECTED TRANSACTINIUM ISOTOPES. Quantities in parentheses represent uncertainties in the least significant figure (or figures) of the associated value.

Nuclide	Half-Life Units	ENSDF[a]	Table of Isotopes	ENDF/B	CRP-I
Th-228	y	1.9131(9)	1.9131	1.91313(88)	1.913(3)
230	10^4y	7.7(3)	8.0	7.7(3)	7.7(3)
232	10^{10}y	1.405(6)	1.41	1.405(6)	1.405(6)
Pa-231	10^4y	3.276(11)	3.28	3.276(11)	3.276(11)
232	d	1.31(2)	1.31	1.31(2)	1.31(2)
233	d	27.0(1)	27.0	27.0(1)	27.0(1)
U-232	y	72.(2)	72.	71.7(9)	72.(1)
233	10^5y	1.592(2)[b]	1.592	1.5918(15)	1.592(2)
234	10^5y	2.445(10)	2.45	2.446(7)[c]	2.446(7)
235	10^8y	7.038(5)	7.038	7.038(5)	7.038(7)
236	10^7y	2.3416(39)	2.342	2.3415(14)	2.342(4)
237	d	6.75(1)	6.75	6.75 (1)	6.75(1)
238	10^9y	4.468(3)	4.468	4.4683(24)	4.468(4)
239	m	23.50(5)	23.5	23.50(5)	23.50(5)
Np-236[d]	10^5y	1.15(12)	1.1	1.15(12)	1.15(12)
236m[e]	h	22.5(4)	22.5	22.5(4)	22.5(4)
237[e]	10^6y	2.14(1)	2.14	2.14(1)	2.14(1)
238[e]	d	2.117(2)	2.117	2.117(2)	2.117(2)
239	d	2.355(4)	2.35	2.354(6)	2.354(6)
Pu-236[e]	y	2.851(8)	2.85	2.851(8)	2.851(8)
237	d	45.3(2)	45.4	45.63(20)	45.6(2)
238	y	87.74(4)	87.74	87.75(5)	87.74(9)
239	10^4y	2.411(10)	2.41	2.411(10)	2.411(3)
240	10^3y	6.537(10)	6.57	6.55(7)[c]	6.553(8)
241	y	14.4(2)	14.4	14.7(4)	14.7(4)
242	10^5y	3.763(20)	3.76	3.763(20)	3.76(2)
244	10^7y	8.26(9)	8.1	8.2(1)[c]	8.2(1)
Am-241	y	432.2(5)	433.	432.2(2)	432.6(6)
242	h	16.02(2)	16.01	16.01(2)	16.01(2)
242m[e]	y	152.(7)	152.	152.(7)	152.(7)
243	10^3y	7.380(40)	7.37	7.380(40)	7.38(4)
Cm-242	d	162.8(4)	162.8	162.9(3)	162.8(4)
244	y	18.11(2)	18.11	18.11(1)	18.11(2)
Cf-252	y	2.638(10)	2.64	2.638(10)	2.64(1)

a) Data as summarized in Ref. [7].

b) Uncertainty given as 0.020 x 10^5y in Ref. [7].

c) Value taken from R. Vaninbroukx (Ref. [8]).

d) Only one measured value reported.

e) Listed value based essentially on only one measurement.

are taken from a proposed list of recommended values drawn up during the first meeting of the participants in the CRP [2]. They were derived largely from the INEL data base, represented by the ENDF/B values. However, in some cases the uncertainties have been increased, reflecting the consensus of the group that, in consideration of the experimental techniques involved, the total uncertainty ascribed should in no case be smaller than $\sim$ 0.1%.

Generally, the status of the half-life data is reasonably good. In most instances, the accuracy criteria established at the first TND meeting appear to be met. The outstanding exception at present is the important Pu isotope, ^{241}Pu. However, it is to be anticipated that the results of measurement programs currently underway (see below) will help to clarify this situation, as well as to provide increased accuracy and precision for the half-life values of ^{239}Pu and ^{240}Pu. As indicated in Table II, the half-life values for several nuclides are based on one, or essentially only one, measurement. For those applications where these data are of importance, it might be useful to re-measure these values to provide a check on their accuracy.

3.2 Spontaneous-fission branching ratios

The spontaneous-fission branching-ratio data for those trans-actinium isotopes considered at the first meeting of the participants in the CRP [2] are summarized in Table III. The spontaneous-fission branching ratios are not listed explicitly in the Table of Isotopes for most of these nuclides; only the S.-F. half-lives are given. Since no "adopted" values for these latter quantities are listed in Ref. [5], we have chosen not to derive branching ratios from these data. Since the data base for the three evaluations in Table III is essentially the same, values deduced from the Table of Isotopes information should not differ strikingly from those listed. A number of the S.-F. branching ratios are based on only one measurement and several result from two rather discrepant measurements. The spontaneous-fission half-life of ^{238}U has been extensively investigated, with roughly 40 measurements reported. This situation has been carefully evaluated by Apt [11]; and he adopts the value $\lambda_{S.F.} = 8.46 \times 10^{-17} y^{-1}$, with an estimated uncertainty of $\sim$ 1%. This is the value from which the ^{238}U S.-F. branching ratio included in ENDF/B was derived. (Incidentally, Apt's adopted value is essentially identical to that measured by Galliker et al. [12].) The two sets of evaluated S.-F. branching-ratio data listed in Table III are in generally good agreement, except possibly for ^{241}Am, where different evaluation criteria were adopted.

TABLE III. SUMMARY OF SPONTANEOUS-FISSION BRANCHING RATIOS FOR SELECTED TRANSACTINIUM ISOTOPES.
Quantities in parentheses represent uncertainties in the least significant figure (or figures) of the associated value.

Nuclide	S.-F. Branching Ratio (in %)[a]					
	ENSDF[b]		Table of Isotopes[c]		ENDF/B	
U-232[d]	1.	x10^{-10}			0.9(7)	x10^{-10}
-233[d]	1.3(4)	x10^{-10}			1.3(3)	x10^{-10}
-234[d]	1.2(6)	x10^{-9}			1.2(6)	x10^{-9}
-236[d]	≈1.2	x10^{-7}			1.2	x10^{-7}
-238	5.4(8)	x10^{-5}			5.45(6)	x10^{-5}
Pu-236[d]	8.1(23)	x10^{-8}			8.1(23)	x10^{-8}
-238	1.84(6)	x10^{-7}			1.84(5)	x10^{-7}
-239[d]	4.4	x10^{-10}			4.4	x10^{-10}
-240	4.95(20)	x10^{-6}			5.0(2)	x10^{-6}
-242	5.50(6)	x10^{-4}			5.50(6)	x10^{-4}
-244[e]	0.125(6)				0.125(6)	
Am-241[e]	3.77(8)	x10^{-10}			4.1(1)	x10^{-10}
-242m[d]	1.6(6)	x10^{-8}			1.6(6)	x10^{-8}
-243[e]	2.2(2)	x10^{-8}			2.2(2)	x10^{-8}
Cm-242	6.8(7)	x10^{-6}			6.8(6)	x10^{-6}
-244	1.347(2)	x10^{-4}			1.347(2)	x10^{-4}
-246	0.02614(5)				0.02614(5)	
-248	8.26(3)		8.26(3)		8.26(3)	
Bk-249	4.7(2)	x10^{-8}			4.60(25)	x10^{-8}
Cf-249	5.2(2)	x10^{-7}			5.02(10)	x10^{-7}
-250	0.077(3)				0.077(3)	
-252	3.092(8)		3.092(8)		3.092(8)	
Es-253	8.7(3)	x10^{-6}			8.7(3)	x10^{-6}

a) These values have generally been computed from the measured spontaneous-fission half-lives and total half-life values.

b) Values summarized in Ref. [7].

c) With the exceptions listed, the spontaneous-fission branching ratios are not explicitly given in this reference. See the discussion in the text.

d) Only one measured value is reported.

e) Two discrepant values are reported. For ^{241}Am, several measurements are reported.

3.3 Absolute α-transition intensities

The absolute α-transition intensity data for selected "important" transactinium isotopes, as summarized in a number of data compilations, are given in Table IV. We have followed the usual convention, labelling the individual α transitions by the energy of the daughter-nucleus state which is directly fed by the transition. We have also, for convenience, given the initial- and final-state spin-parity (J^{π}) values. Generally, only the more intense α transitions, those subject to direct experimental measurement, are included.

Since the appearance in 1973 of the major evaluation of α-transition data by Rytz[13], a number of α-intensity measurements have been published. Consequently, in a number of cases the α-intensity values in this reference have been superseded. It still remains authoritative, however, as regards α-transition energies. The intensity values of Baranov et al. [15] are those given in their review paper, presented at the Karlsruhe meeting on TND [1].

The agreement among all the evaluations (except that of Ref. [15]) for the α-intensity data for ^{238}U and ^{237}Np results from the fact that they are all based on the results of a single measurement for each nuclide. A number of differences in the listed I_α values for other isotopes is apparent from inspection of Table IV. Of some interest, although not perhaps of overriding importance from a practical point of view, are the differences in the reported intensities of the α transitions feeding the 4^+ members of the ground-state rotational bands in the doubly even nuclei. In some cases (e.g., ^{234}U) these differences result from the fact that the intensity values for these transitions deduced from level-scheme intensity-balance considerations are not the same as those determined experimentally. Since these former values are based on γ-ray intensity measurements (together with the associated internal-conversion coefficients) and since both absolute I_α and I_γ measurements will be carried out under the CRP for several of these nuclides, it is to be hoped that one of the results of this Program will be a resolution of these differences.

TABLE IV. ABSOLUTE-INTENSITY DATA FOR SELECTED α-TRANSITIONS FROM TRANSACTINIUM ISOTOPES OF INTEREST TO THE CRP. Quantities in parentheses represent uncertainties in the least significant figure (or figures) of the associated values.

Nuclide and J^π	α-group[a], and final-state J^π	I_α (% per decay)					
		Rytz [13]	Nuclear Data Sheets	Table of Isotopes	ENDF/B	Rogers [14]	Baranov et al. [15]
^{234}U 0^+	α_0 , 0^+	72.(2)	72.5(20)	72.	72.5(30)	72.(2)	
	α_{53} , 2^+	28.(2)	27.5(15)	28.	27.5(15)	28.(2)	
	α_{174}, 4^+	-	0.24(3)[b]	0.3	0.3	0.3	
^{235}U $7/2^-$	α_0 , $5/2^+$	4.	5.0(5)	4.6	5.4(5)	1.2	
	α_{42} , $7/2^+$	-	4.2(3)	3.7	4.5(5)	1.7	
	α_{205}, $7/2^-$	56.	55.(3)	57.	56.(3)	53.	
	α_{237}, $9/2^-$	18.	~17. [c]	18.	17.(2)	12.3	
	α_{278}, $11/2^-$	-	4.6(5)	3.	4.7(5)	3.5	
	α_{388}, $7/2^-$	6.	5.7(6)	5.7	5.7(6)	6.2	
^{238}U 0^+	α_0 , 0^+	77.(4)	77.(4)	77.(4)	77.(4)	77.(4)	
	α_{50} , 2^+	23.(4)	23.(4)	23.(4)	23.(4)	23.(4)	
	α_{143}, 4^+	-	0.23(7)	0.23(7)	0.23(7)	0.23(7)	
^{237}Np $5/2^+$	α_0 , $3/2^-$	2.6(2)	2.6(2)	2.6(2)	2.6(2)	2.6(2)	-
	α_{57} , $7/2^-$	-	2.5(4)	2.5(4)	2.5(4)	2.5(4)	-
	α_{86} , $5/2^+$	47.(9)	47.(9)	47.	47.(9)	47.(9)	51.3(8)
	α_{104}, $7/2^+$	25.(6)	25.(6)	25.	25.(6)	25.(6)	19.4(4)
	α_{109}, $9/2^+$	8.(3)	8.(3)	8.	8.(3)	8.(3)	16.8(4)
	α_{238}, $5/2^+$	6.2(1)	6.18(12)	6.18(12)	6.18(12)	6.18(12)	-
^{238}Pu 0^+	α_0 , 0^+	71.1(12)	71.6(6)	72.	71.1(12)	71.1(12)	72.13(6)
	α_{43} , 2^+	28.7(12)	28.3(6)	28.	28.7(12)	28.7(12)	27.87(3)
	α_{143}, 4^+	-	0.10(3)	0.11	0.13(1)	0.068(5)	-
^{239}Pu $1/2^+$	$\alpha_{0.07}$, $1/2^+$	73.3	73.3(7)	73.	73.3(7)	73.3	73.3(7)
	α_{13} , $3/2^+$	15.1	15.1(2)	15.1	15.1(2)	15.1	15.1(2)
	α_{52} , $5/2^+$	11.5	11.5(2)	11.5	11.5(2)	11.5	11.5(2)
^{240}Pu 0^+	α_0 , 0^+	76.	73.4(8)	73.3	73.4(8)	76.	73.4(8)
	α_{45} , 2^+	24.	26.5(4)	26.6	26.5(4)	23.	26.5(4)
	α_{149}, 4^+	-	0.091(6)	0.084	0.091(6)	0.09	-
^{242}Pu 0^+	α_0 , 0^+	77.	77.5(30)	74.	77.5(30)	77.	79.7(27)
	α_{45} , 2^+	23.	22.4(20)	26.	22.4(20)	23.	20.2(11)
	α_{148}, 4^+	-	0.098(17)	0.11	0.098(17)	-	-

a) The subscript gives the energy (in keV) of the state in the daughter nucleus to which the α transition proceeds.

b) Intensity value inferred from level scheme.

c) Two α groups are presumed to lie within this peak. The listed value is the sum of the two intensities.

3.4 Absolute photon-intensity values

Table V presents a summary of absolute-intensity values for selected prominent γ-ray transitions from the decay of transactinium isotopes to be investigated in the CRP. The evaluation of Kocher [16] is derived largely from data contained within the Nuclear Data Sheets and ENSDF; and because of intensity-limit considerations adopted in the computer programs employed to produce the data listings in Ref. [16], no intensity values are given for the γ-ray transitions for a number of these isotopes. The values of Gunnink et al. [17] represent an upgrading of data presented in an earlier report [18]. Where available, the data of Ref. [17] are those incorporated into the decay data in ENDF/B. The errors given in Ref. [17] are generally those associated with the γ-ray peak fitting alone and, for this reason, are not reproduced in Table V. The errors given for the "Gunnink et al." intensity values in ENDF/B (see Column 7, Table V) represent estimates by the compilers of that data file, based on the listed "peak-fitting" errors [17] and estimates of the other errors, in consultation with Gunnink.

In several instances, the absolute γ-ray intensities are based on intensity-balance considerations in the adopted decay schemes. This procedure is generally rather sensitive to the details of these schemes and, as is evident, can lead to significant differences in the inferred intensity values. The I_γ value listed in ENDF/B for the 311.9-keV γ ray from ^{233}Pa is the result of a recent measurement at INEL [19] and will be discussed later (see Section 5 below). Similarly, the ENDF/B value for the intensity of the 185.7-keV γ ray from ^{235}U decay is that supplied by Bemis [20]. Previously, the only reported value for this quantity was 54.%, reported in 1957 with no quoted uncertainty [21].

The determination of the isotopic composition of Pu samples has important applications for fuel reprocessing and for the safeguards and waste-management aspects of the nuclear fuel cycle, as well as for the physics of reactors operating under different spectrum and fuel-burnup conditions. Since Ge(Li)-based γ-ray spectrometry provides a non-destructive, relatively convenient and flexible means of measuring these isotopic concentrations, considerable attention has been focused on obtaining values for the absolute intensities of the γ rays emitted from the important Pu isotopes ($238 \leq A \leq 241$). A recent summary of these data, as used by various groups, has been given by Banham [22]. In Table VI we present a somewhat modified version of these data as listed in Ref. [22]. The latest I_γ data of Gunnink et al. [17] were not available to Banham; we have included them in Table VI partly to trace the evolution of these values from 1971 [18] to 1976 [17] and partly to illustrate how they compare with those used by the other groups. Significant differences in the three data sets ([17], [22] and [23]), particularly for the even-A Pu isotopes, are observed.

TABLE V. ABSOLUTE-INTENSITY VALUES OF SELECTED γ-RAY TRANSITIONS FROM TRANSACTINIUM ISOTOPES OF INTEREST TO THE CRP. Quantities in parentheses represent uncertainties in the least significant figure (or figures) of the associated values.

Nuclide	E_γ(keV)	I_γ (photons/100 decays)				
		Nuclear Data Sheets	Table of Isotopes	Kocher [16]	Gunnink [17]	ENDF/B
^{233}Pa	311.9	36.(2)[a]	37.(2)[a]	33.7[a]		38.6(5)
^{233}U	42.4	0.062(9)	0.062(9)			0.062(8)
	54.6	0.015(2)	0.015(2)			0.015(2)
	97.1	0.022(3)	0.022(3)			0.022(3)
	317.2	0.008(1)	0.008(1)			0.008(1)
^{234}U	53.2[a]	0.119(10)	0.119(10)	0.118(10)		0.12(1)
	120.9[b]	0.041(4)	0.041(4)			0.041(6)
^{235}U	185.7	54.	54.	54.		54.1(19)
^{237}U	208.0	21.7(23)[a]	23.[a]	23.3[a]	21.7	21.7(3)
^{239}Np	228.2	10.7(7)	10.7(7)	10.7(7)		11.3(2)
	277.6	14.1(4)	14.1(4)	14.1(4)		14.3(2)
^{238}Pu	43.5	0.0390(5)	0.0394(11)[a]		0.0393	0.0393(5)
	99.8	0.00724(20)	[c]		0.00724	0.00724(10)
	152.7	0.00101(20)	[c]		0.000956	0.000956(15
^{239}Pu	51.6	0.0208(6)	0.0208(2)		0.0270	0.0270(4)
	129.3	0.00620(20)	0.00620(6)		0.00626	0.00626(9)
	413.7	0.00151(5)	0.00151(2)		0.00149	0.00149(2)
^{240}Pu	45.2	0.0450(5)	0.0450(5)		0.0453	0.0453(6)
	104.2	0.0070(1)	0.00700(7)		0.00698	0.00698(10)
	160.3	0.000420(4)	0.000420(4)		0.000402	0.000402(7)
^{241}Pu[d]	103.7	1.01(1)	1.03(6)		1.01	1.01(2)
	148.6	1.86(2)	1.9(1)		1.87	1.87(1)
^{241}Am	26.3	2.4(1)	2.4(1)	2.58(22)	2.45	2.45(3)
	59.5	35.9(6)	35.7(5)	36.3(4)	35.9	35.9(4)

a) Intensity values deduced from level scheme

b) Intensity deduced from measured $I_\gamma(120)/I_\gamma(53)$ ratio.

c) Only relative I_γ values listed. These are consistent with the other listed I_γ values

d) These I_γ values are based on a value of 0.00245% for the intensity of the α-decay branch of ^{241}Pu. The listed I_γ values must all be multiplied by a factor of 10^4 in order to represent photons/100 decays.

Interest in L-x-ray intensity data was voiced at the first meeting of the participants in the CRP [2]. In Table VII, we summarize the results of a recent measurement [24] of the L-x-ray spectra for a number of transactinium isotopes. Also included in the table are the results of a determination [25] of the intensities of the prominent L-x-ray lines from the decay of ^{238}Pu and those for the ^{241}Am decay, measured several years ago by Campbell and McNelles [26]. The measured values reported in [24] and [25] represent absolute determinations. However, the intensity standards utilized to determine the absolute detection efficiencies in these two studies are those of Campbell and McNelles and, consequently, the reported intensity data are not completely independent of the ^{241}Am L-x-ray intensity data measured by these authors [26].

TABLE VI. COMPARISON OF ABSOLUTE INTENSITIES OF GAMMA RAYS FROM PU ISOTOPES, AS LISTED IN VARIOUS REFERENCES. The table is adapted from that given in Ref. [22].

Isotope	E_γ(keV)	Absolute Intensity (photons/10^6 decays)			
		Parker [23]	Gunnink [18]	Gunnink [17]	Banham [22]
238	152.8	10.1	10.1	9.56	9.5
239	129.3	62.	62.	62.6	62.
	144.2	3.25	2.86	2.83	2.96
	161.5	1.25	1.3	1.20	1.24
	171.4	1.13	1.09	1.105	1.11
	195.7	1.07	1.07	1.064	1.09
	203.5	5.6	5.6	5.60	5.70
	345.0	5.61	5.61	5.592	5.96
	375.0	15.8	15.8	15.70	16.4
	413.0	15.	15.1	14.89	15.1
240	160.3	4.2	4.2	4.02	4.2
241	148.6	1.9	1.9	1.87	1.88
	164.6	0.45	0.45	0.453	0.46
	208.0	5.12	5.12	5.34	5.6
	267.5	0.177	0.177	0.182	0.19
	332.4	0.280	0.280	0.298	0.30
^{241}Am	125.3	39.5	39.5	40.8	39.5
	146.6	4.58	4.58	4.61	4.58
	208.0	7.6	7.6	7.91	7.6
	332.3	1.45	1.45	1.490	1.45
	335.4	4.7	4.7	4.960	4.7

TABLE VII. MEASURED INTENSITIES OF L-X-RAYS FROM TRANSACTINIUM ISOTOPES. Unless otherwise indicated, the data are those of Bemis and Tubbs (Ref. [24]). Quantities in parentheses represent uncertainties in the least significant figure (or figures) of the associated value.

Nuclide	L-X-ray intensity (in photons/100 decays).				
	L_ℓ	L_α	L_β	L_γ	Total L
^{234}U	0.22(1)	3.66(8)	4.87(10)	1.05(4)	9.81(13)
^{235}U[a]	2.01(10)	45.4(20)	94.3(42)	15.2(7)	157.(4)
^{237}Pu	1.06(5)	16.3(4)	17.0(5)	3.83(20)	38.2(7)
^{238}Pu	0.26(1)	4.15(7)	5.61(7)	1.36(2)	11.38(10)
^{238}Pu[b]	-	5.05(6)	7.41(9)	1.48(2)	-
^{239}Pu	0.113(5)	1.82(4)	2.16(4)	0.53(1)	4.63(6)
^{240}Pu	0.24(1)	3.78(6)	4.84(7)	1.20(3)	10.06(10)
^{242}Pu	0.21(2)	3.10(8)	4.15(10)	1.08(4)	8.54(14)
^{241}Am[c]	0.86(3)	13.20(35)	19.25(60)	4.85(20)	38.2(7)
^{243}Am[d]	1.8(1)	27.5(6)	30.6(8)	7.69(21)	67.6(10)
^{244}Cm	0.25(1)	3.86(7)	4.30(7)	1.03(2)	9.44(10)
^{245}Cm	3.2(2)	49.8(22)	47.6(21)	12.5(6)	113.1(31)
^{246}Cm	0.21(1)	3.33(7)	3.71(7)	0.86(2)	8.11(10)
^{250}Cf	0.21(1)	3.27(8)	3.85(8)	0.85(3)	8.18(12)
^{252}Cf	0.23(2)	3.09(28)	3.80(34)	0.93(8)	8.05(45)

[a] Includes Pa L-x-rays from the decay of the ^{231}Th daughter.

[b] Values reported by Vasilik and Martin, Ref. [25].

[c] Values reported by Campbell and McNelles, Ref. [26].

[d] Includes Pu L-x-rays from the decay of the ^{239}Np daughter.

3.5 Recent measurements

Several recent measurements, not yet generally incorporated into the evaluations, of interest to the work of the CRP should be noted. The first formal publication of the work of the Half-Life Evaluation Committee has recently appeared [27]. It describes the comprehensive effort undertaken by that group to provide an accurate value for the half-life of ^{239}Pu. Their recommended value for this quantity is

$$T_{\frac{1}{2}}\ (^{239}\text{Pu}) = 24{,}119 \pm 26\ \text{y}.$$

A measurement of the half-life of ^{240}Pu has recently been published [28]. The value quoted by the authors for this quantity is

$$T_{\frac{1}{2}}\ (^{240}\text{Pu}) = 6569 \pm 6\ \text{y}.$$

The α-particle spectra of ^{246}Cf, ^{248}Cm and ^{240}Pu have been remeasured [29]. For ^{240}Pu, these authors report for the intensities of the α transitions to the 0-, 45- and 149-keV levels in ^{236}U the values

$$I(\alpha_0) = 73.51(36)\%$$
$$I(\alpha_{45}) = 26.39(21)\%$$
and $$I(\alpha_{149}) = 0.071(1)\%$$

The absolute-intensity values for the prominent γ rays from the decays of ^{233}Pa and ^{235}U have been mentioned in Sect. 3.4 above and listed in Table V.

4. STATUS OF CURRENT MEASUREMENTS BEING PERFORMED IN THE CONTEXT OF THE CRP

In this section, we present brief summaries of the measurement activities being conducted at the participating laboratories which are related to the objectives of the CRP. These summaries have been taken from material kindly supplied by the representatives of these participating laboratories.

4.1 CBNM

The present effort largely involves measurements of the half-lives of ^{239}Pu and ^{241}Pu.

The determination of the half-life of ^{239}Pu has been finished. During the reporting period the disintegration rates of five samples of a Pu material containing 99.98 atom % ^{239}Pu have been determined by counting α particles in a defined solid angle of low geometry. Corrections for the contribution of ^{238}Pu and ^{240}Pu have been allowed for. The first was determined by α-particle spectrometry and the latter calculated from the isotopic composition of the sample which was deduced from mass-spectrometric measurements. Finally, the specific α-emission rate of ^{239}Pu and its half-life have been calculated.

In a following step the α-emission rate of samples of the same Pu material, but after spiking with ^{242}Pu for the determination of the Pu content by mass-spectrometric isotope dilution techniques, were determined by liquid scintillation counting. Corrections for the contribution of ^{238}Pu, ^{240}Pu, and the spike material ^{242}Pu to the count rates were applied and again the specific α-emission rate and the half-life of ^{239}Pu were deduced.

The results of both series of measurements are given in Table VIII in which the uncertainties quoted are at the 1σ level taking into account random and systematic effects.

TABLE VIII

SPECIFIC α-EMISSION RATE AND HALF-LIFE OF ^{239}Pu

Method	Specific α-emission $s^{-1}/\mu g\ ^{239}Pu$	Half-life years
Low geometry	2298 ± 3	$(2.4085 \pm 0.0030)10^4$
Liquid Scintillation	2295 ± 3	$(2.4114 \pm 0.0030)10^4$
Mean	2296 ± 3	$(2.4100 \pm 0.0030)10^4$

In an attempt to resolve the existing discrepancy of several percent between the values reported for the half-life of ^{241}Pu, a new determination was performed. The half-life was determined by following the change in time of the Pu isotopic composition by mass spectrometry and by measuring the ^{241}Am ingrowth using α- and γ-counting techniques. As a sideproduct the partial α half-life was determined. The following results were obtained: $T_{1/2}$ = (14.30 ± 0.14)y and (14.60 ± 0.10)y for the mass spectometric and ingrowth method, respectively, and $T_{1/2}$ (α) = $(6.04 \pm 0.06)10^5$y.

4.2 Harwell

Measurements of the half-life and absolute α- and γ-ray intensities for ^{237}Np have been initiated. These measurements will be followed by studies of the uranium isotopes.

4.3 LMRI

The measurement of the energies and absolute intensities of the γ rays in the energy range from 20 keV to 60 keV from the decay of ^{241}Am has been completed. In addition,the energies and absolute intensities of the γ rays from the ^{239}Pu decay have been measured.

Measurements of the energies and absolute intensities of γ rays from the decay of ^{238}Pu and ^{240}Pu are in progress and are expected to be completed later on this year.

4.4 JAERI

The measurement program has had as its emphasis an accurate half-life determination for ^{242}Cm. The ^{242}Cm can be very purely prepared by means of milking decay products from 152-y ^{242m}Am. In the present work, americium was extracted from a plutonium bearing fuel specimen and purified for curium and other actinides. Curium-242 was separated from the americium after allowing it to stand for a several-month period. Several samples of ^{242}Cm were prepared for measurement, and alpha activities have been measured with a proportional counter and a silicon surface barrier detector. Measurements of spontaneous fissions are also being studied at present.

Although ^{241}Am and ^{243}Am coexisted with ^{242m}Am, which is the ancestor of questioned nuclide, ^{242}Cm has grown in as the only curium nuclide in the americium and could be extracted pure by performing the same chemical treatment as the purification of the americium, after allowing it to stand for an appropriate period for the growth of ^{242}Cm. Six samples were prepared for the half-life measurement by depositing a drop of the hydrochloric solution of purified ^{242}Cm on a platinum plate of 24mm diameter and 0.2mm thick. Alpha activities of those samples are being measured with a windowless proportional counter. Decay of the alpha activity has been followed for 4 months. The efficiency of the counter has slowly changed within a one or two percent range through the whole period of the measurements. The deviation was estimated by measuring a reference sample of ^{238}Pu.

The results obtained so far from the decay measurements are summarized in Table IX. The measurements will be continued further to obtain more accurate results.

TABLE IX
RESULTS OF HALF-LIFE MEASUREMENTS ON ^{242}Cm SAMPLES

Sample No	Half-life (days)
1	164.79
2	163.41
3	163.94
4	160.66
5	164.74
6	162.12
Mean	163.28
Standard deviation	1.62

4.5 Measurement within the U.S.

4.5.1 Half-Life Evaluation Committee.

The objectives of this committee, consisting of participants from six laboratories (see Sect. 2.1 above), are the measurement of accurate half-life values for ^{239}Pu, ^{240}Pu and ^{241}Pu. The first phase of this work, the measurement of the ^{239}Pu half-life, has now been completed. The results have been published as a collection of papers in the August, 1978 issue of The International Journal of Applied Radiation and Isotopes [27]. The value of the ^{239}Pu half-life recommended from this work is 24,119 ± 26 y (as indicated in Sect. 3.5 above).

The members of the committee are currently measuring the half-lives of ^{240}Pu and ^{241}Pu. The measurement procedures for ^{240}Pu are similar to those employed for ^{239}Pu [27]. The sample material has been acquired and has been distributed to the participating laboratories for characterization, and measurements have gotten under way. The ^{241}Pu half-life measurement is of a more limited scope, involving only a mass-spectrometric technique. This investigation was undertaken earlier than the ^{240}Pu study but, because of the nature of the measurement, will not be completed until some time after the ^{240}Pu work is finished. At the present time, the early results from this study suggest a value of ∿14.4 y for the ^{241}Pu half-life, in reasonable agreement with independent measurements at the U.S. National Bureau of Standards and at the CBNM in Geel, Belgium (See Sect. 4.1 above).

4.5.2 ANL.

Absolute α-intensity measurements will be getting under way this Spring. The first isotopes to be studied will be $^{238,239,240,242}Pu$. Samples, containing a nominal few-μg amounts of Pu, will be prepared by isotope separation. A small (25mm^2 area) Si surface-barrier counter, with an energy resolution of ∿12 keV, will be used to count the α particles. The counting geometry will be at 1% or lower; and measurements will be taken at several geometries, to assess the effects of electron-α summing.

4.5.3 INEL

The INEL measurement [19] of the absolute γ-ray intensities from the β^- decay of ^{233}Pa has been completed and the results accepted for publication. 4π β-γ coincidence techniques were utilized to determine the absolute disintegration rates of the ^{233}Pa sources (obtained from milking an 0.5-g sample of ^{237}Np). The value obtained for the absolute intensity of the prominent 312-keV γ ray was 38.6 ± 0.5 photons/100 decays (see Table V and Sects. 3.4 and 5.).

The next nuclides for which absolute I_γ measurements will be made are ^{239}Pu and ^{240}Pu. High-purity samples of ^{239}Pu (99.995% in mass 239) and ^{240}Pu (≤1% ^{238}Pu by α activity) have been acquired for these measurments.

To permit absolute-intensity measurements of γ rays from actinide samples to be made with precisions of 1% or better, careful attention must be given to all aspects of the measurement process. The improvement of our techniques of precision γ-ray spectrometry to make possible measurements with this required precision has gotten underway this year. An early emphasis of this activity is a careful study of the shapes of full-energy γ-ray peaks observed in spectra measured using Ge-based spectrometers. This has as its object the development of a method of reliably and consistently determining the number of events contained in these peaks. To do this requires a means of treating the effects of "tailing" in the peaks and accounting for the spectral distribution underlying the peaks in a reproducible manner. Typical peak shapes observed in spectra acquired using two different Ge-semiconductor spectrometers are shown in Figs. 1 and 2. Inspection of these figures reveals that the contribution of tailing (as defined in the Figures) can be 1-2%

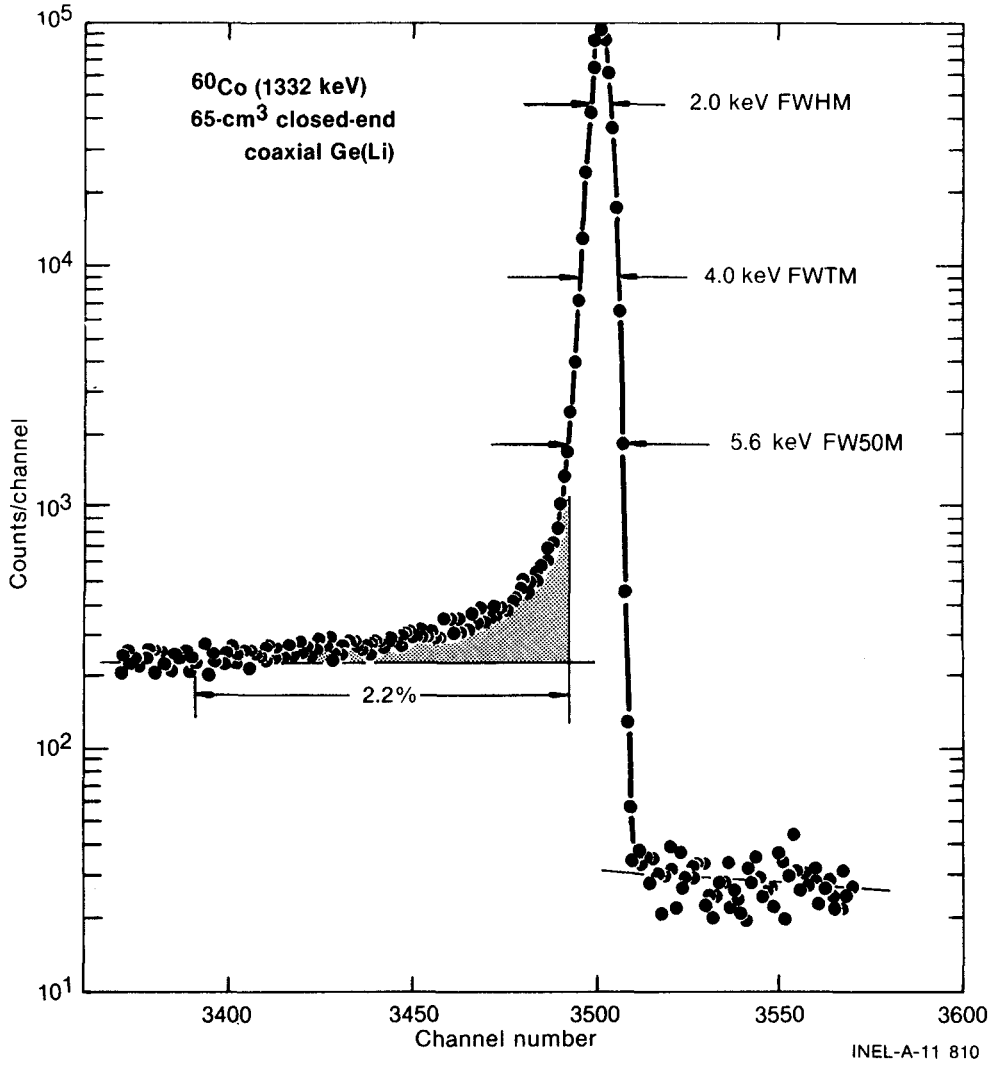

Fig. 1 Spectrum of the full-energy peak of the 1332-keV γ ray from ^{60}Co, measured using a 65-cm^{3}closed-end coaxial Ge(Li) detector. The shaded area represents the contribution of the low energy "tail" to the peak area. This figure was provided by R. G. Helmer.

of the peak area and extends over a large number of channels. If peak-area determinations to a precision of 1% or so are desired, these effects can be accounted for fairly simply. However, if the overall intensity data are desired to a precision of <1%, the contribution of the uncertainty in peak area must be significantly reduced, say to the order of a few tenths of a %. To achieve this precision, a careful investigation of all facets of γ-ray peak-shape analysis is required.

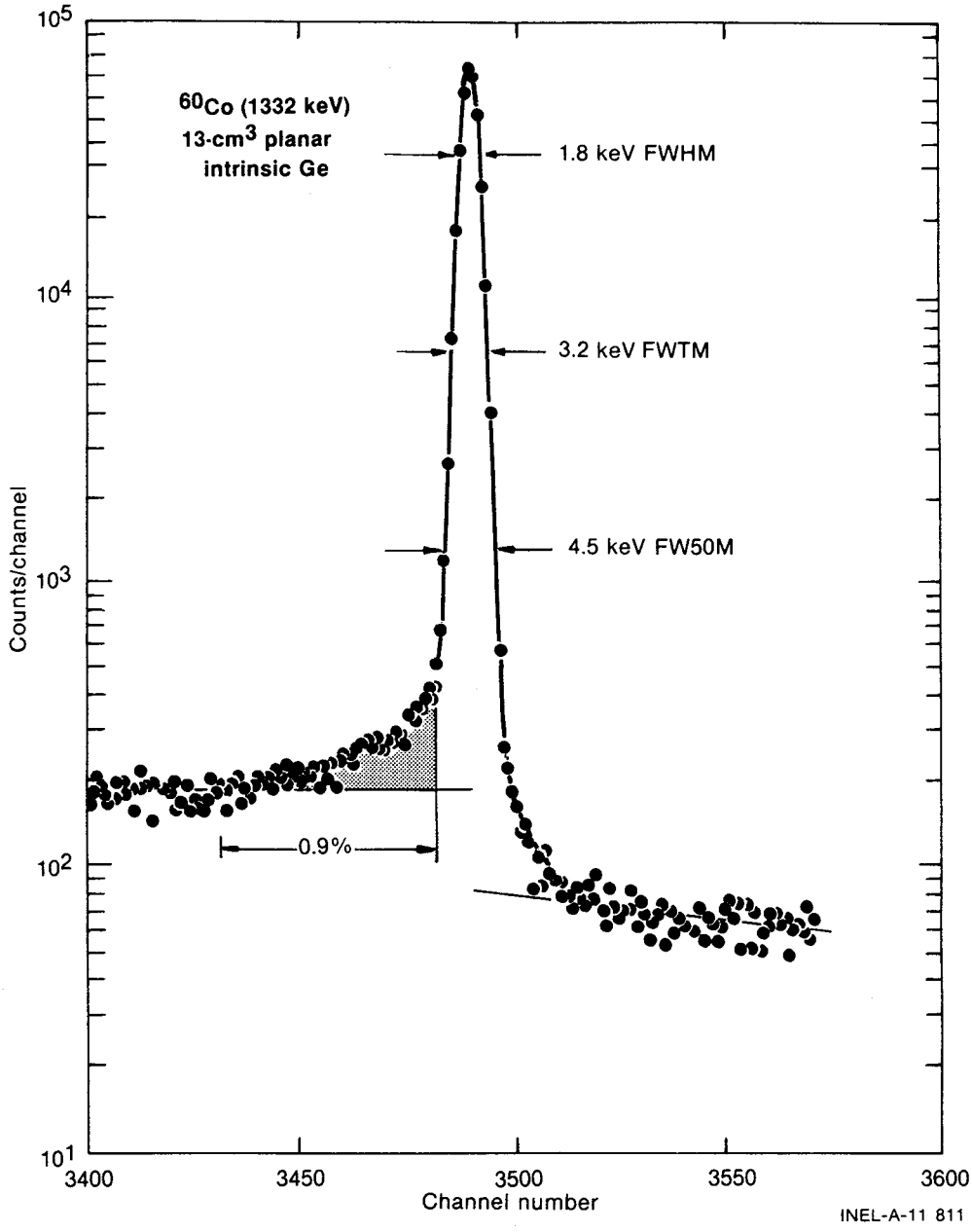

Fig. 2. Spectrum of the full-energy peak of the 1332-keV γ ray from ^{60}Co, measured using a 13-cm^3 planar intrinsic Ge detector. The shaded area represents the contribution of the low-energy "tail" to the peak area. This figure was provided by R. G. Helmer.

5. INTENSITY-BALANCE CONSIDERATIONS IN THE ^{233}PA DECAY SCHEME[†]

The essential features of the ^{233}Pa decay scheme are illustrated in Fig. 3. From the measured value, 38.6 ± 0.5 photons/100 decays, of the absolute intensity of the 311.9-keV γ ray and the relative intensities of the γ rays, the sum of the transition intensities (γ-ray plus conversion-electron) of the γ rays which feed into the ground-state rotational band of ^{233}U is calculated to be (101.4 ± 1.0)%, assuming zero uncertainty in

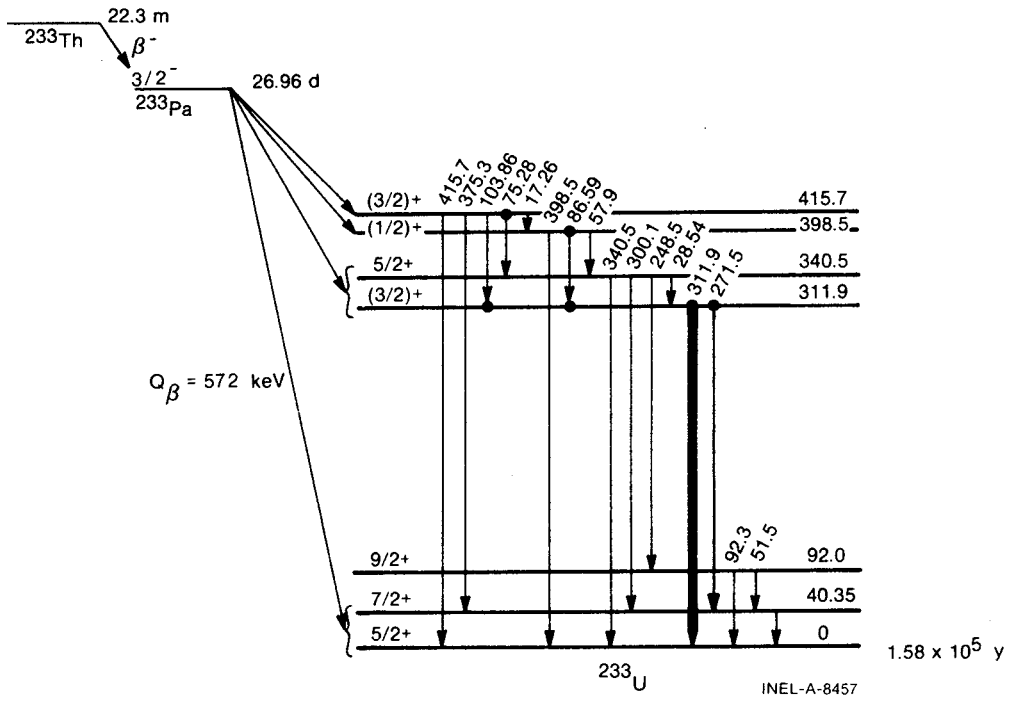

Fig. 3 Partial decay schemes of ^{233}Th and ^{233}Pa.

[†] The discussion in this section is drawn from that given in Ref. [19].

in the multipolarities and internal-conversion coefficients (ICC). This calculation was performed with the reported [4] multipolarities (including M1 for 300 and 312 keV and 90% M1 + 10% E2 for 340 keV), the K, L and M ICC tables of Hager and Seltzer [30] and N tables of Dragoun et al. [31]. (Higher shells will contribute an additional ∿ 0.3% conversion and were omitted.)

It might be argued that this summed γ-transition intensity is sufficiently close to the 100% upper limit that no significant intensity balance problems exist; but to do so would require the assumption of essentially zero direct β⁻ feeding of the ground and 40-keV states in ^{233}U. It seems clear, however, that there is appreciable direct feeding of these two states. The results of Refs. [32] and [33] give a value of 5% for this feeding intensity, while those of Ref. [34] yield a value of 12%. Unfortunately, no uncertainties are reported for these values

so that it is not possible to assess the extent of their agreement (or disagreement). Nonetheless, a definite excess of feeding intensity beta + gamma + conversion-electron) at the ^{233}U ground state is implied; and this amount probably lies in the range of 6-13%.

At present, the origin of this problem cannot be established with certainty. It is conceivable that this imbalance results from errors in the ^{233}Pa decay scheme, our absolute γ-intensity values or the γ-ray multipolarities but, while such a situation is always possible, we do not regard it as a likely explanation here. It seems to us more likely that the problem is associated with the internal-conversion coefficients.

Since the ICC values, denoted here by α, of the γ rays from ^{233}Pa decay are large (e.g., $\alpha \sim$ 1.0 for an M1 transition of energy 300 keV and $\sim$ 0.2 for an E2 transition), the calculated transition intensities will depend significantly on the values employed for these coefficients. There are three pieces of evidence that indicate that the theoretical M1 ICC values of Ref. [30] may be too large. First, our measured K-x-ray intensities are $\sim$ 16% lower than the values calculated using theoretical [30] α_K values and our γ-ray intensities. Since the major contribution to the K x rays is from the M1 transitions, this suggests smaller α_K (M1) values. Second Bisgård *et al.*[34] report a measured $\alpha_K(312) = 0.69 \pm 0.07$ which is consistent with a smaller α_K value (although it is also consistent with the theoretical value of 0.76). Third, in the electron data of Albridge *et al.* [35] the K-line intensities of the M1 transitions are weaker relative to the K lines of the E2 transitions than expected from the theoretical values. Interestingly, recent calculations by Band *et al.* [36] give K- and L-shell ICC values for M1 transitions in this region of Z that are $\sim$ 6% lower [37] than those of Ref. [30]. We have consequently recalculated the above summed transition intensity of the eight γ rays >200 keV feeding the ground and the 40-keV states, assuming the maximum E2 content reasonably consistent with the experimental measurements for mixed M1/E2 transitions and assuming α(M1) values 6% lower than those of Ref. [30]. This yields a value of $\sim$ 98% for the summed γ-ray transition intensities and would allow some feeding of the ground and 40-keV levels of ^{233}U, but still appears to conflict with the reported 5-12% beta feeding. Thus if all the errors are in the same direction, the "conflict" may be within the experimental uncertainties.

The question of the intensity balance in the ^{233}Pa decay, thus, remains open at present. To assess the extent to which it results from inaccuracies, resulting either from errors in the theoretical calculations or from other effects such as penetration, in the presently used values of the internal-conversion coefficients would require a number of careful experimental ICC-value measurements. However, intensity-balance considerations, based in part on theoretical ICC values, are quite generally employed by evaluators of nuclear decay data in deducing β- and α-feeding

intensities in the decay schemes of transactinium nuclei and, where absolute γ-ray intensities are not experimentally determined, such considerations are frequently used to deduce values for them (see,e.g., Table V). Consequently, the possibility that this procedure may produce erroneous results, at least for the transactinium nuclei, underscores the need for additional studies to resolve this question.

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N.D.S. 19, No. 1 (1976); A=243,245,247
N.D.S. 20, No. 2 (1977); A=230,232,236,240
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CURRENT STATUS OF EVALUATED HEAVY ELEMENT DECAY DATA FOR REACTOR CALCULATIONS: PROBLEMS AND ANOMALIES

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ABSTRACT

The current status of evaluated heavy element decay data for reactor-related calculations is discussed. This includes a listing of data compilations and evaluations that have been published since the end of 1975 and are judged to be relevant to heavy element decay data. Detailed comments are also made on the current status of those actinide decay data which were identified as important at the First Advisory Group Meeting on Transactinium Isotope Nuclear Data, November 1975.

1 INTRODUCTION

Numerical data are essential in all branches of science and technology, aiding in the design and safe operation of many industrial facilities. Unfortunately, the scientific literature contains data that differ in the measurement of the same parameter; these differences can be large or small. If there are wide disparities in the measured values, considerable background experience and effort are required to evaluate the data in order to produce reliable figures with realistic uncertainties. It is these evaluated data that must be used to calculate the consequences of plant operation and planned modifications. The production and availability of computer files of these evaluated data can save considerable effort and expense for the users, if the data have been thoroughly researched, carefully selected and documented, and are recognized as the best available at the time of the evaluation. The benefits of such evaluations can be immense, not least in the field of nuclear data and reactor technology. However, the groups undertaking these evaluations have one major problem: it is an unglamorous activity and its importance can be underestimated.

This review considers only those data associated with the decay of heavy element nuclides used in or produced by nuclear fission reactors. There are approximately 120 of these nuclides, including the reactor fuel actinides, all the principle actinide reaction products up to 253-Es, and their major decay chain nuclides down to 206-Hg. The data are required for many reactor-related calculations, dealing with the design and operation of reactors, fuel reprocessing, waste disposal, and shielding and transport problems. The aim of this review is to assess the adequacy of the present evaluated decay data for these applications and to indicate areas where further measurements may be required.

Decay data are defined as data relating to the normal radioactive decay mode of a nuclide and do not include cross-section data. Figures 1 and 2 illustrate the nuclides for which evaluations are required, indicating their half-lives and modes of decay by alpha or beta emission, electron capture, isomeric transition, or spontaneous fission. Reich (1) has emphasised the importance of the gamma data and their associated conversion electrons to a proper understanding of the heavy nuclide decay schemes. Internal conversion coefficient data are extremely important in determining absolute gamma ray intensities, particularly for the plutonium gamma rays used in fuel safeguards and accountancy measurements.

The plutonium isotopes of consequence in core reactivity calculations are 239-, 240-, 241- and 242-Pu. The build-up of 242-Pu is not very significant for reactivity calculations, but it is important for fuel transport and handling problems because neutron capture in 242-Pu leads on to 244-Cm. The curium nuclides 242- and 244-Cm contribute over 90% of the alpha activity in fast reactor fuel at 10% burnup. Also, through spontaneous fission, they contribute more than 95% of the neutron emissions during storage and reprocessing. The production of these two nuclides depends upon the quantities of 241- and 242-Pu in the fuel. A selection of important nuclides, including those mentioned above, form the core of this review. Their data were highlighted by the 1975 Advisory Group Meeting on Transactinium Isotope Nuclear Data (2). Relevant data files that have been published and revised since 1975 are reviewed, and an attempt has been made to describe the philosophy of a decay data evaluator. Emphasis is placed on the problems that may face an evaluator when he attempts to produce a consistent comprehensive decay scheme from the measured data, incomplete and conflicting as they often may be.

2 DECAY DATA COMPILATIONS AND EVALUATIONS

2.1 General Data Compilations

Several compilations have been or are about to be published which contain data for the whole range of radioactive nuclides, and the heavy element decay data form only a small sub-set.

2.1.1 A. H. Wapstra and K. Bos, Atomic Data and Nuclear Data Tables, Vol 19, No 3, 1977.

This compilation provides consistent and comprehensive tables of atomic masses and reaction Q-values and their uncertainties. They are obtained by least squares analysis of the available experimental data on mass differences, reaction Q-values, and Q-values from alpha and beta decay measurements. The experimental data used in this evaluation are listed and discussed by the authors in Atomic Data and Nuclear Data Tables, Vol 20, No 1, 1977.

2.1.2 F. Rösel, H. M. Fries, K. Alder and H. C. Pauli, Atomic Data and Nuclear Data Tables, Vol 21, No 2-5, 1978.

The gamma ray internal conversion process is well understood theoretically. This is the latest detailed compilation of internal conversion coefficients listed by subshell for Z = 30 to 104, calculated from the models of Pauli et al (3). Similar tabulations have been produced in the past and their agreement with the equivalent tabulations of Hager et al (4) is good for the small order multipolarities. These new tabulations are more detailed than previous publications and should become a useful aid for the multipolarity assignments of gamma transitions.

2.1.3 C. M. Lederer and V. S. Shirley, Table of Isotopes, Seventh Edition, 1978 (John Wiley and Sons, New York - London).

The earlier edition became a standard reference work for the majority of gamma spectroscopists. This comprehensive work is to be the final one in this exact form (5). It is to be hoped that this compendium will be replaced in due course by similar documentation arising from the International Network for Nuclear Structure Data Evaluation (See 2.2.2).

2.2 Specific Decay Data Evaluations

Several evaluated compilations and data files are specific to the decay data of the heavy element nuclides. A number of these files are constructed in the ENDF/B formats as defined for reactor-related applications (6,7). The contents of these files are described in this section, and their data provide the main sources for the remainder of this review.

2.2.1 F. Manero and V. A. Konshin, Atomic Energy Review, Vol 10, 637, 1972.

This is an excellent evaluation of the neutron yields in fission, $\bar{\nu}$, for the heavy nuclides (Z > 90). The neutron induced fission yields are expressed as a function of neutron energy from thermal energies to 15MeV and $\bar{\nu}$ values for spontaneous fission are also listed. It continues to be the main reference for $\bar{\nu}$ data.

2.2.2 Nuclear Data Sheets, edited by the Nuclear Data Project for the International Network for Nuclear Structure Data Evaluations (Academic Press, New York).

Table 1 lists only those Nuclear Data Sheets of relevance to heavy element decay data. Nowadays these publications are compiled from ENSDF (the evaluated nuclear structure data file) and they will continue to be updated, the aim being to decrease this updating cycle to four years. These publications and the data file are particularly valuable sources of decay data and are the subject of another review paper.

Other dedicated compilations originate from ENSDF and the following are of special note.

Nuclear Decay Data for Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities, edited by D. C. Kocher, ORNL/NUREG/TM-102, 1977.

This report lists the decay data for 240 nuclides that occur in routine nuclear fuel cycle releases: selected decay data for 80 heavy element nuclides are included.

W. B. Ewbank, Y. A. Ellis and M. R. Schmorak, Spontaneous Fission Activities, Nuclear Data Sheets, Vol 26, 1, 1979.

This publication is of obvious relevance; however, a copy was not available for comment in time for this report.

2.2.3 US ENDF/B-V Decay Data Files (C. W. Reich and R. L. Bunting).

The US Cross-Section Evaluation Working Group have prepared an actinide data file as described by Reich (1) and Schenter (8). The decay data are for 60 actinides listed in table 2 and represent a carefully evaluated subset of data from the ENSDF. The ENDF/B-V format is described as a readily usable format for reactor-related calculations.

2.2.4 French Heavy Element Data File (J Blachot and C Fiche).

This subsection of the French decay data file (9) is part of their effort to produce a data file for reactor calculations. The main source of data is the ENSDF, but more recent experimental data have also been included when appropriate. The heavy element data file contains data for nuclides above 206-Tl in a modified ENDF/B format.

2.2.5 UK Chemical Nuclear Data Committee File of Heavy Element Decay Data (A. L. Nichols and M. F. James).

The IAEA First Advisory Group Meeting on Transactinium Isotope Nuclear Data (2) recommended that new evaluations of the existing data be made and for realistic estimates of data uncertainties to be included. This UK file is designed to meet these specific requirements and the format adopted is that of ENDF/B-V. Discussions with scientists at the CEGB Berkeley Nuclear Laboratories, UK, provided a list of nuclides requiring decay data evaluation (10). This list has been used as the main guide in the evaluation effort, though significant additions were made from other sources (11,12). Table 3 lists 119 nuclides of which the decay data of 95, including 68 actinides, had been evaluated by April 1979. The decay data required for the file are listed in table 4. After evaluation, the data are input to the computer code COGEND (13,14) which generates a file in the ENDF/B-V format; some of the required parameters are calculated in this code, reducing the burden on the evaluator (for example, mean beta energies, x-ray, Auger and conversion electron emission data).

3 ENDF/B-V FORMAT AND REACTOR-RELATED CALCULATIONS

There is an international flavour to the adoption of the ENDF/B format for data files to be used in conjunction with reactor codes. Full descriptions of the basic ENDF/B format are given by Drake (15) and Garber et al (16), and much of the data within this format require neither explanation nor definition. However, certain useful parameters are listed which do require precise explanation. For the UK file the following definitions have been adopted.

(i) The quantity $\overline{E}_\beta$, termed the mean beta energy per decay, is defined as the average energy of all electron emissions such as β^-, β^+, conversion electrons and Auger electrons:

$$\overline{E}_\beta = \sum_i^{\text{all } \beta^-} \overline{E}_{\beta_i^-} I_{\beta_i^-} + \sum_j^{\text{all } \beta^+} \overline{E}_{\beta_j^+} I_{\beta_j^+} + \sum_k^{\text{all Auger}} \overline{E}_{A_k} I_{A_k} + \sum_l^{\text{Conv.}} \overline{E}_{c_l} I_{c_l}$$

where $\overline{E}_{\beta_i^-}$, $\overline{E}_{\beta_j^+}$, $\overline{E}_{A_k}$, and $\overline{E}_{c_l}$ are the mean negatron, positron, Auger electron, and conversion electron energies of the i, j, k, and l^{th} transition of each type respectively, and $I_{\beta_i^-}$, $I_{\beta_j^+}$, I_{A_k}, and I_{c_l} are the corresponding absolute fractional intensities per disintegration. The mean beta energies ($\overline{E}_{\beta_i^-}$ and $\overline{E}_{\beta_j^+}$) are calculated as described by Tobias (17).

(ii) The quantity $\overline{E}_\alpha$, loosely termed the mean alpha energy, is essentially the mean energy of all heavy particles; this includes alpha particles, recoil nuclei, protons, neutrons, and spontaneous fission fragments:

$$\overline{E}_\alpha = \sum_i^{\text{all } \alpha} \overline{E}_{\alpha_i} I_{\alpha_i} + \sum_j^{\text{all recoil}} \overline{E}_{R_j} I_{R_j} + \sum_k^{\text{all protons}} \overline{E}_{p_k} I_{p_k} + \sum_l^{\text{all neutrons}} \overline{E}_{n_l} I_{n_l} + \sum_m^{\text{fiss frag.}} \overline{E}_{F_m} I_{F_m}$$

where $\overline{E}_{\alpha_i}$, $\overline{E}_{R_j}$, $\overline{E}_{p_k}$, $\overline{E}_{n_l}$, and $\overline{E}_{F_m}$ are the mean alpha, recoil nucleus, proton, neutron, and fission fragment energies of the i, j, k, l and m^{th} component of each type respectively, and I_{α_i}, I_{R_j}, I_{p_k}, I_{n_l}, and I_{F_m} are the corresponding absolute fractional intensities per disintegration.

(iii) The quantity $\overline{E}_\gamma$, termed the mean gamma energy, includes all electromagnetic radiation such as gamma rays, X-rays, annihilation radiation, and bremsstrahlung:

$$\overline{E}_\gamma = \sum_i^{\text{all } \gamma} \overline{E}_{\gamma_i} I_{\gamma_i} + \sum_j^{\text{all X-rays}} \overline{E}_{X_j} I_{X_j} + \sum_k^{\text{all } \beta^+} 1.022\, I_{\beta_k^+} + \sum_l^{\text{all } \beta^+\beta^-} \overline{E}_{\beta_l} I_{\beta_l}$$

where $\overline{E}_{\gamma_i}$ and $\overline{E}_{X_j}$ are the mean gamma and X-ray energies of the i and j^{th} transition of each type respectively, I_{γ_i} and I_{X_j} are the corresponding fractional intensities per disintegration (I_{γ_i} is the unconverted photon intensity), $\overline{E}_{\beta_l}$ is the mean internal bremsstrahlung energy of beta transition l which has an absolute fractional intensity I_{β_l}, and $I_{\beta_k^+}$ is the absolute fractional intensity of positron transition k.

In the UK data file the component contributions to $\overline{E}_\beta$ and $\overline{E}_\gamma$ are calculated from the evaluated input data using the COGEND in-built data library of fluorescence yields, Auger electron energies, mean X-ray energies, and electron capture ratios. The decay data listed in the ENDF/B-V output for X-rays and discrete electrons (Auger and conversion) are calculated by COGEND from the input gamma data using various parameters in the COGEND data library. Consequently there is no necessity to evaluate published X-ray and electron emission measurements.

The ENDF/B-V format requires input information describing the nuclear level properties of the decaying nuclide. These data comprise the

spin and parity of the decaying state of the parent nuclide, and the energy of the state with respect to the ground state, if it is a metastable state.

Data requirements for spontaneous fission decay involve prompt gamma and neutron emissions and the fission fragment distribution (14). The following definitions apply:

Q_{sf} = kinetic energy of fission fragments + energy of prompt gamma radiation + energy of prompt neutrons

$\bar{\nu}$ = the number of prompt neutrons emitted per fission.

4 DECAY DATA EVALUATION PHILOSOPHY: A PERSONAL VIEW

The published decay data measurements for a nuclide may vary in quality. The time available for a comprehensive review of the data and production of a consistent decay scheme is limited. Faced with such a situation, I find it useful to frame a number of general criteria to aid in the quick and reliable production of a recommended data set (18).

The judgement and discretion of the evaluator play an important role in the final choice of the evaluated data. They must be supported with the ability to understand and appreciate the limitations of numerous experimental techniques, including assessments of the quality of data from specific research groups. Expert evaluations from other laboratories and groups can be extremely useful. For example, in-depth evaluations of specific half-lives may be beyond the competence of a decay scheme evaluator and, at such times, greater benefit is obtained from the adoption of the in-depth evaluated data rather than a less competent re-evaluation.

If there are two or more measurements in reasonable agreement, the evaluator is justified in adopting a value obtained by an appropriate averaging technique. Complete documentation should indicate which measurements have been used in the evaluation and how they were combined; reference to omitted measurements should be preserved. However, this is a utopian situation, because there is no such thing as a purely objective evaluation: all decisions are subjective and the evaluator should feel no obligation to justify his choices. The evaluator must not try too hard to understand and explain why measurements do not agree with the ridiculously small uncertainties quoted: that is the measurers' problem. If it is really important to obtain correct data, the evaluator should report that better measurements are required.

For some data it may be advantageous to adopt only one of a number of measurements. In this way a self-consistent data set may be obtained. With improvements in measuring techniques, a new measurement is sometimes better than the old. Using intense sources and high resolution spectroscopy, one experiment may stand out as being more detailed and complete than those which preceded it, both in terms of the number of gamma emissions reported and in their relative intensities. When evaluating gamma data, the wholesale adoption of the measurements of one particular laboratory is often the most realistic procedure. Often it is the evaluation of the normalization factor to convert relative intensities into absolute intensities that can prove to be a graver problem: more effort should be made by the measurers to determine these important absolute calibration factors experimentally. A recent publication (19) has criticised the calculation of beta transitions from experimentally determined gamma data. However, the task of an evaluator, within the time available, is to evolve a reasonably complete and self-consistent decay scheme, making fullest use of available experimental data and of theory: despite the criticisms of Hardy et al, he has no other option than to make use of the gamma intensities.

The completion of a decay scheme may involve the introduction of some transitions that have not been observed experimentally. It may be necessary, for example, to ensure that there is as much intensity depopulating an excited state as there is feeding it. The evaluator should consider why these postulated transitions were not observed. A simple example is given in figure 3, the decay of 218-Po. The observation of the 5181 keV alpha emission requires a gamma transition to depopulate the resultant 837 keV excited state of 214-Pb. Although no such gamma transition has yet been observed, the evaluator has no option but to

include this 837 keV gamma emission with an intensity of 0.0011%. Sometimes supporting evidence for missing gamma transitions may be obtained when two different nuclides decay to the same daughter nuclide; for example, the gamma transition probabilities calculated from the 230-Pa (β^-) 230-Th decay scheme may be used to complete the decay scheme for 234-U (α) 230-Th decay. Similarly, charged particle reaction data can be used to identify some of the higher energy nuclear levels, and aid the assignment of observed gamma transitions. For example, the 230-Th (d,t) studies can be used to define specific nuclear levels of 229-Th, thus aiding the assignment of gamma data observed in the decay of 233-U (α) 229-Th.

The decay data of 234-Pa (half-life 6.7 h) are an example of the complexity that can arise when the quantity of measured data is prodigious. The gamma data can be used to derive twenty beta transitions, but the total beta intensity from these transitions is 138%. There are also a further 38% by intensity of gamma emissions that cannot be placed in this proposed decay scheme. The gamma emissions have been incorrectly assigned to the ground state beta decay of 234-Pa, the normalization factor for the gamma intensity data has been incorrectly calculated, the gamma transition internal conversion coefficient data are anomalous, or some multipolarities have been incorrectly assigned. These four explanations need to be explored in order to produce the correct gamma transition probabilities and beta intensity data for 234-Pa.

Every effort is made to determine a consistent, complete decay scheme and to produce an evaluated data set that can be used with confidence to study reactor operation, reprocessing, and waste management. The consistency of the approved data can be determined by calculating the percentage deviation between the effective Q-value and the calculated Q-value.

The effective Q-value is the weighted sum of the Q-values of the nuclide:

$$\text{effective Q-value} = \sum_{i}^{\text{all decay modes}} Q_i \, BR_i$$

where BR_i is the branching ratio of the i-th decay mode. The calculated Q-value is the sum of the individual decay components (β^-, β^+, α etc) which constitute the total decay. Percentage deviations above 5% are regarded as high and indicate a poorly defined decay scheme as proposed by the evaluator. A value less than 5% indicates the construction of a reasonably consistent decay scheme; however, it should be noted that a detailed study of the decay properties may still be lacking because of specific activity problems and/or availability of sample.

5 DECAY DATA OF SPECIFIC ACTINIDES

The decay data requirements for specific actinides are listed in the tabulations and recommendations of the working groups of reference (2). The current status and accuracy of data for these important nuclides are reviewed in this section. Table 5 lists selections of half-life data from measurements and evaluations and, when appropriate, detailed discussions of this important parameter are given in the paragraphs below.

Figures 4 to 17 and tables 6 to 8 illustrate and list the more salient features of the relevant decay schemes. In the figures the numbers in brackets represent the evaluated standard deviation expressed in terms of the last significant figure(s) for that datum. Dotted line transitions represent dubious unobserved emissions that are required to complete the proposed decay scheme. The figures and tabulations contain only selected alpha and gamma data, and TP(%) represents the transition probability of the gamma transition before allowing for internal conversion. I_γ^{abs} is the absolute intensity of the gamma transition and $\alpha_{K,L,M}$ are the internal conversion coefficients for the K, L and M shells, respectively.

234-U (Figure 4)

This nuclide undergoes spontaneous fission and alpha decay to 230-Th with a half-life of $(2.446 \pm 0.007) \times 10^5$y. Detailed alpha decay measurements are lacking: the data of Baranov et al (20) were produced whilst undertaking a study of 233-U.

The energies of the major gamma emissions (53.20 and 120.88 keV) have been accurately measured (21,22), and the less accurately measured intensity data can be used to calculate the alpha intensities of the 4603, 4721.1, and 4773.4 keV emissions. Further alpha energy and intensity measurements are desirable.

The detailed decay measurements for the electron capture decay of 230-Pa can be used to determine the nuclear level energies of 230-Th. In this way the low intensity alpha data can be calculated from these nuclear level energies and the Q(alpha) for 234-U. Accurate measurements of the gamma intensities are required in order to improve confidence in the completeness and consistency of the decay scheme.

235-U (Figure 5 and table 6)

The alpha half-life of $(7.038 \pm 0.005) \times 10^8$ y appears to be known with reasonable accuracy (23). However, there are some significant disagreements with respect to the spontaneous fission contribution (24) that have still to be resolved.

There is no satisfactory agreement between the relatively detailed alpha (25) and gamma (25,26) measurements. In an evaluation some consistency can be achieved by adjusting specific alpha energies and introducing a number of low intensity alpha transitions (intensities less than 0.4%) that can be derived from the gamma data. Combined alpha and gamma measurements have been made in the past (25), but further careful studies are still needed to improve confidence in the proposed decay scheme.

It should be noted that 235-U has a short-lived (half-life 26 ± 2m), low energy (73 ± 5 eV) metastable state. Decay is by isomeric transition and the half-life has been shown to be dependent upon the chemical environment of the nuclide (27).

236-U (Figure 6)

This nuclide undergoes spontaneous fission and alpha decay to 232-Th with a half-life of $(2.3416 \pm 0.0039) \times 10^7$ y. A simple, adequate decay scheme can be produced by adopting the relatively detailed alpha data of Baranov et al (28). This recent publication has resulted in a re-adjustment of the Q(alpha) for 236-U.

The proposed decay scheme is dominated by the ground state 0^+, 2^+, 4^+ rotational band gamma cascade. The low gamma transition intensities have been calculated from the theoretical internal conversion coefficient data of Hager et al (4) and the transition probabilities which can be calculated from the available alpha data. An assessment of the extremely low intensity alpha and gamma data involved comparisons with the equivalent measurements of other even-even actinides (21).

238-U (Figure 7)

Decay is by spontaneous fission and alpha decay to 234-Th with a half-life of $(4.468 \pm 0.010) \times 10^9$ y. The decay scheme is dominated by the low intensity gamma cascade of the ground state 0^+, 2^+, 4^+ rotational band. A single accurate gamma measurement (22) is in reasonable agreement with the alpha data of Kocharov et al (29). The proposed 110 keV gamma emission has not been observed experimentally, but the alpha population of the 160 keV nuclear level implies its existence. High resolution alpha studies are required in order to improve the accuracy of the major alpha emission intensities.

237-Np (Figure 8 and table 7)

Only one accurate measurement of the half-life of this nuclide has been reported (30), using absolute alpha counting techniques to obtain a value of $(2.14 \pm 0.01) \times 10^6$ y. Quite obviously, further measurements are required to support the continued use of this single measurement.

As illustrated in table 7, there are major disagreements between the alpha intensity data of Baranov et al (31) and Browne et al (32). The work of Browne et al is tentatively supported by recent detailed gamma measurements (33). However, this agreement should be treated with some uncertainty because the gamma normalization factor of reference (33) originated from the work of reference (32). The value of

this normalization factor is extremely important to the production of a consistent decay scheme. The complexity of the gamma data from another source (34) only adds to the overall confusion, and there are serious problems associated with the gamma depopulation of specific, important nuclear levels of 233-Pa.

Detailed alpha intensity measurements are required to clarify and remove the existing anomalies. Specific, low energy gamma transitions need to be studied: the ringed gamma transitions in figure 8 are examples of data introduced during an evaluation to depopulate important nuclear levels. A confident evaluation can only be made following measurements that prove or disprove the existence of such transitions.

238-Pu (Figure 9)

Recent measurements of the half-life of this nuclide have been in good agreement (table 5), giving an evaluated value of (87.7 ± 0.2)y. However, whether an evaluated accuracy of 0.02% will ever be achieved is highly questionable (2).

Many of the low intensity alpha transitions have been calculated from the gamma data of Lederer et al (35) and Gunnink et al (36). The resultant alpha intensities show only minor disagreements with the measurements of Baranov et al (37).

Alpha decay of 238-Pu leads to 234-U, and some of the multipolarity assignments, internal conversion coefficients and intensities of the low intensity gamma emissions can be derived from 234-Pa beta decay measurements. In this way, nine gamma transitions that have not been observed in the alpha decay of 238-Pu can be proposed to complete a consistent decay scheme.

Spontaneous fission neutrons from this nuclide are of some importance in decay heat calculations for transport flasks and extensively stored irradiated fuel.

239-Pu (Figure 10 and table 8)

Historically, there have been problems determining the half-life of 239-Pu. Recent measurements in a number of different laboratories (table 5) are all in reasonable agreement with a value of (24115 ± 80)y.

The decay data for this very important actinide are extremely comprehensive. A large number of gamma spectroscopy measurements reveal extremely fine detail not observed to the same degree in alpha spectroscopy. Data have been extensively adopted for the proposed decay scheme from two specific laboratories (36,38) that show excellent agreement. Using these data some considerable effort can be expended to derive consistent alpha decay data, particularly for the low intensity transitions. Although this method can be criticised, the quality of the gamma data merit this approach. No inconsistency problems arise when incorporating the accurate, high intensity alpha measurements into the proposed decay scheme. Decay to both the ground and metastable (half-life 25m) states of 235-U are proposed and the branching ratios for these two decay modes can be evaluated with confidence.

240-Pu (Figure 11)

This nuclide undergoes spontaneous fission and alpha decay to 236-U with a half-life of (6537 ± 10)y. The spontaneous fission neutron data are of some importance for irradiated fuel stored for over one year.

The relatively simple decay scheme is dominated by the ground state 0^+ , 2^+ , 4^+ rotational band gamma cascade. There is reasonable agreement between the gamma data (21,36) and alpha data (39).

241-Pu (Figure 12)

The uncertainty associated with the important beta decay half-life of this nuclide is large (3.4%). Recent measurements vary from 14.35 to 15.02y: the value adopted, (14.6 ± 0.5)y, is the mean of these data coupled to an uncertainty that covers the wide range of measured values. It is difficult to explain such large discrepancies and further careful measurements are required. Accurate calculations

to determine 241-Am and 242-Cm inventories depend upon the half-life of 241-Pu, particularly when the irradiated fuel is stored for a long period of time before being recycled.

$$^{241}\text{Pu} \xrightarrow{\beta^-} {}^{241}\text{Am}\ (n,\gamma)\ {}^{242}\text{Am} \xrightarrow{\beta^-} {}^{242}\text{Cm}$$

Upon re-irradiation the build-up of ^{242}Cm, a major neutron source, needs to be accurately known. Waste storage calculations and plutonium assay measurements for nuclear safeguards also require an accurate 241-Pu half-life. The spread of values may indicate the existence of a metastable state of similar half-life, but there is theoretical evidence against such a possibility. Perhaps the most important reason to resolve the discrepancies is that their existence follows a series of careful measurements by competent laboratories. Measurements of other decay parameters may have similar, unknown systematic errors, but these data are accepted as correct because of their general agreement.

The decay scheme is dominated by the beta decay mode to the ground state of 241-Am. The small alpha decay mode produces a number of gamma transitions (35,40,41) with low intensities.

242-Pu (Figure 13)

This nuclide undergoes spontaneous fission and alpha decay to 238-U with a half-life of $(3.76 \pm 0.03) \times 10^5$y. The simple proposed decay scheme combines the alpha data of Baranov et al (41) with the gamma measurements of Schmorak et al (21).

241-Am (Figure 14)

The alpha half-life of (432 ± 2)y is known to a reasonable degree of accuracy. However, although some detailed gamma studies have been made of this nuclide (36,42), it is difficult to produce a consistent decay scheme. Agreement between the gamma and alpha data (41) is poor particularly for alpha emission intensities within the measured range (41) of 1.5 to 0.01%. The major gamma emissions are known with a reasonable degree of certainty, but some of the multipolarity assignments for the low intensity gamma emissions are extremely tentative. Alpha and conversion electron studies may aid in the clarification of this relatively complex decay scheme.

242-Cm (Figure 15)

The alpha half-life measurements show reasonable agreement (table 5) to give a value of (162.8 ± 0.5)d, although further measurements are required to achieve greater accuracy. The spontaneous fission half-life and neutron data are important and require further studies. A simple decay scheme can be constructed from the alpha decay data (43).

244-Cm (Figure 16)

The spontaneous fission half-life and alpha half-life $(18.11 \pm 0.02$y) are known to reasonable accuracies. Two major alpha emissions (43) populate the ground and first excited state of 240-Pu resulting in a simple decay scheme.

252-Cf (Figure 17)

Further measurements are required to improve the accuracy of the evaluated total half-life of (2.638 ± 0.010)y. A simple decay scheme can be derived from measured alpha data (43).

Table 9 summarizes the important decay data parameters as defined by the IAEA Advisory Group Meeting (2). The evaluated accuracy, 1979 demonstrates the advantage of evaluating the published data and determining realistic uncertainties. Some of the decay constants are known to within the desired accuracy of 1975, in particular, the half-lives of 235-, 236-U, 239-, 240-, 242-Pu, 241-Am and 244-Cm. However, the more detailed requirements for alpha and gamma intensities still remain unsatisfactory for the majority of the tabulated nuclides.

239-U and 239-Np are important in decay heat calculations at the beginning of irradiated fuel handling and storage. 239-U undergoes β^- decay (Q_β = 1267 keV) with a half-life of (23.50 ± 0.05)m. Detailed gamma intensity measurements have been made to within an accuracy of 10 to 15%; minor inconsistencies occur, but a satisfactory decay scheme can be produced. 239-Np also undergoes β^- decay (Q_β = 721.5 keV) with a half-life of (2.355 ± 0.004)d. A consistent, comprehensive decay scheme can be evaluated from the published data, and the major gamma intensities are known to within an accuracy of 3 to 12%.

Within the last ten years the half-lives of the ground and metastable states of 236-Np have been reassigned: 236m-Np, half-life (22.5 ± 0.4)h, and 236-Np, half-life (1.15 ± 0.12) x 10^5y. Older reactor computer codes and calculations that use cross-section data for the production of the metastable state may need to be checked to determine that these data are correctly linked to the 22h decay data.

Other important actinides that were not tabulated in reference (2) are listed in the appendix. General comments have been made, outlining the overall quality and consistency of their evaluated decay data. Numerous minor discrepancies occur throughout all of these evaluations. The majority of these imbalances involve gamma multipolarity assignments and internal conversion coefficients. Alpha and gamma emission studies will continue, but greater benefit may accrue from conversion electron and, when appropriate, beta decay studies.

6 CONCLUDING COMMENTS

Specific data for 237-Np, 241-Pu, 241-Am, and 242-Cm require further measurements. There are also some problems of detail involving plutonium nuclides and accurate gamma intensities. However, the data users need to give further thought to placing realistic accuracies on their requests of 1975 (2). It is difficult to envisage achieving decay data accuracy better than 0.1%, nor is it immediately apparent that such high accuracies are ever likely to be required for reactor-related calculations, since there are more important uncertainties in the necessary cross-section data which would first need to be resolved.

As for the evaluator, striving to tidy up some of the fine details of a complex decay scheme, there is a risk that he will request further detailed measurements than cannot be justified realistically, and are most certainly not merited for fuel cycle applications. The need for further measurements must be defined and justified by the data users with only a modicum of guidance from evaluators and measurers. This necessitates good communications between decay data measurers, evaluators, and users.

Balanced against the need for realism with respect to data requests is the problem of predicting accuracy requirements for <u>future</u> calculations. Recent interest in detailed studies of the 232-Th/233-U fuel cycle is an example of an unexpected development leading to unforeseen demands for more accurate data. This unpredictability supports the need to maintain viable teams that are able to meet sudden changes in priority and sudden demands for new measurements and new evaluations. Metrology laboratories that specialize in producing extremely accurate measurements can also help in satisfying future requirements.

There is some evidence for world-wide adoption of common data formats, easing the interchange of data files between laboratories. The development of the ENSDF and ENDF/B should be encouraged. By using standard formats, files can be rapidly compared and discrepancies and errors identified. It is extremely convenient for the reactor physicist, who is able to concentrate upon the modelling aspects of his codes without having to worry about the quality of the decay data he is using. Furthermore, a <u>reliable</u> data file stored on disc or magnetic tape can be used rapidly in a number of vastly different applications, for example, inventory, decay-heat, and incineration calculations, dosimetry, and the implications of alternative fuel cycles. However, there is a danger in this, and it is questionable whether a single decay data file should be put forward as an internationally recommended data set when other files of comparable quality are available or in production. For the time being some duplication of efforts should be encouraged in this field, and similar files should be maintained to aid in the identification of the inevitable errors and anomalies in the data.

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TABLE 1
THE INTERNATIONAL NETWORK FOR NUCLEAR STRUCTURE DATA EVALUATION,
NUCLEAR DATA SHEETS: CUMULATED INDEX OF HEAVY ELEMENT DECAY DATA BY MASS CHAIN
(DECEMBER 1978)

Mass number	Reference	Mass number	Reference
206*	B7-161, 1972	230	20, 139, 1977
207	22, 487, 1977	231	21, 91, 1977
208*	B5-243, 1971	232	20, 165, 1977
209	22, 545, 1977	233	24, 289, 1978
210*	B5-631, 1971	234	21, 493, 1977
211	25, 397, 1978	235	21, 117, 1977
212*	B8-165, 1972	236	20, 192, 1977
213*	10, 597, 1973	237	23, 71, 1978
214	21, 437, 1977	238	21, 549, 1977
215	22, 207, 1977	239	21, 153, 1977
216	17, 329, 1976	240	20, 218, 1977
217*	10, 611, 1973	241	23, 123, 1978
218	21, 467, 1977	242	21, 615, 1977
219	22, 223, 1977	243	19, 103, 1976
220	17, 341, 1976	244*	17, 402, 1976
221*	10, 625, 1973	245	19, 143, 1976
222	21, 479, 1977	246	17, 410, 1976
223	22, 243, 1977	247	19, 181, 1976
224	17, 351, 1976	248	17, 426, 1976
225*	10, 643, 1973	249	18, 396, 1976
226	20, 119, 1977	250	17, 436, 1976
227	22, 275, 1977	251	18, 416, 1976
228	17, 367, 1976	252	17, 450, 1976
229	24, 263, 1978	253	18, 428, 1976

*Re-evaluations are in progress

TABLE 2
US ENDF/B-V HEAVY ELEMENT DECAY DATA (MAY 1978)

208-Tl	233-U	239-Pu	243-Cm
212-Pb	234-U	240-Pu	244-Cm
212-Bi	235-U	241-Pu	245-Cm
216-Po	236-U	242-Pu	246-Cm
220-Rn	237-U	243-Pu	247-Cm
224-Ra	238-U	244-Pu	248-Cm
228-Th	239-U	240-Am	249-Cm
230-Th	236-Np	241-Am	249-Bk
231-Th	236m-Np	242-Am	250-Bk
232-Th	237-Np	242m-Am	249-Cf
233-Th	238-Np	243-Am	250-Cf
231-Pa	239-Np	244-Am	251-Cf
232-Pa	236-Pu	244m-Am	252-Cf
233-Pa	237-Pu	241-Cm	253-Cf
232-U	238-Pu	242-Cm	253-Es

TABLE 3
UK CHEMICAL NUCLEAR DATA COMMITTEE FILE OF HEAVY ELEMENT DECAY DATA (APRIL 1979)

Nuclide	Evaluated	Nuclide	Evaluated	Nuclide	Evaluated
206-Hg	Yes	224-Ra	Yes	236-Pu	Yes
206-Tl	Yes	225-Ra	No	237-Pu	Yes
207-Tl	Yes	226-Ra	Yes	238-Pu	Yes
207m-Tl	Yes	228-Ra	Yes	239-Pu	Yes
208-Tl	No	225-Ac	No	240-Pu	Yes
209-Tl	Yes	227-Ac	No	241-Pu	Yes
210-Tl	No	228-Ac	Yes	242-Pu	Yes
209-Pb	Yes	227-Th	No	243-Pu	Yes
210-Pb	No	228-Th	Yes	244-Pu	Yes
211-Pb	Yes	229-Th	No	245-Pu	Yes
212-Pb	No	230-Th	Yes	246-Pu	Yes
214-Pb	Yes	231-Th	Yes	240-Am	Yes
210-Bi	No	232-Th	Yes	241-Am	Yes
210m-Bi	No	233-Th	No	242-Am	Yes
211-Bi	Yes	234-Th	Yes	242m-Am	Yes
212-Bi	No	235-Th	Yes	243-Am	Yes
213-Bi	No	231-Pa	Yes	244-Am	Yes
214-Bi	No	232-Pa	Yes	244m-Am	Yes
215-Bi	Yes	233-Pa	Yes	245-Am	Yes
210-Po	No	234-Pa	No	246-Am	Yes
211-Po	Yes	234m-Pa	No	246m-Am	Yes
211m-Po	Yes	235-Pa	Yes	241-Cm	Yes
212-Po	No	232-U	Yes	242-Cm	Yes
212m-Po	No	233-U	Yes	243-Cm	Yes
213-Po	No	234-U	Yes	244-Cm	Yes
214-Po	Yes	235-U	Yes	245-Cm	Yes
215-Po	Yes	235m-U	Yes	246-Cm	Yes
216-Po	Yes	236-U	Yes	247-Cm	Yes
218-Po	Yes	237-U	Yes	248-Cm	Yes
215-At	Yes	238-U	Yes	249-Cm	Yes
217-At	No	239-U	Yes	250-Cm	Yes
218-At	Yes	240-U	Yes	249-Bk	Yes
219-At	Yes	236-Np	Yes	250-Bk	Yes
218-Rn	Yes	236m-Np	Yes	249-Cf	Yes
219-Rn	Yes	237-Np	Yes	250-Cf	Yes
220-Rn	Yes	238-Np	Yes	251-Cf	Yes
222-Rn	Yes	239-Np	Yes	252-Cf	Yes
221-Fr	No	240-Np	Yes	253-Cf	Yes
223-Fr	No	240m-Np	Yes	253-Es	Yes
223-Ra	Yes	241-Np	Yes		

TABLE 4
DECAY DATA REQUIREMENTS
ENDF/B-V

Basic Input for UK processing code COGEND
half-life, Q-values, branching fractions, alpha decay data: energy and intensity, beta decay data: energy, intensity and transition type, gamma decay data: energy, intensity and internal conversion coefficients, spontaneous fission decay data: mean number of neutrons per fission and continuous spectral data
Also included with the above input data are their uncertainties.

Table 5 Actinide Half-life Data

Nuclide	Reference	Half-life
234-U	P de Bièvre et al, Int Conf Nucl Data, Canterbury, 1971	2.446(7) x 10^5 y
	M Lounsbury et al, Int Conf Nucl Data, Canterbury, 1971	2.444(12) x 10^5 y
	*R Vaninbroukx, EUR-5194-E, 1974	2.446(7) x 10^5 y
235-U	*R Vaninbroukx, EUR-5194-E, 1974	7.038(5) x 10^8 y
236-U	K F Flynn et al, J Inorg Nucl Chem, 34, 1121, 1972	2.3415(14) x 10^7 y
	*R Vaninbroukx, EUR-5194-E, 1974	2.34(2) x 10^7 y
238-U	*R Vaninbroukx, EUR-5194-E, 1974	4.468(10) x 10^9 y
237-Np	F P Brauer, J Inorg Nucl Chem 12, 234, 1960	2.14(1) x 10^6 y
238-Pu	*R Vaninbroukx, EUR-5194-E, 1974	87.8(8) y
	W W Strohm et al, Trans Am Nucl Soc 18,185, 1974	87.77(2) y
	V G Polyukhov et al, Sov J At Energy, 40, 66, 1976	86.98(39) y
	H Diamond et al, Phys Rev, 15C, 1034, 1977	87.71(3) y
239-Pu	*R Vaninbroukx, EUR-5194-E, 1974	24300(25) y
	K M Glover et al, UKNDC (75) P71, 55, 1975	24118(80) y
	A H Jaffey et al, Phys Rev, 16C, 354, 1977	24131(16) y
	*W W Strohm, Int J Appl Rad Isotopes 29, 481, 1978	24119(26) y
	R Vaninbroukx, CBNM/RN/40-79	24100(30) y
240-Pu	W W Strohm et al, Trans Am Nucl Soc, 18, 185, 1974	6524(10) y
	*R Vaninbroukx, EUR-5194-E, 1974	6550(70) y
241-Pu	R K Ziegler et al, J Inorg Nucl Chem, 35, 3417, 1973	14.89(11) y
	W W Strohm et al, Trans Am Nucl Soc, 18, 185, 1974	14.355(7) y
	*R Vaninbroukx, EUR-5194-E, 1974	14.5(5) y
	M Wilkins, AERE - R 7906, 1974	15.02(10) y
	I C McKean et al, UKNDC (76) P80, 41, 1974	14.4(2) y
	R Vaninbroukx, Int Conf Neutron Phys, Harwell, 1978	14.45(30) y
242-Pu	J Halperin et al, ORNL-4306, 31, 1968	3.82(2) x 10^5 y
	*R Vaninbroukx, EUR-5194-E, 1974	3.87(5) x 10^5 y
	D W Osborne et al, Phys Rev, 14C, 1174, 1976	3.763(9) x 10^5 y
241-Am	*R Vaninbroukx, EUR-5194-E, 1974	432(4) y
	W W Strohm et al, Trans Am Nucl Soc, 18, 185, 1974	435.0(7) y
	H Ramthun et al, Int J Appl Rad Isotopes, 26, 589, 1975	432.0(2) y
242-Cm	K M Glover et al, Nature, 173, 1238, 1954	162.46(14) d
	W J Kerrigan et al, J Inorg Nucl Chem, 37, 641, 1975	163.2(2) d
	H Diamond et al, Phys Rev, 15C, 1034, 1977	162.76(4) d
	H Umezawa et al, IAEA Progress Report, 1979	163.28(162) d
244-Cm	W C Bentley, J Inorg Nucl Chem, 30, 2007, 1968	18.10(2) y
	W J Kerrigan et al, J Inorg Nucl Chem, 34, 3603, 1972	18.13(6) y
252-Cf	B J Mijnheer et al, Int J Appl Rad Isotopes, 24, 185, 1973	2.659(10) y
	V Spiegel, Nucl Sci Eng, 53, 326, 1974	2.638(7) y
	*R Vaninbroukx, EUR-5194-E, 1974	2.64(2) y

*Evaluations

Table 6 235-U: Selected Gamma Decay Data

E_γ (keV)	I_γ^{abs} (%)	α_K	α_L	α_M	α_{tot}	TP (%)
109.2(1)	1.5(2)	-	0.070	0.018	0.088(3)	1.6(3)
143.8(1)	10.5(8)	0.165	0.035	0.008	0.208(6)	12.7(1)
163.4(1)	4.7(4)	0.123	0.025	0.006	0.154(2)	5.4(6)
185.7(1)	54(1)	0.088	0.018	0.004	0.110(3)	60(1)
202.1(2)	1.0(1)	2.1	0.40	0.095	2.595(115)	3.6(5)
205.3(1)	4.7(4)	0.070	0.014	0.003	0.087(3)	5.1(5)

Table 7 237-Np: Alpha Decay Data

E_α (keV)			Intensity (%)		
(1)	(2)	(3)	(1)	(2)	(3)
-	-	4431(3)	-	-	0.005(2)
4514(4)	4513.5	4513(2)	0.04(2)	0.01	0.05(2)
-	4572.7	4574(2)	-	0.054	0.05(2)
4577(3)	4580.0	4578(2)	0.40(4)	0.024	0.42(15)
-	4593.9	-	-	0.085	-
4598(3)	4597.6	4599(2)	0.39(4)	0.063	0.41(5)
4640(2)	4638.4	4640(2)	6.46(13)	4.617	6.5(5)
-	4658.1	4659(2)	-	0.573	0.58(2)
4665(2)	4663.0	4665(2)	3.54(11)	1.605	3.5(4)
4695(4)	4693.4	-	0.37(15)	0.178	-
-	4707.3	4707(2)	-	0.293	0.30(4)
4710(3)	4711.3?	4713(2)	1.30(17)	0.126	0.4(1)
-	4740.3	-	-	0.019	-
-	4764.7	4766(2)	-	16.82	8(4)
4770(3)	4769.8	4771(2)	31(9)	19.38	25(6)
4788(2)	4787.0	4788(2)	48(9)	51.42	48(5)
4799(6)	4802.3	4804(2)	3	1.565	1.6(10)
4816(2)	4816.3	4817(2)	2.93(44)	1.487	2.5(3)
4864(3)	4861.8	-	0.3(1)	0.242	-
-	4869.8?	-	-	0.925	-
4872(3)	4872.3	4874(2)	2.6(2)	0.441	2.7(3)

References:
(1) E Browne et al, UCRL-17989, 1968: energy adjustment of 7 keV.
(2) S A Baranov et al, Sov Phys JETP, 14, 1232, 1962.
(3) Adopted values; the intensity data are affected by gamma transition probability calculations.

Table 8 239-Pu: Selected Gamma Decay Data

E_γ (keV)	I_γ^{abs} (%)	α_K	α_L	α_M	α_{tot}	TP (%)
38.66(7)	0.0105(1)	-	226	60	286(8)	3.0(1)
51.629(10)	0.0270(1)	-	230	83	313(12)	8.5(3)
98.78(6)	0.00122(4)	-	10.5	2.9	13.4(11)	0.0176(19)
129.29(1)	0.00626(1)	0.215	0.050	0.0135	0.2785(75)	0.0080(1)
144.2(1)	0.000283(2)	0.229	1.9	0.55	2.679(130)	0.00104(5)
161.450(15)	0.000120(1)	5.0	0.95	0.23	6.18(16)	0.00086(3)
189.32(7)	0.000083(2)	3.1	0.60	0.145	3.845(155)	0.00040(2)
195.67(7)	0.0001064(5)	2.8	0.54	0.13	3.47(13)	0.00048(1)
203.54(5)	0.000560(1)	2.5	0.48	0.115	3.095(125)	0.0023(1)
255.35(6)	0.0000805(16)	1.32	0.25	0.062	1.632(65)	0.00021(3)
297.45(5)	0.0000502(10)	0.88	0.17	0.041	1.091(32)	0.000105(4)
375.04(5)	0.001570(2)	0.30	0.06	0.02	0.38(3)	0.0022(1)
413.71(6)	0.00149(2)	0.20	0.05	0.01	0.26(3)	0.0019(1)

Table 9 Comparison of TND Requirements (1975) for Decay Data and Evaluated Status (1979)

Nuclide	Data Type	Required Accuracy, 1975 (%)	Evaluated Accuracy, 1979 (%)
U 234	α-intensities γ-intensities	1 5	4 8 - 10
U 235	$T_{\frac{1}{2}}$ (α) α-intensities γ-intensities	1 1 1	0.1 10 10
U 236	$T_{\frac{1}{2}}$ (α)	1	0.2
U 238	α-intensities	1	5 - 20
Np 237	α-intensities	1	25
Pu 238	$T_{\frac{1}{2}}$ (α) α-intensities γ-intensities	0.5 - 0.02 0.1 1	0.3 1 - 2 0.3*
Pu 239	$T_{\frac{1}{2}}$ (α) α-intensities γ-intensities	0.2 1 1	0.3 1 - 2 0.2 - 10*
Pu 240	$T_{\frac{1}{2}}$ (α) α-intensities γ-intensities	0.2 0.2 1	0.2 0.5 - 0.8* 0.2 - 0.7*
Pu 241	$T_{\frac{1}{2}}$ (β^-) γ-intensities	1 1	3.4 3
Pu 242	$T_{\frac{1}{2}}$ (α) α-intensities	1 4	0.8 6
Am 241	$T_{\frac{1}{2}}$ (α) γ-intensities	1 1	0.5 0.5 - 1.7*
Cm 242	$T_{\frac{1}{2}}$ (α) $T_{\frac{1}{2}}$ (sf)	0.1 3	0.3 11
Cm 244	$T_{\frac{1}{2}}$ (α) $T_{\frac{1}{2}}$ (sf)	2 3	0.1 0.5
Cf 252	$T_{\frac{1}{2}}$ (α)	0.2	0.4

* Data from a single consistent set of measurements

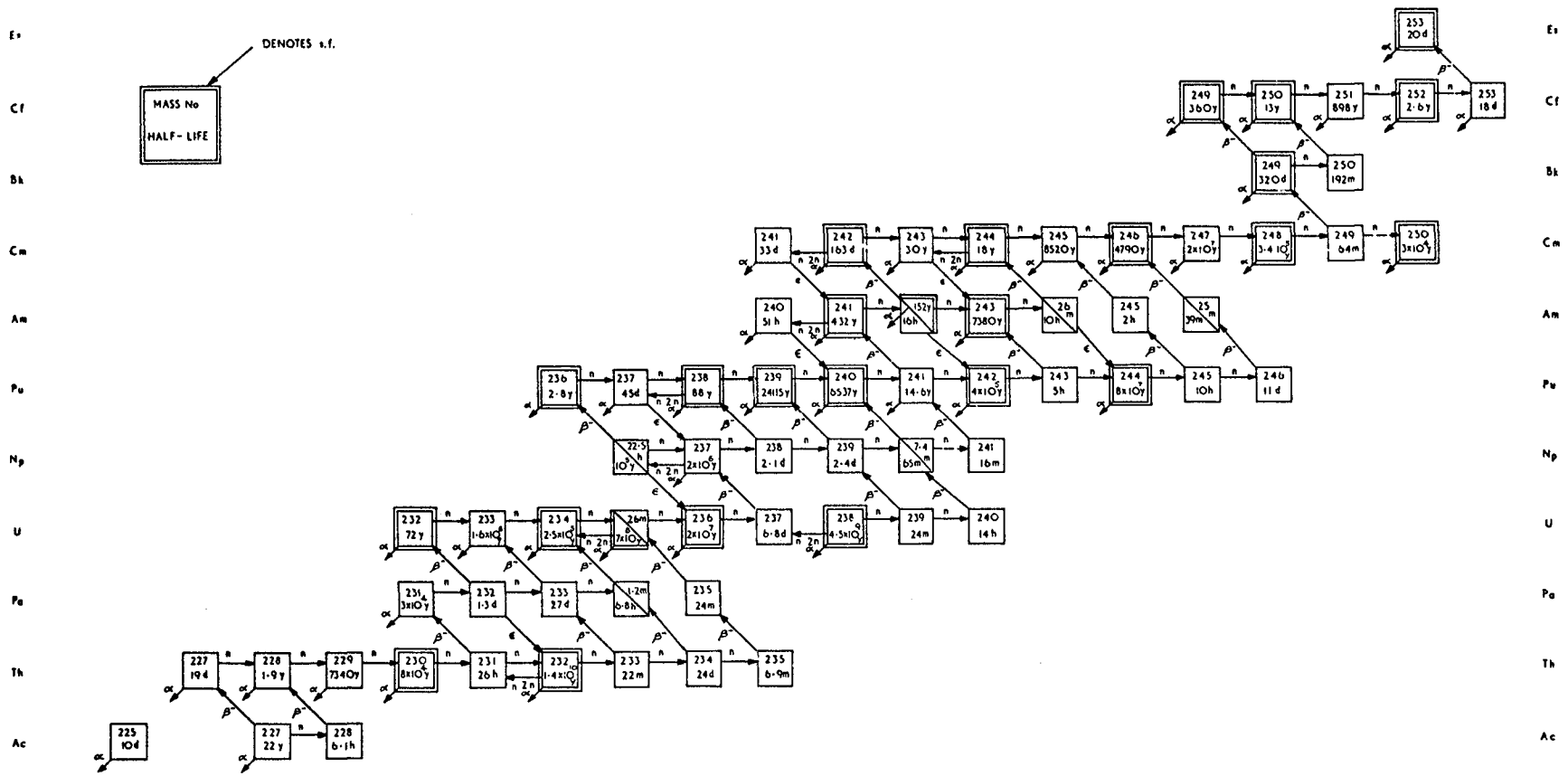


FIG. 1 DECAY AND TRANSMUTATION CHAINS PRODUCING HEAVY ELEMENT NUCLEI — ACTINIDES

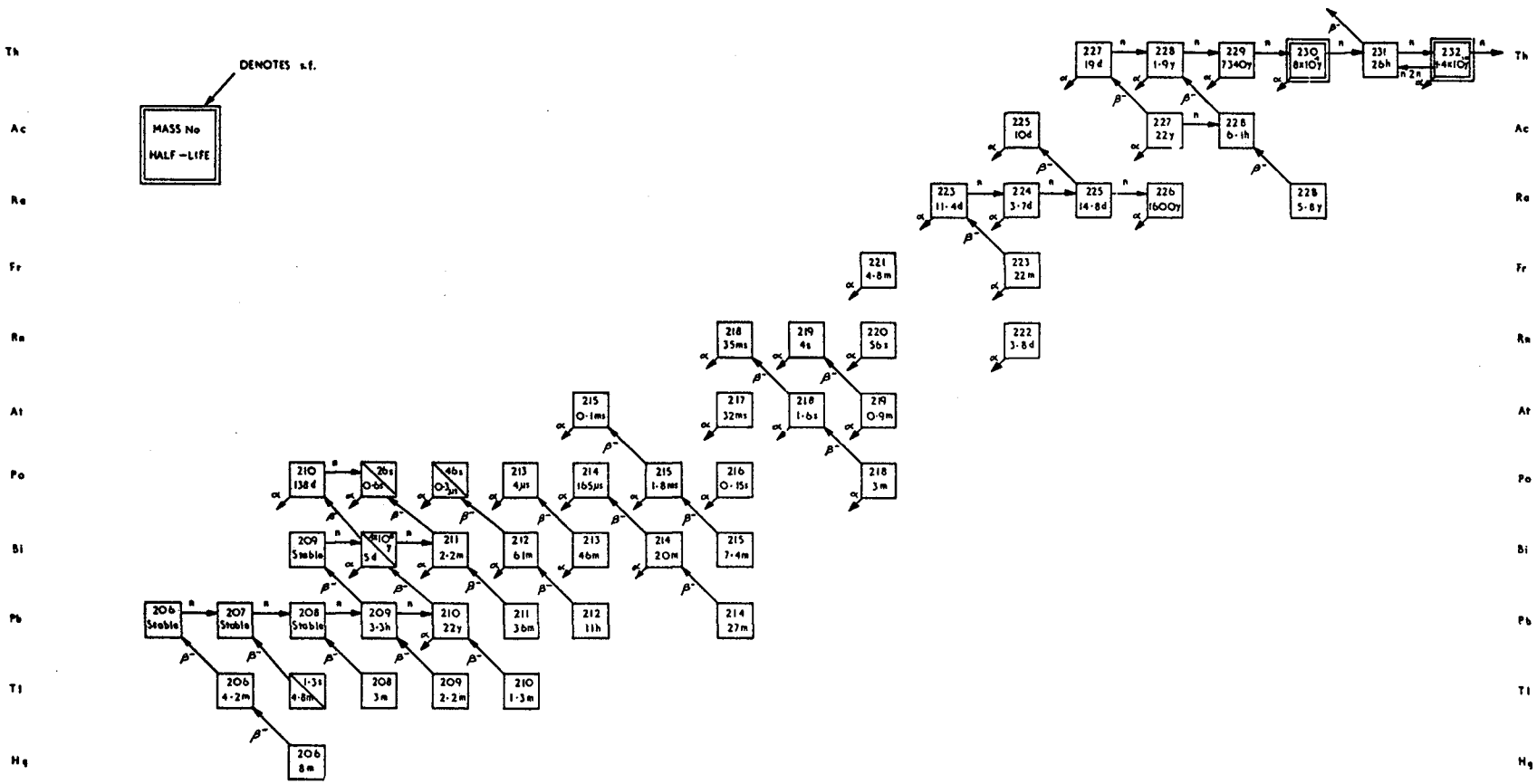
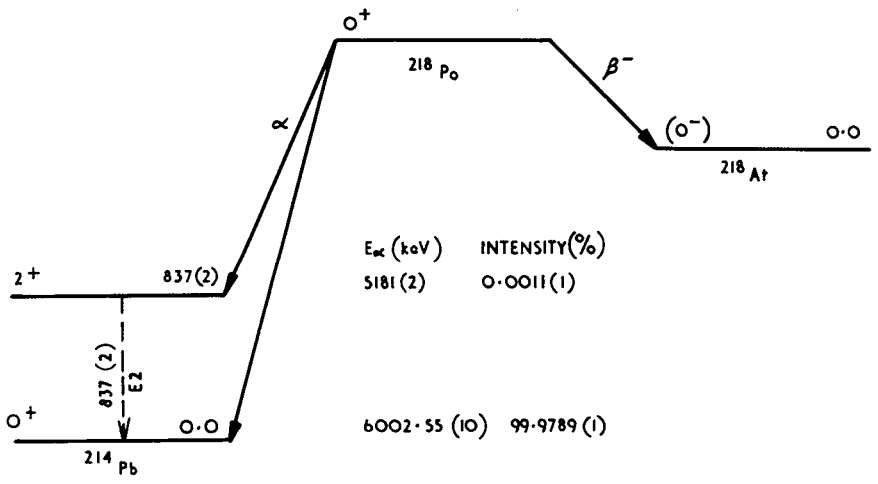


FIG. 2 DECAY AND TRANSMUTATION CHAINS PRODUCING HEAVY ELEMENT NUCLEI – DECAY CHAINS

HALF LIFE: M. CURIE et al, REV. MOD. PHYS. 3, 427, 1931 3·05 (9) m

Q_{β^-} = 256 (13) keV BR_{β^-}=0·0002(1)

Q_{α} = 6114·88 (10) keV BR_{α}=0·9998(1)



PUBLISHED α − DATA

B. GRENNBERG et al, METROLOGIA, 7, 65, 1971

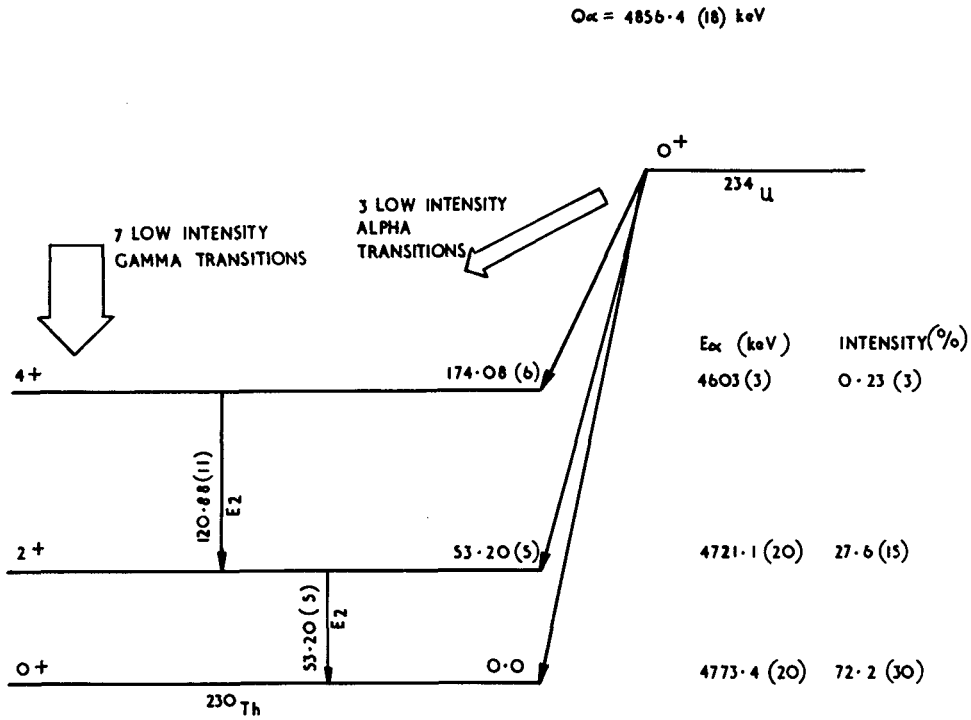
E_{α} = 6002·55 (9) keV

R. J. WALEN et al, C.R. CONG. INT PHYS. NUCL, PARIS, 1958

E_{α} (keV)	INTENSITY (%)
5181 (2)	0·0011
6002 (4)	100

THE EXISTENCE OF THE 5181 keV ALPHA TRANSITION REQUIRES THE GAMMA DEPOPULATION OF THE 837 keV NUCLEAR LEVEL OF ^{214}Pb

FIG. 3 ^{218}Po: THE INTRODUCTION OF DATA DURING AN EVALUATION IN ORDER TO PRODUCE A CONSISTENT AND COMPLETE DECAY SCHEME, A TRIVIAL EXAMPLE



E_γ (keV)	I_γ^{abs} (%)	αK	αL	αM	α tot	TP(%)
53·20 (5)	0·119 (10)	—	186	47	233(11)	27·8 (38)
120·88 (11)	0·041 (4)	0·26	3·5	0·93	4·69 (13)	0·23 (3)

FIG. 4. 234 – U DECAY SCHEME

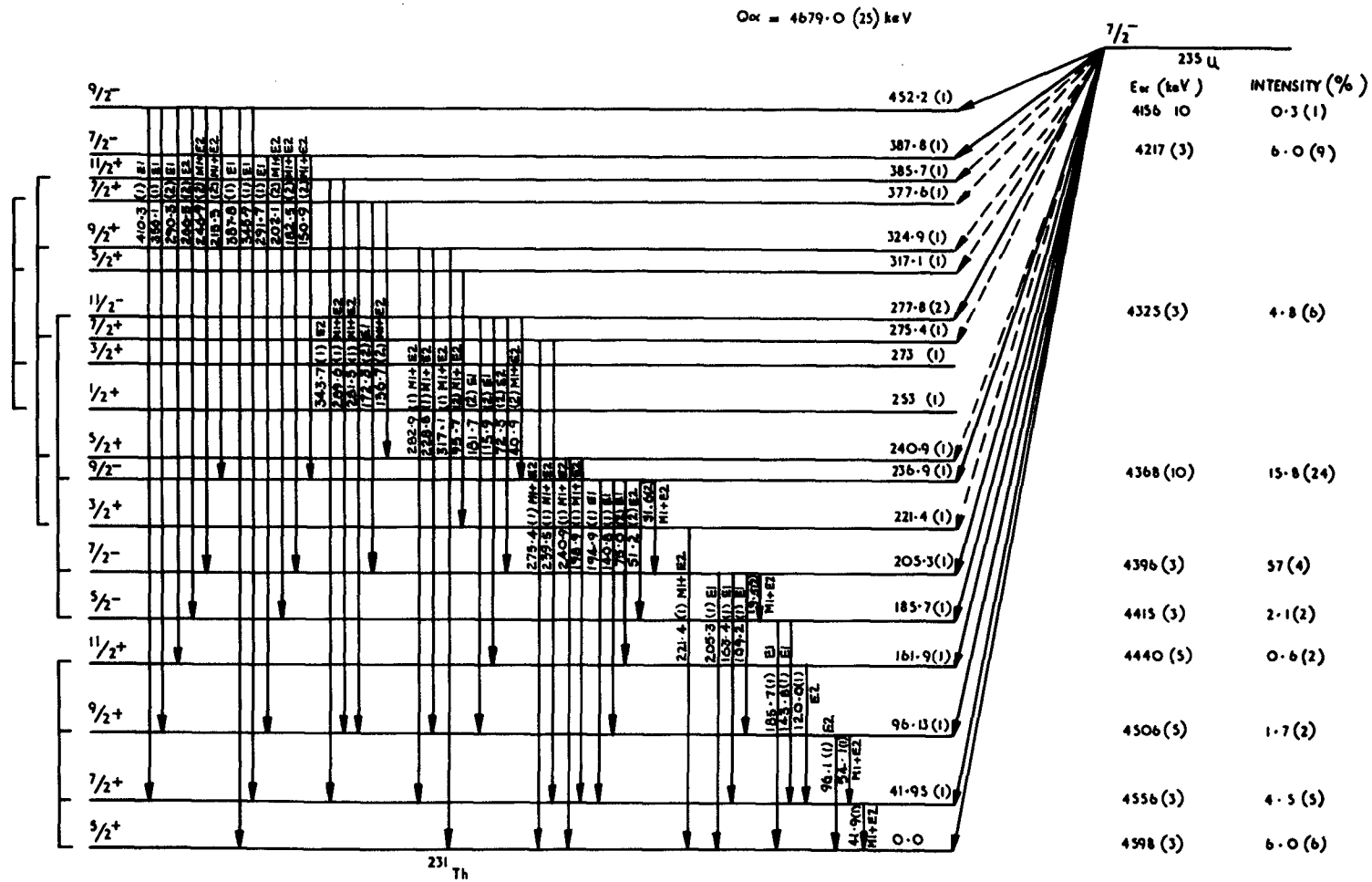
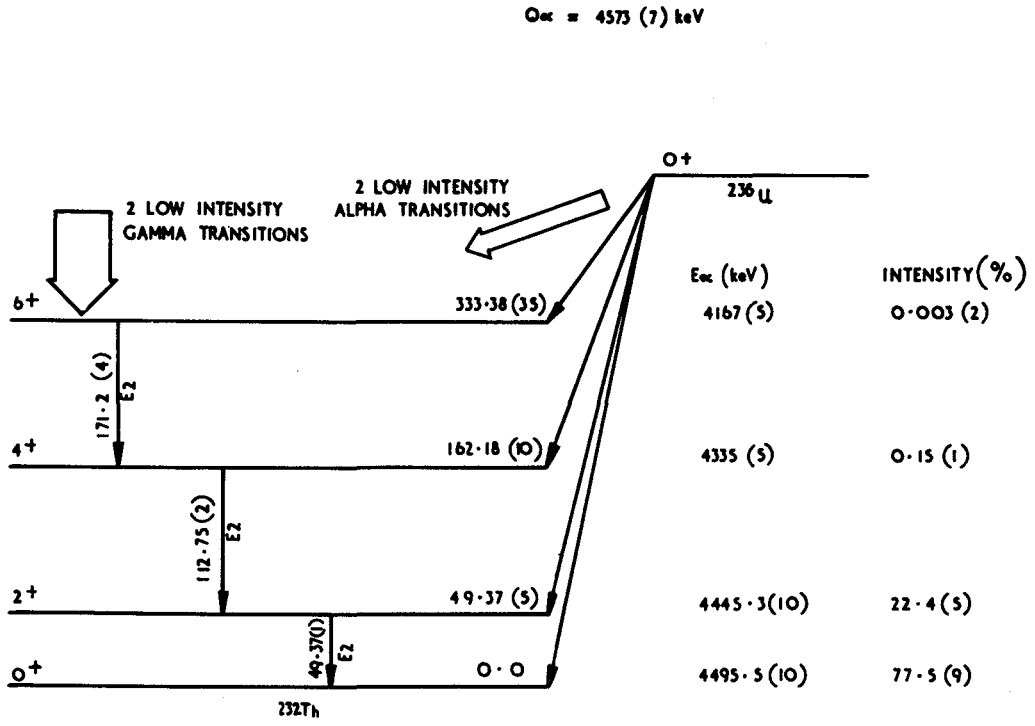
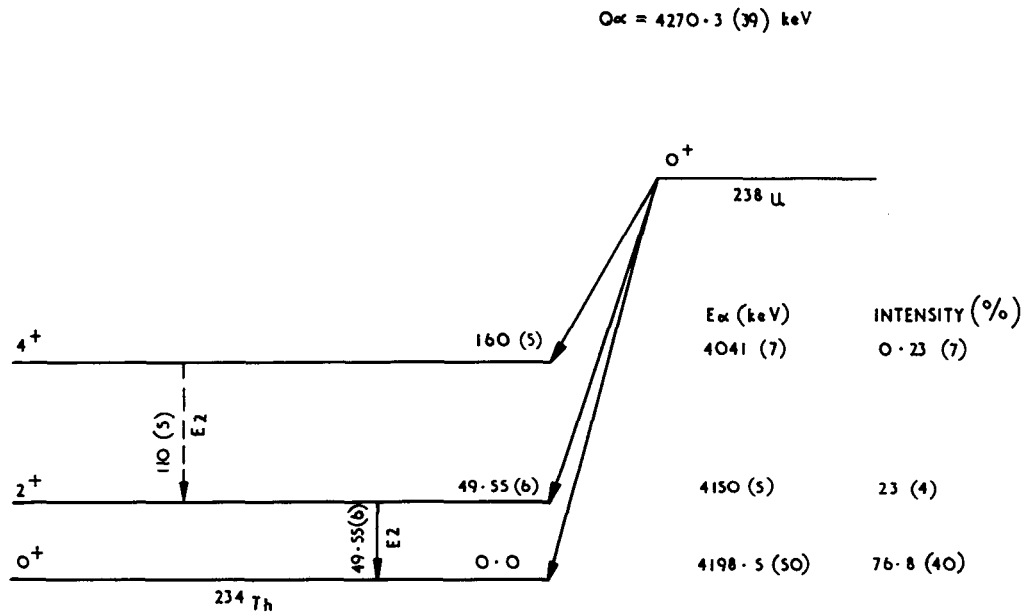


FIG. 5 235 – U DECAY SCHEME



Eγ (keV)	I_γ^{abs} (%)	αK	αL	αM	α tot	TP (%)
49·37 (1)	0·067 (5)	–	264	70	334 (14)	22·5 (5)
112·75 (2)	0·020 (2)	0·23	5·2	1·4	6·83 (43)	0·15 (1)
171·2 (4)	0·0014 (10)	0·21	0·75	0·21	1·17 (7)	0·003 (2)

FIG. 6. 236 – U DECAY SCHEME



E_γ (keV)	I_γ^{abs} (%)	αK	αL	αM	αtot	TP (%)
49·55 (6)	0·076 (15)	–	245	60	305 (7)	23·2 (40)
110 (5)	0·029 (10)	–	5·5	1·52	7·02(31)	0·23 (7)

FIG. 7 238 – U DECAY SCHEME

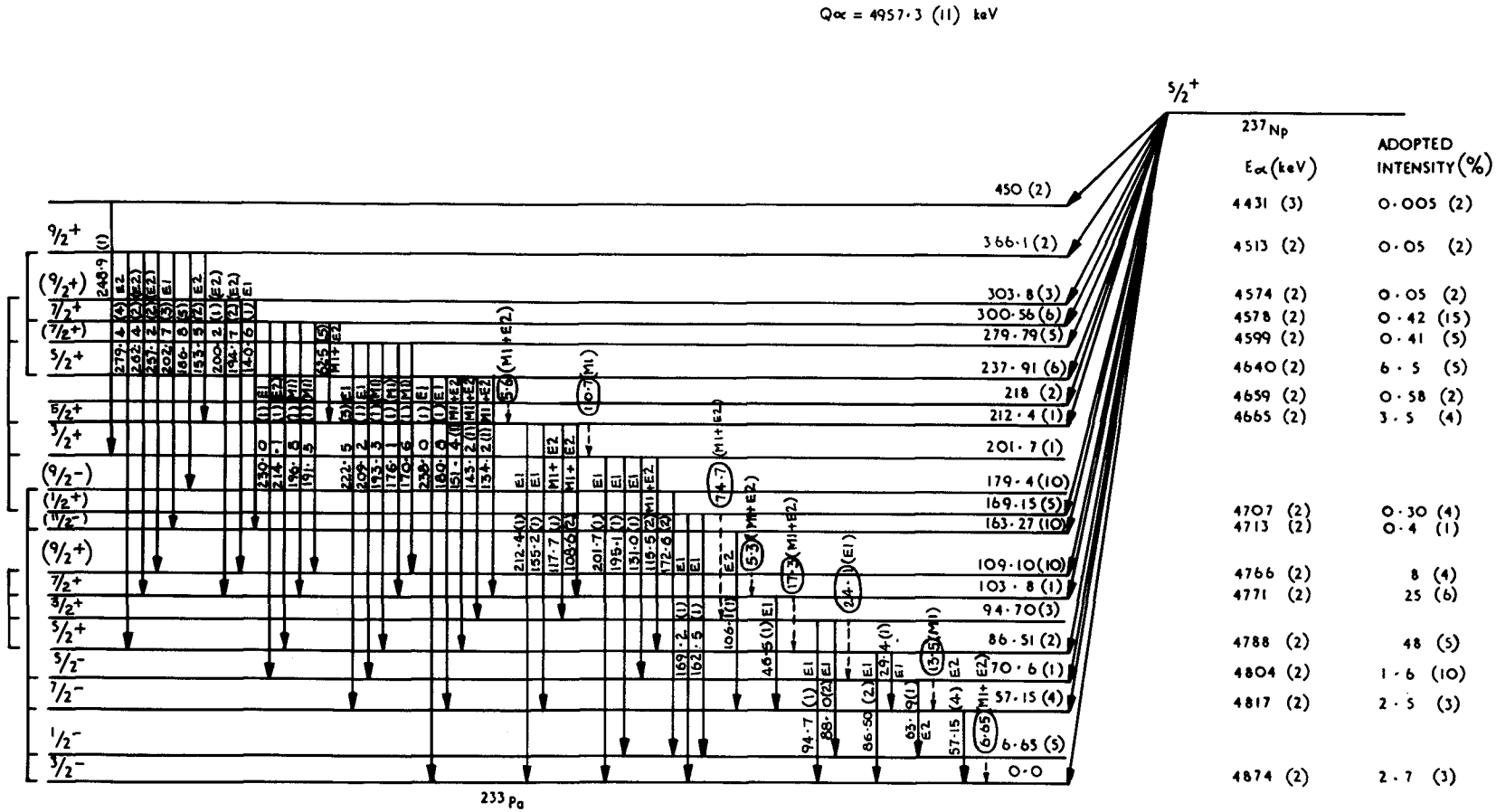
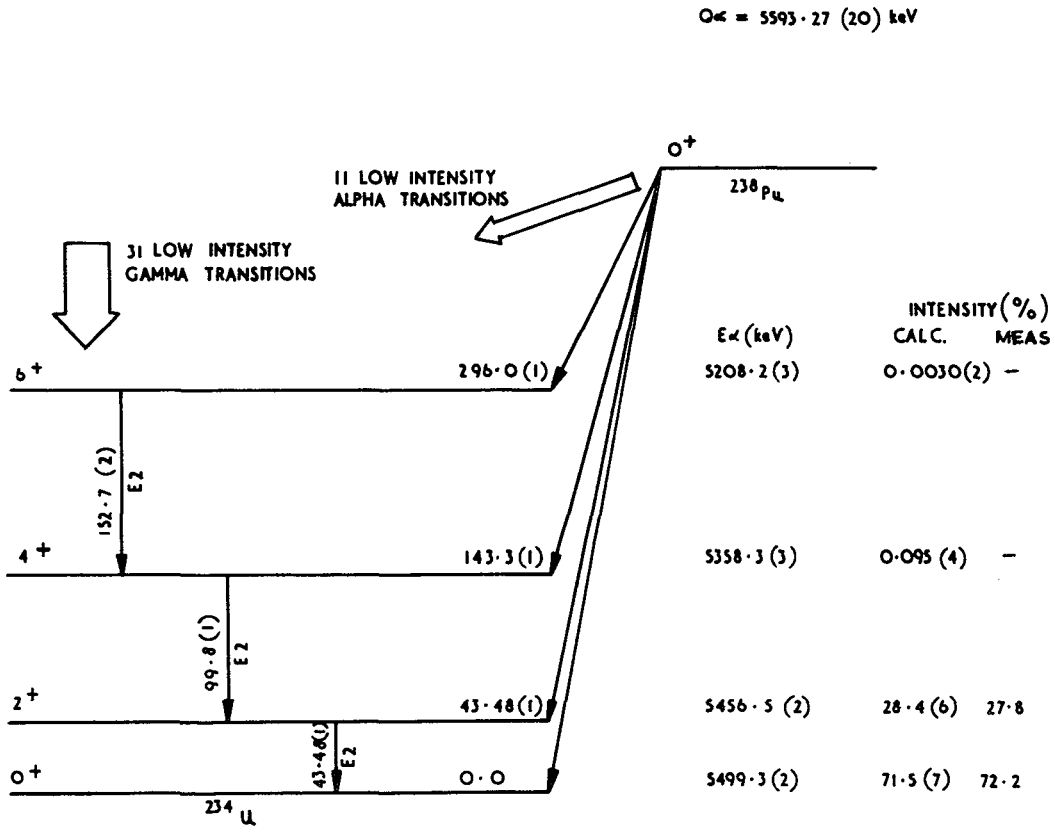


FIG. 8 237—Np DECAY SCHEME



E_γ (keV)	I_γ^{abs} (%)	α K	α L	α M	α tot	TP (%)
43·48 (1)	0·0393 (1)	–	565	160	725 (25)	28·5 (30)
99·8 (1)	0·00724 (1)	–	9·9	2·7	12·6 (3)	0·098 (3)
152·7 (2)	0·000956 (5)	0·22	1·6	0·37	2·19 (13)	0·0030 (2)

FIG. 9. 238 – PU DECAY SCHEME

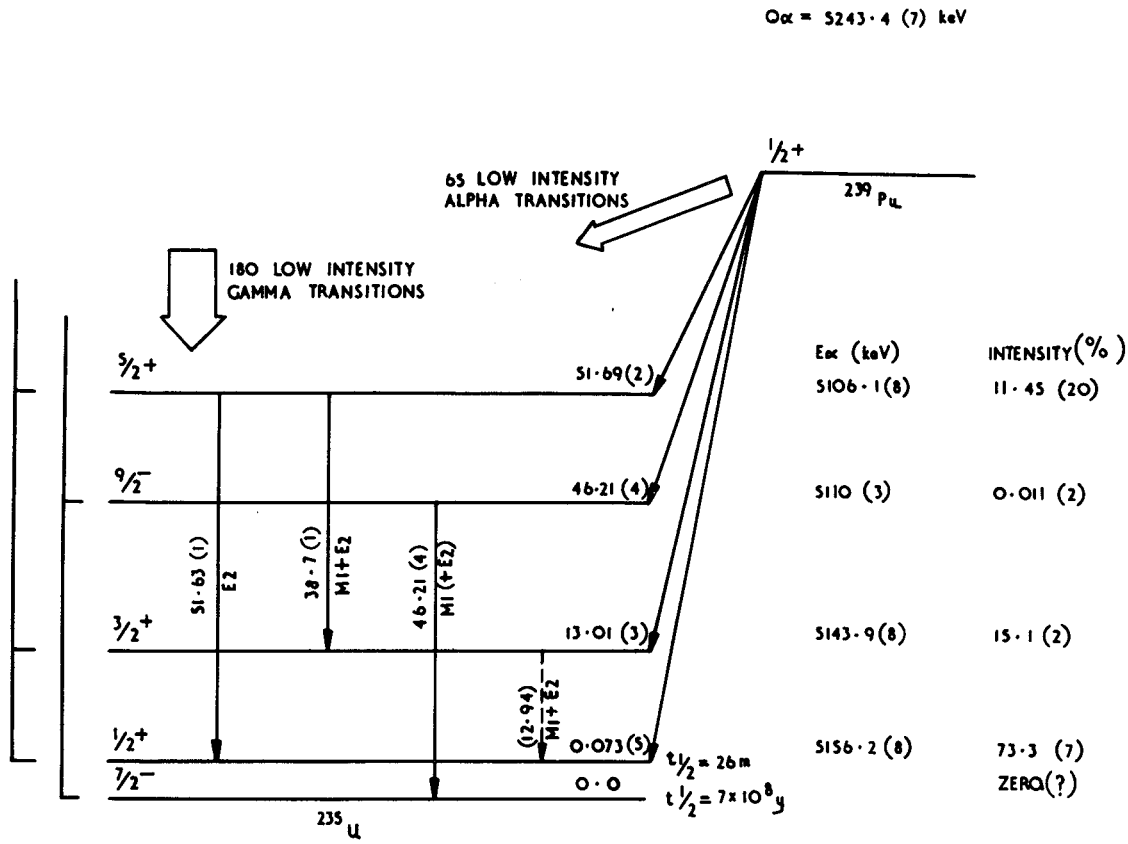
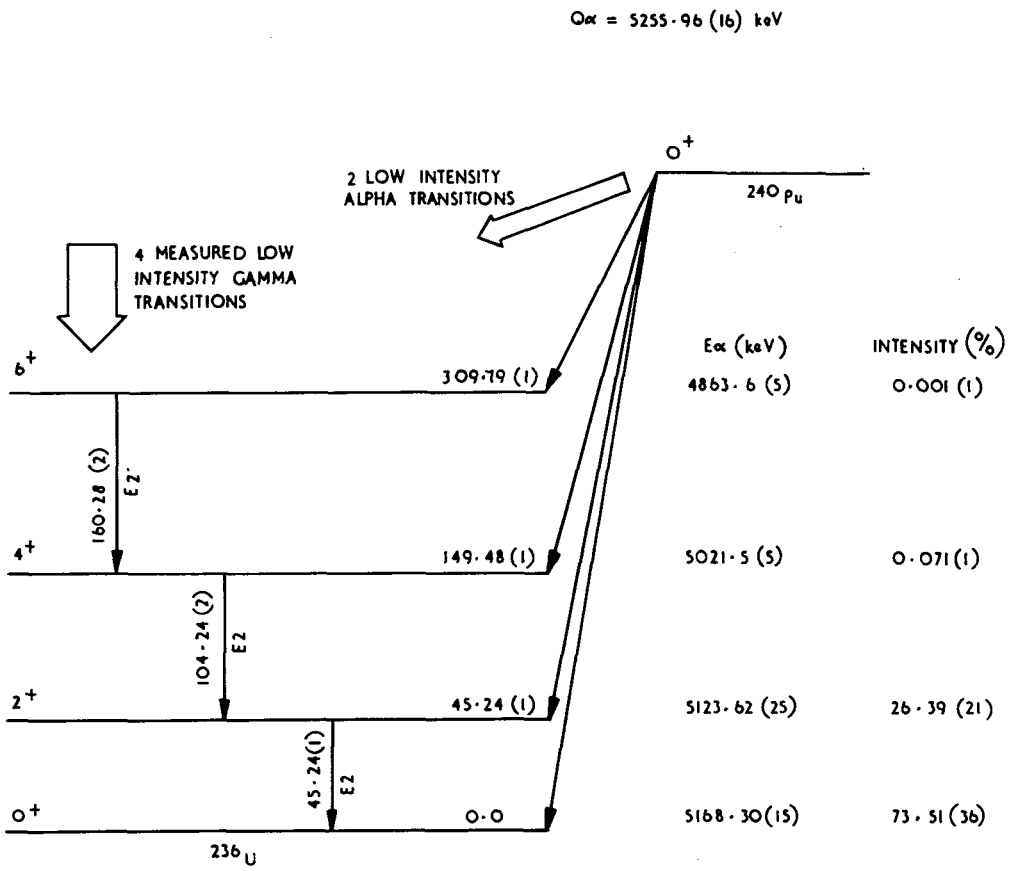


FIG. 10 239 – PU DECAY SCHEME

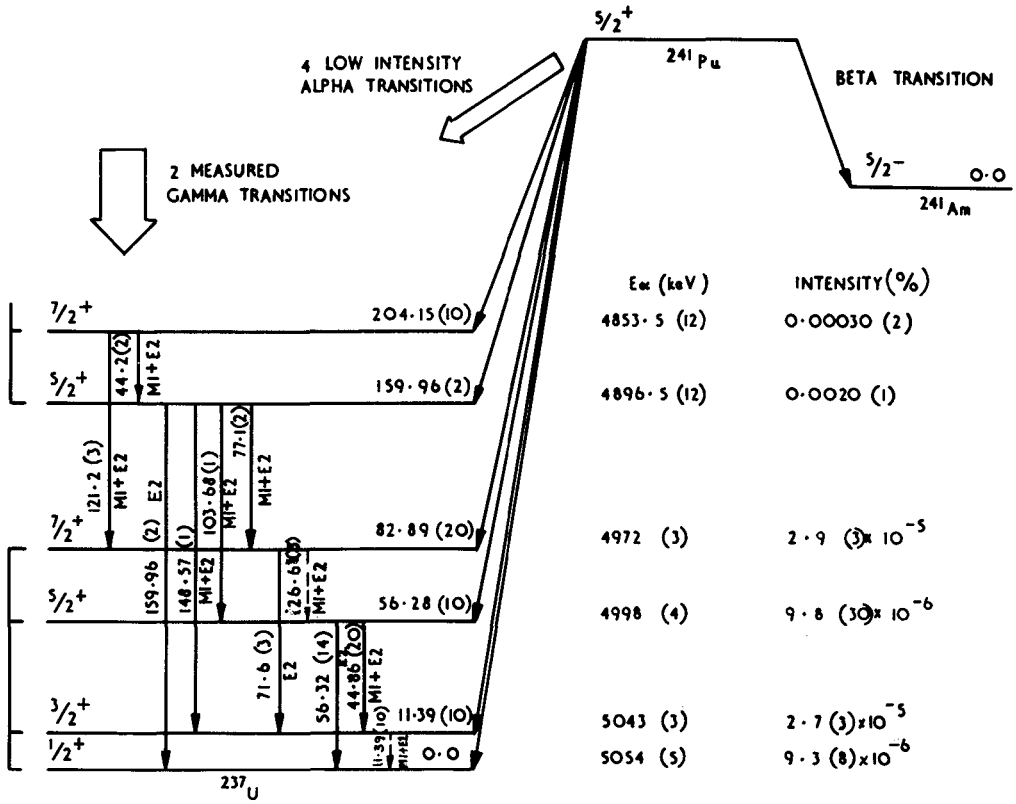


E_γ (keV)	I_γ^{abs} (%)	αK	αL	αM	αtot	TP(%)
45·24 (1)	0·0453 (1)	–	448	123	571 (10)	25·9 (5)
104·24 (2)	0·00698 (3)	–	8·2	3·0	11·2 (2)	0·085 (2)
160·28 (2)	0·000402 (3)	0·21	1·15	0·44	1·80 (3)	0·0011 (1)

FIG. 11 240 – Pu DECAY SCHEME

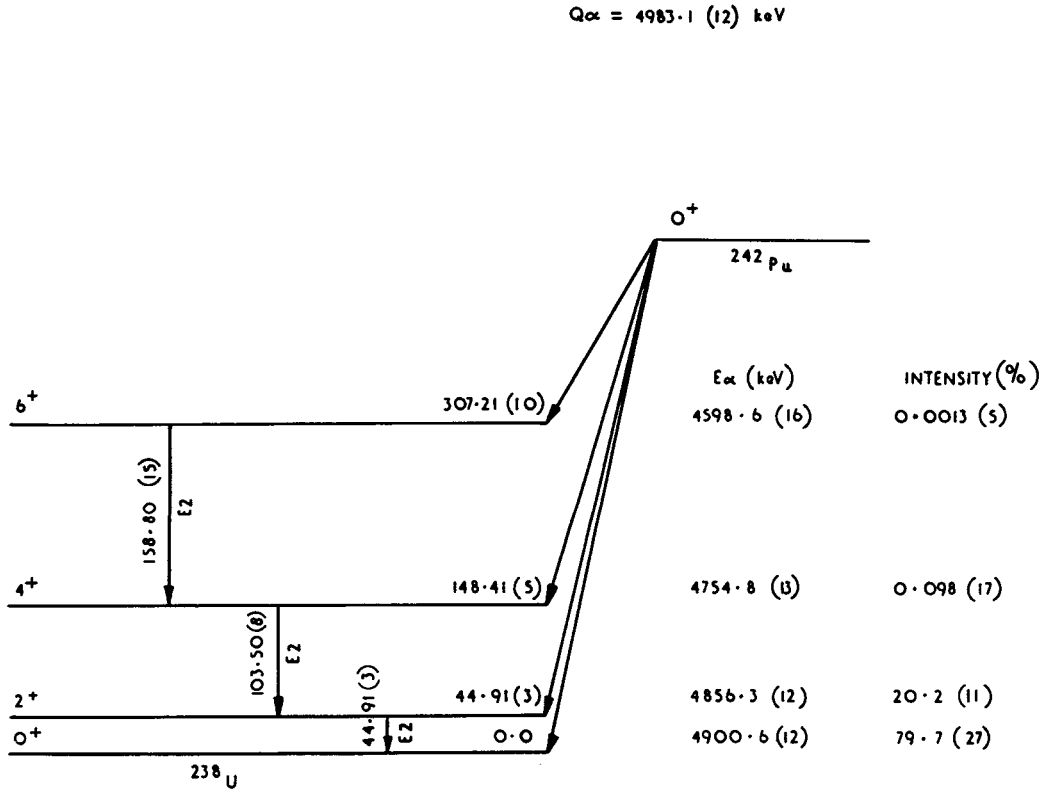
Q_β = 20·81 (20) keV BR_β = 0·9999755(8)

Q_α = 5139·3 (11) keV BR_α = 0·0000245(8)



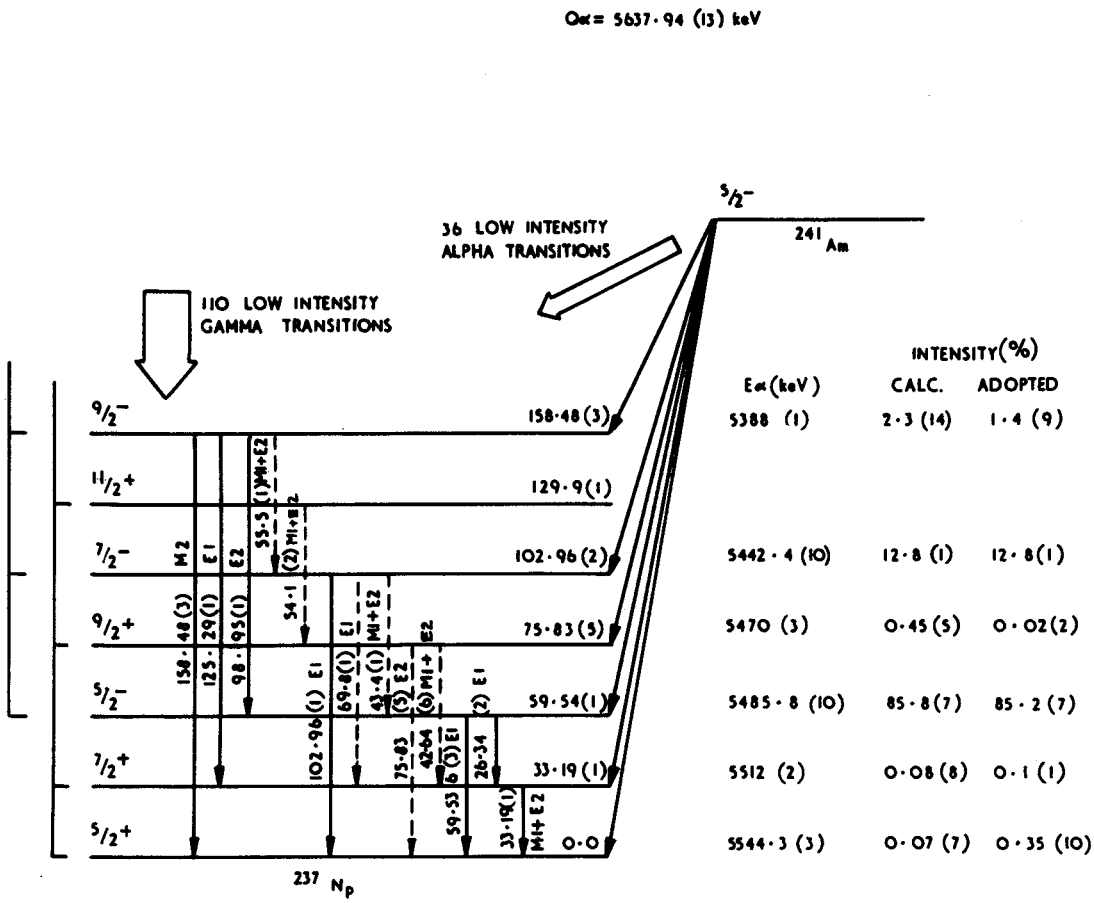
Multipolarity	E_γ(keV)	I_γ^{abs} (%)	αK	αL	αM	αtot	TP(%)
(M1)	103·68 (1)	$1·0(1)\times10^{-4}$	–	3·6	0·85	4·45 (25)	$5·5(3)\times10^{-4}$
M1+E2	148·57 (1)	$1·87(1)\times10^{-4}$	5·72	1·22	0·36	7·30 (30)	$1·6(1)\times10^{-3}$
E2	159·96 (2)	$6·7(2)\times10^{-6}$	0·22	1·3	0·35	1·87 (12)	$1·9(2)\times10^{-5}$

FIG 12 241 – Pu DECAY SCHEME



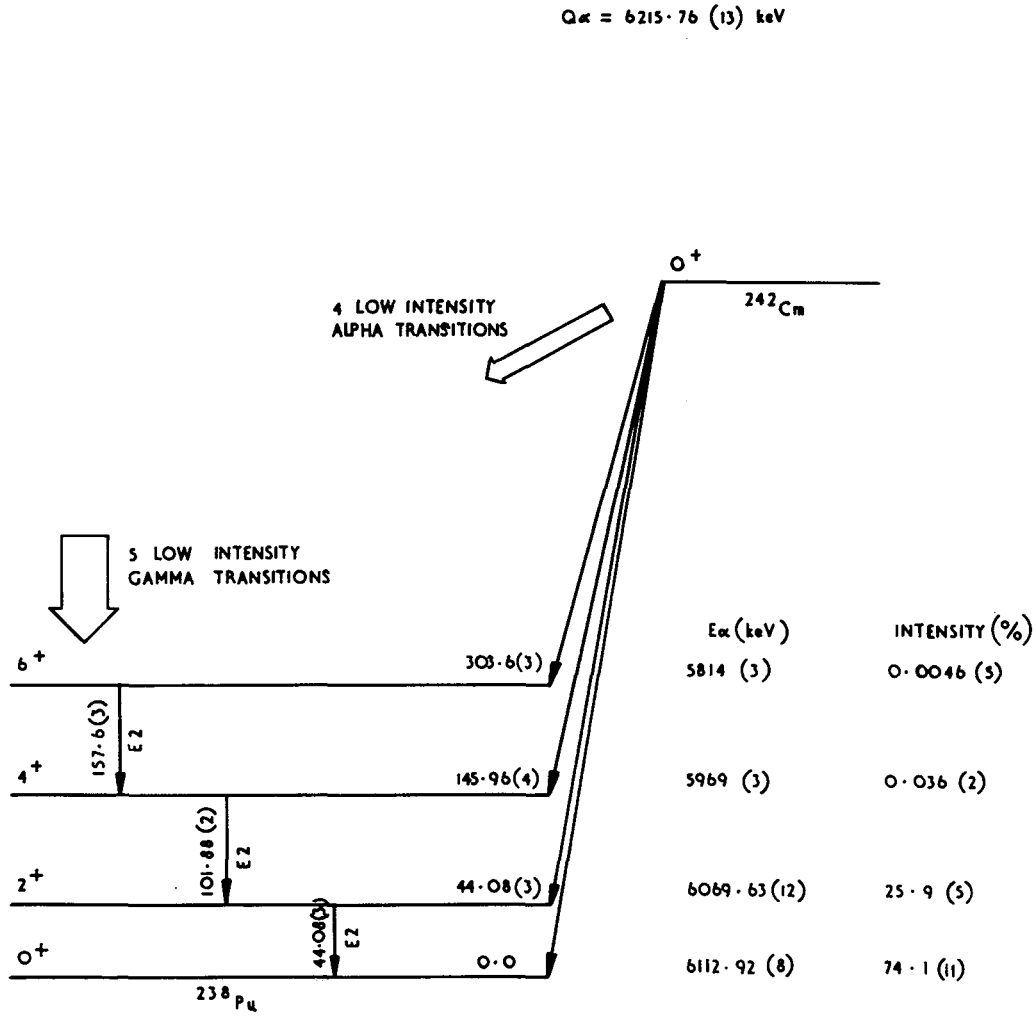
E_γ (keV)	I_γ^{abs} (%)	αK	αL	αM	αtot	TP (%)
44·91 (3)	0·035 (3)	–	450	130	580 (20)	20·3 (11)
103·50 (8)	0·0074 (14)	–	9·8	2·7	12·5 (3)	0·0993 (175)
158·80 (15)	0·00045 (20)	0·22	1·3	0·38	1·90 (13)	0·0013 (5)

FIG. 13 242 – Pu DECAY SCHEME



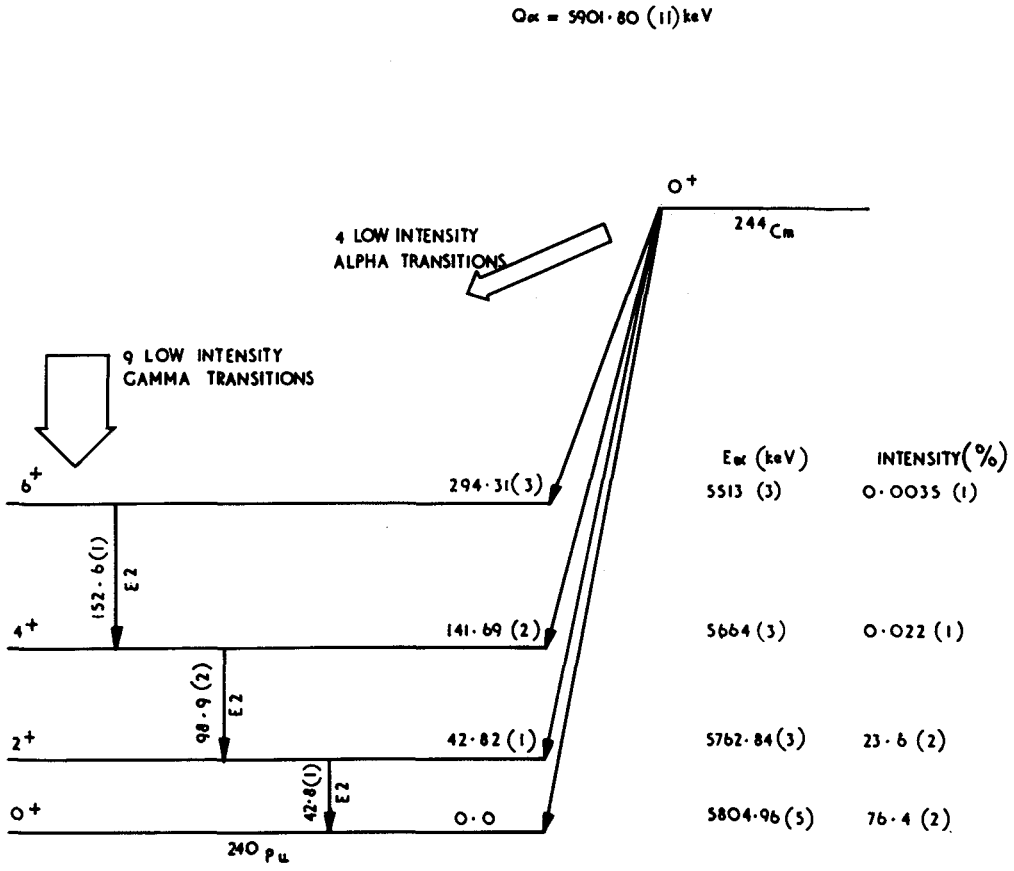
E_γ(keV)	I_γ^{abs}(%)	αK	αL	αM	α tot	TF(%)
26·34 (2)	2·45 (11)	—	6·9	1·7	8·6(4)	23·5 (10)
59·536 (3)	35·9 (6)	—	0·91	0·21	1·12(6)	76 (3)
102·96 (1)	0·0195 (1)	—	0·093	0·022	0·115(6)	0·023(1)
125·29 (1)	0·00408 (2)	0·23	0·054	0·013	0·297(13)	0·0053(1)
146·56 (1)	0·000458(5)	0·21	2·0	0·49	2·70(12)	0·0017 (1)
208·00(4)	0·000791(4)	2·5	0·50	0·115	3·115(125)	0·00325(12)
332·35 (2)	0·000149(1)	0·064	0·063	0·017	0·144 (4)	0·000170(2)
335·40 (2)	0·000496(2)	0·38	0·10	0·02	0·50 (4)	0·000744 (23)

FIG. 14 241 – Am DECAY SCHEME



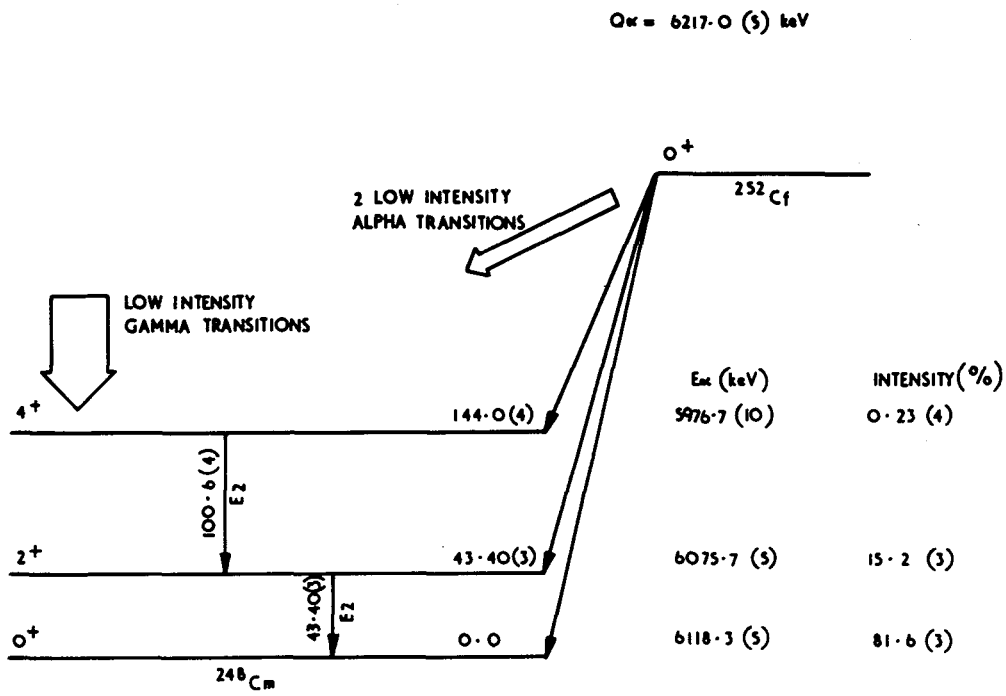
E_γ(keV)	I_γ^{abs} (%)	αK	αL	αM	αtot	TP(%)
44·08 (3)	0·0323 (20)	—	580	220	800(30)	25·9 (26)
101·88 (2)	0·0028 (3)	—	10·5	3·0	13·5 (6)	0·0406 (25)
157·6 (3)	0·0015 (2)	0·20	1·5	0·42	2·12 (12)	0 0046 (5)

FIG. 15 242 – Cm DECAY SCHEME



E_γ(keV)	I_γ^{abs}(%)	αK	αL	αM	αtot	TP(%)
42·8 (1)	0·0262 (11)	–	700	200	900(30)	23·6 (18)
98·9 (2)	0·00154(17)	–	12	3·4	15·4 (11)	0·0253(46)
152·6 (1)	0·00104 (2)	0·20	1·70	0·48	2·38 (5)	0·0035 (1)

FIG. 16 244 – Cm DECAY SCHEME



E_γ (keV)	I_γ^{abs} (%)	αK	αL	αM	αtot	TP(%)
43·40 (3)	0·0150 (6)	—	800	230	1030 (20)	15·5 (9)
100·6 (4)	0·0129 (2)	—	13·4	3·8	17·2 (2)	0·23(4)

FIG. 17 252 – Cf DECAY SCHEME

APPENDIX

COMMENTS ON THE QUALITY AND DECAY SCHEME

CONSISTENCY OF SELECTED, EVALUATED ACTINIDE DECAY DATA

Nuclide	Comments
228-Th	The measured decay data produce an adequate decay scheme.
230-Th	The measured decay data produce an adequate decay scheme.
231-Th	The gamma data for low energy, high conversion emissions result in a low degree of accuracy for the gamma and beta data associated with these emissions. Beta intensities are not reliable, hence large uncertainties.
232-Th	Decay data are difficult to measure because of the long half-life.
231-Pa	The gamma data are well recorded and more recent than alpha data: greater emphasis has been placed on the gamma data when deriving the total decay scheme. Thus the alpha data have been adjusted to fit the observed gamma data. The result is a number of low intensity alpha emissions that have not been observed: an alpha study is desirable. Six alpha transitions have been introduced to complete the decay scheme: 4415, 4430 4555, 4630, 4761 and 4792 keV. Four observed gammas do not fit the decay scheme: 39.57, 39.97, 70.50 and 310.15 keV.
232-Pa	The measured decay data produce an adequate decay scheme.
233-Pa	The proposed decay scheme is strongly influenced by the recently measured value of 38.6% for the 311.98 keV gamma emission. This value has been adopted in conjunction with the relative gamma intensities from two other publications. The 300.12 and 311.98 keV gamma transitions have been assigned 85% M1 + 15% E2 multipolarity, giving transition probababilities in reasonable agreement with beta measurements.
232-U	Inconsistencies occur between the alpha and gamma data. Two high energy, low intensity gamma transitions have been introduced: 774 and 830 keV.
233-U	A reasonably consistent and detailed decay scheme has been produced. Gamma transitions have not been assigned to the de-population of the nuclear levels populated by the 4457, 4483, 4641, 4687, 4751, 4759 and 4805 keV alpha transitions. Impurities in the source (232 and 234-U) complicate the evaluation. The charged particle studies for 230-Th(d,t) have been used to determine some of the higher nuclear levels, and there are minor differences between the gamma data depopulating these levels and the measured low intensity alpha data.

Nuclide	Comments
233-U (cont)	Consistency has been achieved by adjusting the internal conversion coefficient data of the 29.15 and 42.7 keV gamma transitions. Further accurate measurements of low intensity alpha emissions may remove the minor discrepancies.
237-U	Gamma transitions have been introduced to complete the decay scheme: 13.81, 38.57, 42.64, 69.77, 75.83, 102.96, 267.54 and 292.8 keV. Some of these transitions have been deduced from the equivalent 241-Am decay data. The 26.34 and 59.536 keV gamma transitions have anomalous conversion coefficients. When possible the consistent gamma intensities of one reference have been adopted. The beta data have been deduced from the gamma data evaluation. Some inconsistencies do occur involving the 238 and 252 keV beta emissions, the 13.81 keV gamma emission and the gamma depopulation of the 59.537 and 75.83 keV nuclear levels. Beta and conversion electron measurements would prove beneficial.
239-U	A relatively complex decay scheme has been derived from the abundant gamma data. Low energy M1 + E2 transitions have 50/50 mixing whilst high energy transitions have been set to 100% M1. Seven low energy gammas have been introduced with high internal conversion that have not been observed; these gammas are 32.9, 43.1, 50.4, 51.4, 71.2, 142.0 and 170.2 keV. There is an imbalance involving the 452.7 and 220.2 keV levels. Minor problems occur involving very low intensity beta transitions; beta transitions 0.01% have been set to zero. Accurately measured beta data would be a major asset in finalising a comprehensive decay scheme. Seven high energy gammas have not been placed in the decay scheme: these gammas are 462.64, 727.47, 764.04, 971.35, 1093.83, 1161.4 and 1204.9 keV.
240-U	Detailed beta and gamma measurements are lacking.
236-Np	Inconsistencies occur, but detailed decay data are difficult to measure because of the long half-life.
236m-Np	Low energy gamma transitions have been introduced to give a consistent complete decay scheme.
238-Np	The consistent gamma data of one reference have been adopted. A low energy gamma transition (44.08 keV) has been introduced to complete the decay scheme. Coupled with data from a second source, these gamma data have been used to deduce the beta data. Beta decay measurements would be beneficial.

Nuclide	Comments
239-Np	The gamma data have been used to produce a consistent set of beta data; the available data indicate that there is no beta transition to the 239-Pu ground state. Three low energy gamma transitions have been introduced to complete the decay scheme: 7.86, 18.43 and 57.3 keV.
240-Np	The decay scheme is poorly defined. The proposed decay scheme has been developed by balancing the gamma transitions from the 100% beta populated 1308.6 keV level of 240-Pu. A single beta transition has been assumed.
240m-Np	The decay scheme is poorly defined. The proposed decay scheme contains beta energies that have been adjusted to produce a consistent data set.
241-Np	A low energy gamma transition (41.8 keV) has been tentatively introduced. The two observed gamma energies have been adjusted from the measured values of 135 and 175 keV: the adjusted values agree with equivalent decay data of 245-Cm. The three gamma transitions have been assigned E2 character; these assignments are arbitrary. Data are extremely unsatisfactory; no beta and gamma intensity data have been reported. However, some unreliable intensities have been introduced influenced by a published comment that the 1360 keV beta emission is strong. Both beta and gamma studies are required. A postulated metastable state (half-life 3.4 hrs) has been discarded; relatively recent attempts to produce this isomer have been unsuccessful
236-Pu	The measured decay data produce an adequate decay scheme.
237-Pu	Detailed decay data are lacking and the proposed decay scheme is based upon a number of nebulous assumptions. The most important assumptions involve the major mode of decay (EC) and are based on comments made in one publication with respect to the relative transition probabilities of the 43.43, 55.5 and 75.83 keV gamma transitions compared with the 59.536 keV gamma transition. Intensity measurements have been reported for only the 26.34, 33.19 and 59.536 keV gamma transitions and all other data are based on these comments and equivalent 241-Am decay data. In the small alpha decay branch the transition probabilities and intensities of the unobserved 21.85, 33.0, 40.35, 51.6, 54.85, 63.1, 92.0 and 114.7 keV gamma emissions are questionable. These data and the alpha intensity data are extremely unreliable.

Nuclide	Comments
243-Pu	Great emphasis has been placed upon the consistent gamma data from one publication. A low energy gamma emission (25.3 keV) has been introduced to produce a consistent decay scheme. A measured normalisation factor of 0.34 for the gamma emissions has been rejected because of the inconsistencies this value produced. Accurate beta decay measurements would greatly clarify the decay scheme; the large uncertainties in the beta intensities indicate the unsatisfactory nature of this section of the data. The beta data problem is aggravated by the intensity inaccuracies of the low energy gamma emissions.
244-Pu	Decay data are difficult to measure because of the long half-life.
245-Pu	There are considerable inconsistencies in the decay data. It is unfortunate that one detailed study has only partially been published, reporting gamma emission energies greater than 800 keV. Therefore, greater emphasis has been placed on the data from another source. A number of low energy gamma transistions are required to depopulate seven 245-Am daughter levels populated in the decay; no attempt has been made to list these transitions. Twelve gammas cannot be placed in the partial decay scheme: 514.6, 642, 691, 702, 743.7, 822, 879.6, 925.4, 945.2, 975, 1007 and 1040.2 keV. The beta intensities have been derived from the gamma data when populating levels above 887 keV. For levels less than 191 keV the combined beta decay has been arbitrarily shared between seven levels. There is a great need for beta decay and conversion electron measurements to aid in resolving the decay properties of nuclear levels below 191 keV.
242-Am	The gamma intensities have been calculated from the internal conversion coefficients and transition probabilities. Detailed gamma and conversion electron measurements are required to clarify the decay scheme.
242m-Am	Gamma decay data associated with the small alpha branch are poorly documented. Some important work has only been partially published and indicates the relative complexity of this branch. A number of gamma transitions not reported would complete a comprehensive decay scheme.
243-Am	There are some relatively serious disagreements between the measured alpha intensities of the 5233.5 and 5275.4 keV emmisions and the corresponding gamma depopulating transitions. These could not be resolved because of the high internal conversion coefficients of the 43.0 keV gamma emission and the inability to determine the transition probability accurately.

Nuclide	Comments
243-Am (cont)	Greater emphasis has been placed on the reliability of the alpha data and, not surprisingly, some of the extremely low intensity gamma emissions arising from this alpha data have not been observed. The total alpha intensity of 4996 and 5008 keV is 0.0016% and of 5031 and 5035 keV is 0.0022%: these intensities have been equally shared between the two relevant alpha emissions, although this is not justified. Although gamma data have been studied in some detail, further studies might prove beneficial. Conversion electron studies would greatly aid in resolving the decay scheme problems.
244-Am	A reasonable decay scheme can be produced if two unobserved low energy gamma transitions are included: 42.9 and 99.4 keV.
244m-Am	Decay data are uncertain, particularly for the beta branch to 244-Cm. Detailed gamma spectroscopy studies would aid in the production of a comprehensive decay scheme.
245-Am	The internal conversion coefficients for the 252.9 keV gamma emission are important data in the decay schemes of 245-Am and 249-Cf: a total value of 1.67 has been adopted, disagreeing with measurements. Two low intensity gammas have been introduced to complete the decay scheme: 54.7 and 198.0 keV. These gamma emissions are supported by the equivalent 249-Cf decay data.
243-Cm	The alpha data have been extensively studied. Unfortunately, there have been no equivalent detailed gamma and conversion electron studies. A complete decay scheme has not been achieved, and the derived 18.43 and 67.84 keV gamma intensities are suspect. Eleven low energy gamma emissions have been introduced to supplement the partial data: 7.86, 18.43, 44.65, 49.41, 57.3, 61.5, 67.84, 106.1, 106.5, 118.3 and 166.4 keV.
245-Cm	There are two doubtful alpha emissions of 5273 and 5370 keV that have been rejected. There are several alpha emissions in the energy range 5050 to 4650 keV with intensities less than 0.00001% that have not been included: further alpha studies are required. There are no detailed gamma data and the intensities of the two gamma emissions are unreliable.
246-Cm	Very little decay data have been reported. The single gamma intensity has been calculated from the theoretical internal conversion coefficients and the transition probability.

Nuclide	Comments
247-Cm	A reasonably comprehensive decay scheme has been produced despite the long half-life. Low energy gammas have been introduced to complete the proposed decay scheme: 45.7, 51.5, 57.9 and 66.5 keV.
248-Cm	Detailed decay data are difficult to measure because of the long half-life.
249-Bk	Only two gamma emissions have been observed via alpha decay. However, the alpha decay mode is only a small part of the decay scheme and no attempt has been made to introduce the missing transitions. The beta decay mode data are well characterised.
250-Cf	The measured decay data produce an adequate decay scheme.

STATUS OF TRANSACTINIUM NUCLEAR DATA IN THE EVALUATED NUCLEAR STRUCTURE DATA FILE*

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Abstract

The structure and organization of the Evaluated Nuclear Structure Data File (ENSDF) which serves as the source data base for the production of drawings and tables for the "Nuclear Data Sheets" journal is described. The updating and output features of ENSDF are described with emphasis on nuclear structure and decay data of the transactinium isotopes.

I. INTRODUCTION

Since 1948, the Nuclear Data Project (NDP) has been a recognized center for the systematic collection and evaluation of data from nuclear structure experiments. The Data Project has helped consolidate the rapid advance of nuclear science by identifying and publicizing conflicting results and by integrating each new measurement with those that preceded it. The organization of nuclear data for publication in *Nuclear Data Sheets* [1] has also led to the development of a natural structure for containing these data.

In 1971 NDP designed a formal structure for entering nuclear structure data into computer files [2]. This structure has been used since then to prepare, maintain, and edit a comprehensive file of Evaluated Nuclear Structure Data (ENSDF), which is used for production of drawings and tables for *Nuclear Data Sheets.*

These computer files of nuclear data are also being used as a means of making the results of basic research quickly and easily available to a broader audience. Radioactivity information, in particular, has wide application in fields such as nuclear medicine, reactor engineering, environmental impact assessment, and nuclear waste management. Often the specialists in these areas have neither the time nor the training to make effective use of the data generated by basic nuclear research. The NDP has made important progress during the last few years toward providing a channel through which the results of new nuclear measurements can be transferred to any engineer or scientist who needs evaluated data to factor into his or her own work.

The value of a scientific data base is determined largely by four properties, each of which represents a compromise between what would be ideal and what is easily attainable. Ideally, the data base should be:

1. Comprehensive – All related quantities (measurable or derived from "reliable" theory) should be included, together with estimates of their uncertainties.
2. Complete – All available data of each type should be included.
3. Up-to-Date – The consequences of each reliable new measurement should appear quickly throughout the data collection.
4. Accessible – Data should be obtainable from the file according to user-defined needs and should be presented in a user-defined format.

*Research sponsored by the Division of Basic Energy Sciences, U. S. Department of Energy, under contract W-7405-eng-26 with Union Carbide Corporation.

An international network of data evaluation centers has been organized [3,4] through IAEA to provide for periodic revisions of ENSDF by the use of new experimental results to prepare new "adopted" estimates for nuclear parameters. Supporting systems for ENSDF make it possible to assemble various collections of data and to present them in a form that is convenient for further study or application.

Nuclear Data Project's MEDLIST program, which provides tables of both atomic and nuclear radiations, has been applied to over 1500 decay schemes in ENSDF. Earlier collections of MEDLIST-type output [5-7] have been widely used in both basic and applied research. Special collections of radioactivity data in computer-readable format have also been assembled from ENSDF by MEDLIST to meet the needs of specific programs [8,9].

The program NDSLIST was developed to prepare standard tables automatically from data extracted from ENSDF. Text pages of *Nuclear Data Sheets* have been prepared by NDSLIST since 1975. NDSLIST has much more extensive capabilities, however, as illustrated by several tables included with this report.

ENSDF thus provides the nuclear scientist with a comprehensive collection of reliable evaluated nuclear structure and decay data, which is also reasonably current. For many applications, a subset of data extracted from ENSDF provides sufficient precision and completeness that no further consideration of possible newer measurements is needed. For the specialist, the tables from ENSDF provide a first approximation to a completely up-to-date tabulation. The ENSDF output shows where specific values are missing or of low precision: the specialist can then focus on a much smaller number of data items, where a search for newer experiments or a new experimental program would have the greatest benefit.

II. GENERAL SURVEY OF ENSDF STRUCTURE

A. ENSDF Organization

The Evaluated Nuclear Structure Data File is built around the properties of nuclear levels. All properties of each level (energy, spin, parity, half-life, decay modes, . . .) are collected into a single record. Grouped with each level record are other records, which describe the spontaneous transitions (α, β, γ, IT, SF) which connect the level to other nuclear levels. The results of a nuclear structure experiment can be represented by a collection of such level records and associated transitions, as shown schematically in Fig. 1. The collection of data for one experiment is referred to as a "data set".

Radiations which have been observed in the experiment but have not been associated with a particular level are placed in the data set before the first level. Other general information concerning the experiment is given near the beginning of the data set. An estimate of the uncertainty is included with each experimental number. Comments and reference keys are inserted wherever appropriate.

Each data set is identified by a keyword string (the data set "name") which serves as a primary retrieval tool. The data set names are taken from the natural language of nuclear structure physics, as illustrated by the section of the ENSDF index shown in Fig. 2. The identification also contains principal reference keys and the date when the data set was merged into the master file.

ENSDF contains at least one data set for each distinct experiment which gives information about a nucleus. This means that each radioactive decay branch is represented in the file by a data set, as is each nuclear reaction. For each nucleus, a data set with the name "adopted levels" summarizes the level properties established by all experiments.

B. ENSDF Management

Data to be included in ENSDF are entered into the computer by means of punched cards or card images. For each record a "standard" format for the card images has been designed [2]. The standard format contains in fixed fields on a single card the data most frequently available for each nuclear level or radiation. Data that appear less frequently are written in a data-directed format onto continuation cards. The fixed format simplifies computer processing of the most frequently encountered data, while the data-directed format allows the inclusion of a wide variety of different types of data.

In the rare cases where the data will not fit into the standard format (because of exceptional precision, for example), a redefinition of the standard formats can be made for a single data set. The data set for ^{240}Pu α-decay (Fig. 3) contains data in both fixed-field and data-directed format.

ENSDF data sets are stored sequentially as card images on a direct-access device. Since each data set begins with an identification card and ends with a blank card, it can be read easily from the sequential file. Since the data sets appear in the master file in random order, however, a second file must be maintained as an index. The index file locates each data set in the main file by pointing to the position of its identification card. A data set is "deleted" from ENSDF by removing its entry in the index. A revision of the data file consists of adding the revised data set to the main file and changing the pointer in the index file. At intervals, superseded data sets are removed, and the master file is compressed according to the current index file.

At ORNL, the data file is maintained in two sections: an archival permanent file and a temporary or buffer file (see Fig. 4). The permanent file is linked to the computers only when needed for search or major revision. The temporary file is smaller and is always available to the computer systems. The temporary file is used for more active data sets, such as those currently being revised. Data sets from the temporary file can be retrieved, edited, and revised interactively by means of the IBM time-sharing option (TSO).

C. Retrieval from ENSDF

The retrieval of specific data from ENSDF usually proceeds in two steps. First, those data sets which may contain relevant data are retrieved from the master file. Each of those data sets is then scanned for specific data items.

The index entry or key for each data set is derived from the identification record by squeezing out blanks and inserting the atomic number for the element. Insertion of the atomic number forces the index listing to be in a more natural scientific order.

Removal of blanks greatly simplifies preparation of retrieval instructions, since exact placement of characters on the card is no longer important, and only the sequence of characters is used for retrieval. The index may not contain two entries with identical keys. This feature of IBM's indexed sequential access method (ISAM) provides a useful check for duplicate data sets. Two nearly identical data sets can be entered, however, if only a single character in the key is changed.

The generic-key feature of ISAM allows retrieval of several indexed entries if only a fragment of a key is given. For example, all data sets for nuclei with mass A = 91 can be retrieved sequentially by making a request for "91". A request card which contained "92ZR 91ZR" would cause retrieval from ENSDF of data sets for all reactions [(d,p), (n,γ), and (^{4}He,^{3}He) on ^{91}Zr which give information about nuclear structure of ^{92}Zr.

Several other tools for defining a search through ENSDF have been constructed:

1. The search may be restricted to a limited range of mass values (A), atomic numbers (Z), or neutron number (N).
2. The search may consider only odd or only even values of A, Z, or N.
3. The search may require the appearance of certain character strings in the key.
4. The search may exclude data sets for which the key contains certain character strings.
5. The search may be restricted to data sets filed between specified dates.

III. STATUS AND UPDATING OF ENSDF

A. ENSDF Current Contents

The Evaluated Nuclear Structure Data File now contains 6600 distinct sets of evaluated nuclear information. This includes:

1950	sets of adopted level properties
1850	decay schemes
3020	nuclear reaction data collections, including
230	(n,γ) reactions
225	(d,p) reactions
500	(charged-particle,xnγ) reactions

For nuclei with $A \geqslant 207$ alone, the corresponding figures are:

362	adopted level properties
374	decay schemes
220	nuclear reaction data

A set of adopted levels and their properties is now included for every nucleus. Several complete collections of level properties have been assembled from ENSDF; e.g., all levels with lifetimes between 1 ps and 1 fs; odd-parity states in even nuclei. A collection of levels with spontaneous fission branching has recently been published [10].

Most decay scheme information in ENSDF is now as complete as the measurements warrant, mostly based on the most recent *Nuclear Data Sheets*. Normalization information is included wherever available, and details of electron capture and internal conversion have been added systematically, so that complete tables of atomic and nuclear radiations can be assembled for approximately 1500 decay schemes. This information is being prepared for publication in microfiche form [11].

The ENSDF computer format has been adopted [4] as an international standard for the systematic storage and exchange of nuclear data. At six-month intervals, since 1977, NDP has prepared complete copies of ENSDF on magnetic tape for distribution through the (U. S.) National Nuclear Data Center at Brookhaven National Laboratory. This tape defines the current version of an International File of Evaluated Nuclear Structure and Decay Data.

B. Regular Revision of the ENSDF Data Base

At the 1977 meeting of the IAEA Advisory Group on Nuclear Structure and Decay Data [4] in Oak Ridge, the responsibility for periodic reevaluation of each mass chain was given to a specific evaluation center. The complete list of evaluation responsibilities is shown in Fig. 5. For the transactinium nuclei, responsibility is shared between the Nuclear Data Project and the Kurchatov Institute in Moscow.

Evaluation responsibilities were allocated with the intent of reaching and maintaining a four-year cycle. That is, every mass chain would be considered for revision at least every four years.

The current status of ENSDF in the transactinium region is based on the most recently published *Nuclear Data Sheets*, which is indicated by the histogram in Fig. 6. In response to special requests [6,7], the decay schemes for ^{208}Tl, ^{210}Pb, and ^{210}Bi were revised more recently (1977). The stated goal of a four-year cycle will be reached before the end of 1979, since revisions for all seven of the older mass chains are in preparation.

At present, the mechanism for updating ENSDF is by means of a complete revision of *Nuclear Data Sheets* for an entire mass chain. We have taken some liberties with older mass chains, where the evaluations were prepared by the Nuclear Data Project. The systematic addition of internal conversion coefficients, average beta energies, and detailed electron-capture ratios was recently completed for several hundred decay schemes, including many among the transactinides. Newer decay data have been incorporated into ENSDF for 380 decay schemes included in the data collections of Kocher [6] and Martin [7]. In general, however, a collection of data extracted from ENSDF will be only as up-to-date as the most recent *Nuclear Data Sheets*.

C. Special Evaluations and ENSDF

There may be little justification for more frequent review of all new nuclear measurements. For some groups of radionuclides (e.g., those isotopes used in medicine) or perhaps for specific data items (such as the ^{239}Pu half-life), a more frequent consideration of newer data could be desirable. Evaluations of particular kinds of data are sometimes prepared by special working groups, and there should also be a means of including these in the ENSDF system.

A file of supporting data for ENSDF (called the "working file") has been established to include measurements or evaluations that appear between regular revisions of the data base. Data sets for the working file are prepared in standard ENSDF format and can be processed with the same analysis or publication programs. The working file can provide alternatives or supplements to the International File of Evaluated Data as documented in *Nuclear Data Sheets.*

Procedures for incorporating important new information into the International File between the regular cycles are being developed by the evaluation network. Documentation of differences between the International File and the published *Nuclear Data Sheets* is especially important. The evaluator or evaluation center which is responsible for the affected mass chain must also accept any changes before ENSDF can be modified. The more frequent evaluation of those data which are especially important or rapidly changing would increase the quality and usefulness of the data base.

IV. USABLE OUTPUT FROM ENSDF

The standard output format from ENSDF is the same as the input. This format is convenient for making revisions or as input for a succeeding program. A number of data analysis programs have also been developed to operate on standard data sets: to identify and mark inconsistent data, to perform systematic theoretical calculations, or to reformat the data for easier use by a research worker.

Choosing a useful format for presenting the data retrieved from a data file is often as difficult as defining the retrieval. The potential user will often have special requirements (or prejudices?) about how the data should be organized and displayed. Unless the user's preferences are considered, the transfer of information from a data file to the user is seriously inhibited. He will often choose to reorganize the data again by hand, even though the recopying will surely introduce errors.

A general table-formatting program (NSDLIST) has been developed to accept standard ENSDF data sets and to prepare the separate tables of information which are needed to produce the journal *Nuclear Data Sheets.* The program will automatically separate each data set into groups of each kind of record contained in the data set. Each group of records is arranged according to increasing values of one or more data items on each record, and all accompanying information (including comments) is attached to the record in its proper place.

Although NDSLIST normally processes one data set at a time, this is not an essential restriction. A merge capability disables the isotope checking so that information from many data sets can be merged into a single table. The three appendices were prepared from ENSDF by the NDSLIST program. Appendix I displays all levels with $T_{1/2} \geq 1$ s in nuclei with $A \geq 207$. The table ordered by nucleus is helpful for checking the data, while the table ordered by half-life may be more useful in isotope identification.

Appendix II lists "strong" γ-rays from radioactive nuclei with $A \geq 207$. Only radiations with an absolute intensity of more than 1% have been included. Again, the different ordering of the same basic data can extend the usefulness of the tables in many directions. Appendix III gives similar tabular data for α-radiations from nuclei with $A \geq 207$.

If a user is interested in the total physical or biological consequences of radioactive decay, it is necessary to include atomic as well as nuclear radiations. A nuclear transition can cause vacancies in the electron shells. The refilling of the electron shells is accompanied by emission of characteristic X-rays and Auger electrons. A second program (MEDLIST) has been developed to combine the basic nuclear data from ENSDF with X-ray and Auger yield tables to prepare complete lists of radiations emitted by each radionuclide. A table of radiations prepared by MEDLIST is shown in Fig. 7. The γ-ray intensity normalization, the page layout, and the bookkeeping (intensity of omitted

weak radiations, etc.) have all been performed automatically. Note that radiations are grouped by type; X-rays included with nuclear γ-rays, Auger lines listed with conversion-electron lines. Several special collections of radioactivity data [5-7] have been prepared by MEDLIST.

The MEDLIST program also prepares a computer-readable file of card images which can be more easily used to make further calculations with the radiation data. This file of atomic and nuclear data radiations has been used [8,9] in reactor and accelerator calculations.

A third summary output from MEDLIST is illustrated in Fig. 8. This table lists the energy emitted as each radiation type and compares the sum with the available energy, i.e., the decay Q-value. Besides giving a gross survey of radiations, the table of energy sums also indicates how completely each decay scheme has been characterized. If the sum of radiated energy is substantially larger or smaller than the branching-adjusted Q-value, then further measurements are probably needed to provide better or more complete information.

A MEDLIST survey of 1500 radioactivity data sets from ENSDF has recently been completed [11]. Over 300 of these are for nuclei with $A > 208$.

V. SUMMARY

1. An Evaluated Nuclear Structure Data File (ENSDF) has been designed to contain most of the data of nuclear structure physics.

2. ENSDF includes adopted level information for all 1950 known nuclei. Detailed data are available for ~1500 decay schemes.

3. An international network of data evaluation centers has been organized to provide for a four-year cycle of ENSDF revisions.

4. Standard retrieval and display programs can prepare various tables of specific data, which can serve as a good first approximation to a complete up-to-date compilation.

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ENSDF Data Set Organization

1. Identification: "name", reference(s), date
2. General information: Q-values, normalization, radioactive parent, general comments, footnotes
3. Unplaced radiations
4. Nuclear level
   a) α-radiation to the level
   b) $\beta^{\pm}$-radiation, EC-decay to the level
   c) γ-radiation from the level
   d) Specific comments
5. END record (a blank card)

Fig. 1. Schematic organization for ENSDF data sets.

```
00284221  239PU    239NP B- DECAY                  NBS-MJM  77NDS                          770518
00284328  239PU    239PU(D,D')                     76TH01  77NDS                           770518
00284358  239PU    243CM A DECAY                     77NDS  WBE                             780201
00284490  239AM    ADOPTED LEVELS                    77NDS  WBE                             780210
00284517  239AM    239CM EC DECAY                  52CA42, 58VA37 77NDS                    770609
00284531  239AM    243BK A DECAY                     77NDS                                 770518
00284576  239CM    ADOPTED LEVELS                    77NDS                                 770518
00284588  239CM    243CF A DECAY                     77NDS                                 770518
00284605  239BK    ADOPTED LEVELS                    77NDS                                 770518
00284611  239BK    243ES A DECAY                     77NDS                                 770518
00284621  240U     ADOPTED LEVELS                    77NDS                                 760719
00284630  240U     238U(T,P)                       73BA72  77NDS                           760719
00284647  240U     244PU A DECAY                   73RYT1  76NDS  77NDS  WBE              780220
00284655  240NP    ADOPTED LEVELS                    77NDS                                 760810
00284677  240NP    240U B- DECAY                   69SC18  77NDS  WBE                     780201
00284693  240PU    ADOPTED LEVELS                    77NDS                                 760909
00284783  240PU    COUL. EX.                       73BE44,74MC15  77NDS                    760726
00284796  240PU    238U(A,2NG)                     72SP06  77NDS                           760812
00284833  240PU    239PU(D,P)                      73FR01  77NDS                           760719
00284845  240PU    239PU(N,G) E=TH                 75WEZA  77NDS                           760719
00284865  240PU    239PU(N,G) E=0.3-58 EV          70CHZR  77NDS                           760909
00284885  240PU    239PU(N,G) E=2 KEV              75WEZA,72OTZZ  77NDS                    760719
00284939  240PU    240AM EC DECAY                  72AH07,71LEZD  77NDS  WBE               771222
00285046  240PU    240NP B- DECAY (65 M)           67WA27,69SC18  77NDS  WBE               780201
00285107  240PU    240NP B- DECAY  (7.4 M)         70SC39,69SC18  77NDS  WBE               780201
00285287  240PU    240PU(D,D')                     75TH11  77NDS                           760719
00285323  240PU    240PU (N,N')                      77NDS                                 761028
00285332  240PU    242PU(P,T)                      72MA15  77NDS                           760719
00285345  240PU    244CM A DECAY (ALPHAS)          73RYT1,66BA07,60AS11,63DZ07  76NDS      760921
```

Fig. 2. A section of the ENSDF index to data sets.

```
236U     240PU A DECAY                    77NDS  WBE                          780201
240PU  P 0                              6537 Y    10              5255.96    16
236U   N 1.00      1            1
236U  CA E         FROM E(A) TO G.S. AND E(G)
236U  CA IA        FROM G+CE INTENSITY BALANCE
236U  C  XK=21E-5 2  71GUZY
236U  C  AG COIN  59TR37,68DU06,69LE05
236U  CG E         72SC01,75OTZX
236U  CG RI        75OTZX,71GUZY, OTHER 72CLZS
236U   L 0            0+
236U   A 5168.3       73.0    3  1
236U   L 45.24        2+                0.234 NS  6
236U  CL T         60BE25,70TO02
236U   A 5123         27.0    3  1.41
236U   G 45.242    6  0.0450 5  E2                      600
236U 2 G LC=437$MC=120$N+=39.7$
236U 2 G L2/L3=1.05 5, M2/M3=1.40 5  58SA21
236U 3 G L2/L3=1.15    M2/M3=1.10 E2 THEORY
236U   L 149.48       4+                0.142 NS  10
236U  CL T         70TO02
236U   A 5016.3       0.0842 13 96.6
236U   G 104.233   5  0.0070 1  E2                      11.2
236U   L 309.79       6+
236U   A 4853.2      0.00112913  610
236U   G 160.310   8  4.20E-44  E2                      1.8
236U   L 522.27       8+
236U   A 4637.1       4.7E-5 5  460
236U   G 212.46    5  2.9E-5 3 (E2)                    0.61
236U   L 687.57      (1-)
236U  CL J         2- ASSIGNMENT BASED ON CE DATA OF 69LE05 IS HARD TO RECONCILE
236U 2CL WITH 236U(D,D') OF 73BO27
236U   A 4469.0       2.0E-5 2  62
236U   G 538.09    15 1.47E-712
236U   G 642.33    10 1.3E-5 1 (E1+M2)                 0.15  2
236U  CG RI        RI RELATIVE TO 239PU G'S MEASURED BY 75DR05
236U   G 687.57    16 3.5E-6 2 (E1)                    0.31  3
236U   L 744          (3-)
236U   G 699          2.5E-8 LT                                                  S
236U   L 919.16      (0+)
236U   A 4233.5       6.3E-7 AP 27
236U  CA           ASSUMING TI(919)/TI(874G) AP 0.1 AS IN 0+ LEVEL OF 240PU
236U   G 873.92    15 5.8E-7 6
236U   G 919                 E0                                                 S
236U   L 958        (2+)
236U   G 958          1E-7   LT                                                 S
236U   L 960
236U   G 960          5E-8   LT                                                 S
236U   L 967.2
236U   G 967.         5E-8   LT                                                 S
```

Fig. 3. Standard ENSDF data set for ^{240}Pu α-decay.

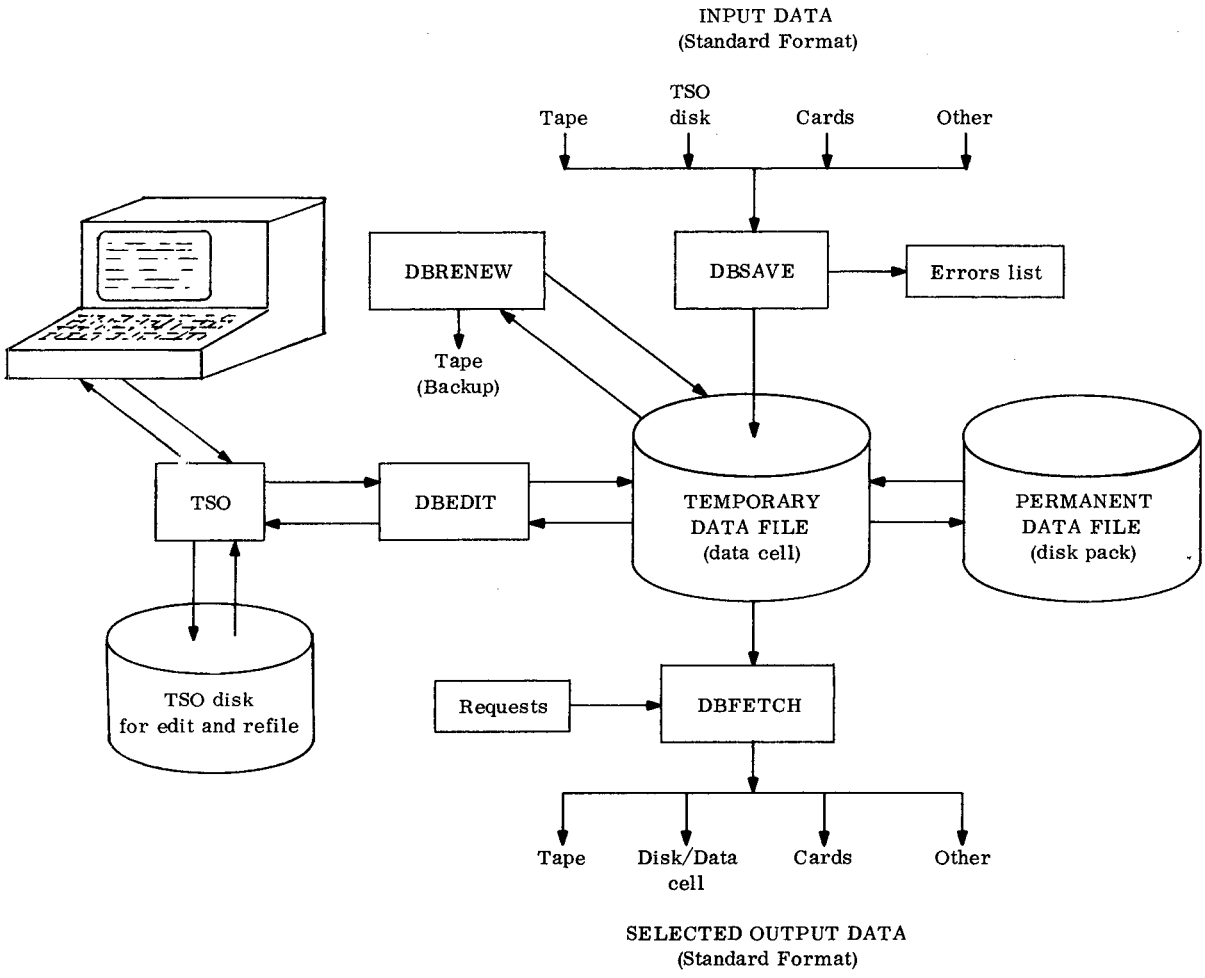

Fig. 4. Schematic diagram of ENSDF operations at ORNL.

A–Chain	Evaluation Center Responsible
1–4	USSR
5–20	US/University of Pennsylvania
21–44	NETHERLANDS/Utrecht
45–64	US/Nuclear Data Project
65–80	UK/Daresbury, includes Kuwait
81–100	FRG/Fachinformationszentrum
101–117	US/Nuclear Data Project, includes Sweden
118–129	JAPAN/Japan Atomic Energy Research Inst.
130–135	USSR
136–145	US/National Nuclear Data Center
146–152	US/Lawrence Berkeley Laboratory
153–162	US/Idaho National Engineering Laboratory
163–194	US/Lawrence Berkeley Laboratory
195–237	US/Nuclear Data Project
238, 240, 242, 244	USSR
239, 241, 243	US/Nuclear Data Project
245–∞	US/Nuclear Data Project

Fig. 5. Evaluation responsibilities established at the 1977 Meeting of the IAEA Advisory Group on Nuclear Structure and Decay Data [4].

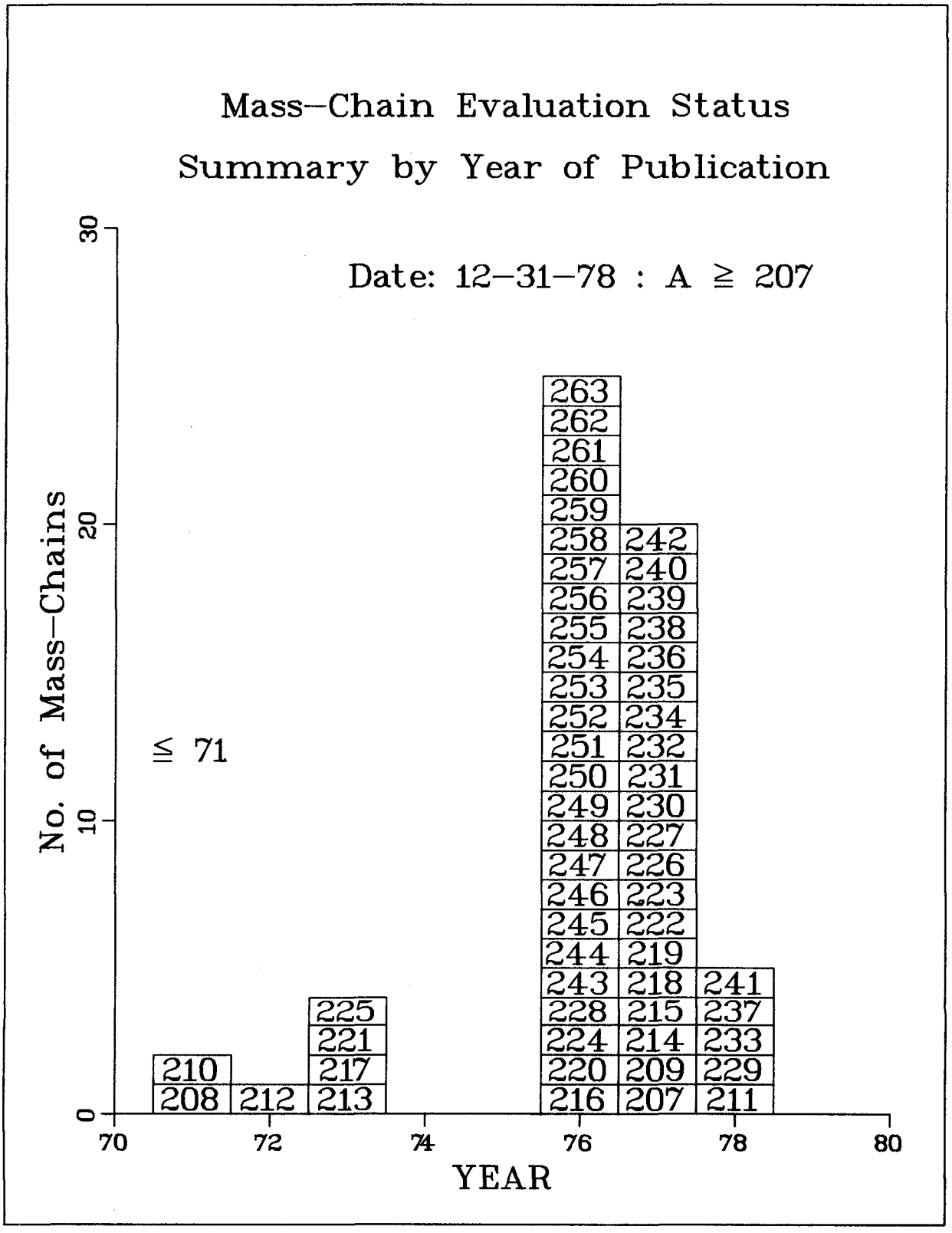

Fig. 6. Current status of ENSDF evaluations for A ⩾ 207.

240PU A DECAY (6537 Y 10) I(MIN) = 0.10%

Radiation Type	Energy (keV)	Intensity (%)	Δ(g-rad/μCi-h)
Auger-L	9.89	8.7 13	0.0018
ce-L-1	23.485 6	19.7 7	0.0098
ce-M-1	39.694 6	5.40 18	0.0046
ce-NOP-1	43.801 6	1.79 6	0.0017
α 1	5123	27.0 3	2.95
α 2	5168.3	73.0 3	8.04
5 weak α's omitted (ΣIα = 0.09%)			
X-ray L	13.6	11.0 13	0.0032
γ 1	45.242 6	0.0450 7	≈0
X-ray $K\alpha_2$	94.6650 20		≈0
X-ray $K\alpha_1$	98.4390 20		≈0
γ 2	104.233 5	0.0070 1	≈0
X-ray Kβ	111		≈0
γ 3	160.310 8	0.00042	≈0
γ 4	212.46 5	0.00002	≈0
γ 5	538.09 15	0.0000001	≈0
γ 6	642.33 10	0.00001	≈0
γ 7	687.57 16	0.000003	≈0
γ 8	699		≈0
γ 9	873.92 15	0.0000005	≈0
γ 10	919		≈0
γ 11	958		≈0
γ 12	960		≈0
γ 13	967		≈0

Fig. 7. Table of atomic and nuclear radiations prepared from ENSDF by the MEDLIST program.

DISTRIBUTION OF DECAY ENERGY AMONG RADIATION TYPES (ALL IN KEV)

DECAY AND DOCUMENTATION	(ENERGY) X (INTENSITY)							AVAILABLE ENERGY	
	ALPHA,RECOIL	BETA	CE,AUGER	PHOTON	ABSORBED	NEUTRINO	TOTAL	(BR)X(Q)	Q(DECAY)
237PU EC DECAY (45.3 D 2) /ENSDF/790323			8.1 8	53.5 22	61.6 24	146 15	208 7	218 6	218 6
237PU A DECAY (45.3 D 2) 78NDS/ENSDF/780616	0.2741				0.28		0.2 1	0.2 1	5747 6
237AM EC DECAY (73.0 M 10) /ENSDF/780323			62 4	366 15	428 15	1110 70	1538 15	1549.513	1550 SY
237AM A DECAY (73.0 M 10) 78NDS/ENSDF/780616	1.53				1.53		1.5 1	1.5 1	5200 SY
238U A DECAY (4.468 E 3) /ENSDF/780201	4266 4		8.4 8	12.5 15	4287 5		4287 5	4270 4	4270 4
238NP B- DECAY (2.117 D 2) /ENSDF/780205		224 7		547 13	771 14	478 13	1249 13	1291.9 11	1291.9 11
238PU A DECAY (87.74 Y 4) /ENSDF/780201	5580.9 1		8.3 2	1.6 1	5590.9 4		5590.9 3	5593.2 2	5593.2 2
238AM EC DECAY (98 M 2) /ENSDF/780205		0.7 5	21.3 21	890 50	920 50	1340 230	2250 60	2260 40	2260 40
239U B- DECAY (23.54 M 5) 77NDS/ENSDF/770518		390 60	11.2 7	58 4	460 60	820 110	1282 5	1267 3	1267 3
239NP B- DECAY (2.355 D 4) /ENSDF/770518		119 9	120 4	169 3	409 10	296 22	704 4	723.1 25	723.1 25
239PU A DECAY (24065 Y) 77NDS/ENSDF/770518	5235.6 6		5.2 1	0.7	5241.5 6		5241.5	5243.5 7	5243.5 7
239AM EC DECAY (11.9 H 1) /ENSDF/771221			142 6	242 8	384 10	440 50	819 9	804 4	804 4
239AM A DECAY (11.9 H 1) /ENSDF/771221	0.585				0.589		0.5	0.5	5924.0 20
240U B- DECAY (14.1 H 2) /ENSDF/780201		82 13	29.5 23	6.9 10	118 13	206 13	324 20	404 20	404 20
240NP B- DECAY (65 M 3) /ENSDF/780201		270		1190 80	1460 80	601.5	2070 80	2180	2180 LT
240NP B- DECAY (7.4 M 2) /ENSDF/780201		619 9	26 5	335 11	980 15	1151 15	2131 23	2178 20	2180 20
240PU A DECAY (6537 Y 10) /ENSDF/780201	5248		8.4 2	1.5 1	5257.7 3		5257.7 2	5255.9 1	5255.9 1
240AM EC DECAY (50.8 H 3) /ENSDF/771222			55 3	1030 40	1080 40	219 21	1300 50	1320 20	1320 20
240AM A DECAY (50.8 H 3) /ENSDF/771222									5670 SY

Fig. 8. Energy distribution among radiation types, prepared from ENSDF by the MEDLIST program.

APPENDIX I.A

NUCLEAR LEVELS WITH $T_{1/2} \geq 1$ s FOR $A \geq 207$

Ordered by A, Z of the Nucleus

nuclear levels from ENSDF: A≥207, $T_{1/2}$≥1 s: 31 March 1979

Nucleus	$T_{1/2}$	E(level)
^{207}Tl	1.33 s 11	1341 6
	4.77 m 2	0.0
^{207}Bi	38 y 3	0
^{207}Po	2.8 s 2	1383.4 2
	350 m 4	0
^{207}At	1.80 h 4	0
^{207}Rn	9.3 m 2	0
^{207}Fr	14.8 s 1	0
^{207}Ra	1.3 s 2	0
^{208}Tl	3.07 m 2	0.0
^{208}Bi	3.68×10^{5} y 4	0.0
^{208}Po	2.898 y 2	0.0
^{208}At	1.63 h 3	0.0
^{208}Rn	24.35 m 13	0.0
^{208}Fr	59.0 s 20	0.0
^{208}Ra	1.4 s 4	0.0
^{209}Tl	2.20 m 7	0.0
^{209}Pb	3.253 h 14	0.0
^{209}Po	102 y 5	0.0
^{209}At	5.41 h 5	0.0
^{209}Rn	28.5 m 10	0.0
^{209}Fr	50.0 s 3	0.0
^{209}Ra	4.6 s 2	0.0
^{210}Tl	1.30 m 3	0.0
^{210}Pb	22.3 y 2	0.0
^{210}Bi	5.012 d 9	0.0
	3.5×10^{6} y 2	268 1
^{210}Po	138.378 d 7	0.0
^{210}At	8.1 h 4	0.0
^{210}Rn	2.5 h 1	0.0
^{210}Fr	3.18 m 6	0.0
^{210}Ra	3.7 s 2	0.0
^{211}Pb	36.1 m 2	0.0
^{211}Bi	2.14 m 2	0.0
^{211}Po	25.2 s 6	1463 6
^{211}At	7.214 h 7	0.0
^{211}Rn	14.6 h 2	0.0
^{211}Fr	3.10 m 2	0.0
^{211}Ra	13 s 2	0.0
^{212}Pb	10.64 h 1	0
^{212}Bi	60.55 m 4	0
^{212}Po	45.1 s 6	2930
^{212}Rn	24 m 2	0
^{212}Fr	19.3 m 5	0
^{212}Ra	14 s 2	0
^{213}Pb	10.2 m 3	0
^{213}Bi	45.65 m 5	0
^{213}Fr	34.7 s 3	0
^{213}Ra	2.74 m 6	0
^{214}Pb	26.8 m	0.0
^{214}Bi	19.9 m 4	0.0
^{214}Ra	2.46 s 3	0.0
^{214}Ac	8.2 s 2	0.0
^{215}Bi	7.4 m 6	0.0
^{215}Th	1.2 s 2	0.0
^{217}Po	< 10 s	0
^{218}Po	3.05 m	0.0
^{218}At	≈ 2 s	0.0
^{219}At	0.9 m 1	0.0
^{219}Rn	3.96 s 1	0.0
^{220}Rn	55.6 s 1	0.0
^{220}Fr	27.4 s 3	0.0
^{221}Rn	25 m 2	
^{221}Fr	4.8 m 1	0.0
^{221}Ra	28 s 2	0.0
^{222}Rn	3.8235 d 3	0.0
^{222}Fr	14.4 m 4	0.0
^{222}Ra	38.0 s 5	0.0
^{222}Ac	4.2 s 5	0.0
	66 s 3	0.0 + X

Nucleus	$T_{1/2}$	E(level)
^{223}Rn	43 m 5	0.0
^{223}Fr	21.8 m 4	0.0
^{223}Ra	11.434 d 2	0
^{223}Ac	2.2 m 1	0.0
^{224}Rn	107 m 3	0.0
^{224}Fr	2.67 m 20	0.0
^{224}Ra	3.66 d 4	0.0
^{224}Ac	2.9 h 2	0.0
^{224}Th	1.04 s 5	0.0
^{225}Rn	4.5 m	
^{225}Fr	3.9 m	
^{225}Ra	14.8 d 2	0.0
^{225}Ac	10.0 d 1	0.0
^{225}Th	8.0 m 5	0.0
^{225}Pa	1.8 s 3	
^{226}Rn	6.0 m 5	0.0
^{226}Fr	48 s 1	0.0
^{226}Ra	1600 y 7	0.0
^{226}Ac	29 h	0.0
^{226}Th	30.9 m	0.0
^{226}Pa	1.8 m 2	0.0
^{227}Fr	2.4 m 2	0.0?
^{227}Ra	42.2 m 5	0.0
^{227}Ac	21.773 y 3	0.0
^{227}Th	18.718 d 5	0
^{227}Pa	38.3 m 3	0.0
^{227}U	1.1 m 3	0.0
^{227}Np	60 s 5	0.0?
^{228}Fr	39 s 1	0.0
^{228}Ra	5.75 y 3	0.0
^{228}Ac	6.13 h	0.0
^{228}Th	1.91313 y 88	0.0
^{228}Pa	22 h 1	0.0
^{229}Fr	50 s 20	0.0
^{229}Ra	4.0 m 2	0.0
^{229}Ac	62.7 m 5	0
^{229}Th	7340 y 160	0.0
^{229}Pa	1.4 d 4	0.0
^{229}U	58 m 3	0.0
^{229}Np	4.0 m 2	0.0
^{230}Ra	93 m 3	0.0
^{230}Ac	80 s 10	0.0
^{230}Th	7.7×10^{4} y 3	0.0
^{230}Pa	17.4 d 5	0.0
^{230}U	20.8 d	0.0
^{230}Np	4.6 m 3	0.0
^{231}Ac	7.5 m 1	0
^{231}Th	25.52 h 1	0
^{231}Pa	32760 y 110	0
^{231}U	4.2 d 1	0
^{231}Np	48.8 m 2	0
^{232}Ac	35 s 5	0
^{232}Th	14.05×10^{9} y 6	0
^{232}Pa	1.31 d 2	0
^{232}U	72 y 2	0
^{232}Np	14.7 m 3	0
^{232}Pu	34.1 m 7	0
^{232}Am	1.4 m 3	0?
^{233}Th	22.3 m 1	0.0
^{233}Pa	27.0 d 1	0.0
^{233}U	1.592×10^{5} y 2	0.0
^{233}Np	36.2 m 1	0.0
^{233}Pu	20.9 m 4	0.0
^{234}Th	24.10 d 3	0.0
^{234}Pa	1.17 m 3	73.92+X
	6.70 h 5	0.0
^{234}U	2.445×10^{5} y 10	0.0
^{234}Np	4.4 d 1	0.0
^{234}Pu	8.8 h 1	0.0
^{234}Am	2.6 m 2	0.0?

Continued on next page

nuclear levels from ENSDF: A≥207, $T_{1/2}$≥1 s: 31 March 1979 continued

Nucleus	$T_{1/2}$	E(level)
^{235}Th	6.9 m 2	0
^{235}Pa	24.1 m 2	0
^{235}U	≈ 25 m	0.073 5
	703.8×10^{6} y 5	0
^{235}Np	396.2 d 12	0
^{235}Pu	25.3 m 10	0
^{236}Th	37.1 m 15	0
^{236}Pa	9.1 m 2	0
^{236}U	2.3416×10^{7} y 39	0
^{236}Np	22.5 h 4	X+.1
	115000 y 12000	0
^{236}Pu	2.851 y 8	0
^{237}Pa	8.7 m 2	0.0
^{237}U	6.75 d 1	0.0
^{237}Np	2.14×10^{6} y 1	0.0
^{237}Pu	45.3 d 2	0.0
^{237}Am	73.0 m 10	0.0
^{238}Pa	2.3 m 1	0.0
^{238}U	4.468×10^{9} y 3	0.0
^{238}Np	2.117 d 2	0.0
^{238}Pu	87.74 y 4	0.0
^{238}Am	98 m 2	0.0
^{238}Cm	2.4 h 1	0.0
^{239}U	23.50 m 5	0
^{239}Np	2.355 d 4	0
^{239}Pu	24110 y 100	0
^{239}Am	11.9 h 1	0
^{239}Cm	≈ 3 h	0
^{240}U	14.1 h 2	0
^{240}Np	7.4 m 2	X+.1
	65 m 3	0
^{240}Pu	6537 y 10	0
^{240}Am	50.8 h 3	0
^{240}Cm	27 d 1	0
^{240}Cf	1.06 m 15	0
^{241}Np	16.0 m 2	0.0
	3.4 h	
^{241}Pu	14.4 y 2	0.0
^{241}Am	432.2 y 5	0.0
^{241}Cm	32.8 d 2	0.0
^{242}Pu	3.763×10^{5} y 20	0.0
^{242}Am	16.02 h 2	0.0
	152 y 7	48.63 5
^{242}Cm	162.8 d 4	0.0
^{242}Cf	3.68 m 44	0.0
^{243}Pu	4.956 h 3	0.0
^{243}Am	7380 y 40	0.0
^{243}Cm	28.5 y 2	0.0
^{243}Bk	4.5 h 2	0.0
^{243}Cf	10.7 m 5	0.0
^{243}Es	21 s 2	0.0
^{244}Pu	8.26×10^{7} y 9	0
^{244}Am	≈ 26 m	69 10
	10.1 h 1	0
^{244}Cm	18.11 y 2	0
^{244}Bk	4.35 h 15	0
^{244}Cf	19.4 m 6	0.0
^{244}Es	37 s 4	0
^{245}Pu	10.5 h 1	0.0
^{245}Am	2.05 h 1	0.0
^{245}Cm	8500 y 100	0.0
^{245}Bk	4.94 d 3	0.0
^{245}Cf	43.6 m 8	0.0
^{245}Es	1.33 m 15	0.0
^{245}Fm	4.2 s 13	0.0
^{246}Pu	10.85 d 2	0
^{246}Am	25.0 m 2	
^{246}Am	39 m 3	0
^{246}Cm	4730 y 100	0
^{246}Bk	1.83 d 15	0
^{246}Cf	35.7 h 5	0
^{246}Es	7.7 m 5	0
^{246}Fm	1.1 s 2	0
^{247}Am	22 m 3	0.0

Nucleus	$T_{1/2}$	E(level)
^{247}Cm	1.56×10^{7} y 5	0.0
^{247}Bk	1380 y 250	0.0
^{247}Cf	3.15 h 4	0.0
^{247}Es	4.8 m 3	0.0
^{247}Fm	9.2 s 23	0.0+y
	35 s 4	0.0
^{248}Cm	3.39×10^{5} y 3	0
^{248}Bk	18 h	
	> 9 y	
^{248}Cf	333.5 d 28	0
^{248}Es	27 m 4	0
^{248}Fm	36 s 3	0
^{248}Md	7 s 3	0
^{249}Cm	64.15 m 3	0
^{249}Bk	320 d 6	0.0
^{249}Cf	351 y 2	0
^{249}Es	1.7 h 1	0
^{249}Fm	2.6 m 7	0
^{249}Md	24 s 4	0
^{250}Cm	≈ 6900 y	0
^{250}Bk	3.222 h 5	0
^{250}Cf	13.08 y 9	0
^{250}Es	2.1 h 2	
	8.3 h 2	
^{250}Fm	1.8 s 1	1000 syst
	30 m 3	0
^{250}Md	52 s 6	0
^{251}Bk	57.0 m 17	0
^{251}Cf	898 y 44	0
^{251}Es	33 h 1	0
^{251}Fm	5.30 h 8	0.0
^{251}Md	4.0 m 5	0
^{252}Cm	< 2 d	
^{252}Cf	2.638 y 10	0
^{252}Es	350 d 50	0
^{252}Fm	22.7 h 7	0
^{252}Md	2.3 m 8	0
^{252}No	2.3 s 3	0
^{253}Cf	17.81 d 8	0
^{253}Es	20.47 d 3	0
^{253}Fm	3.00 d 12	0
^{253}No	1.7 m 3	0
^{254}Cf	60.5 d 2	0
^{254}Es	39.3 h 2	78 2
	275.7 d 5	0
^{254}Fm	3.240 h 2	0
^{254}Md	10 m 3	≈ 0
	28 m 8	≈ 0.0
^{254}No	55 s 5	0
^{255}Es	39.8 d 12	0
^{255}Fm	20.07 h 7	0
^{255}Md	27 m 2	0
^{255}No	3.1 m 2	0
^{255}Lr	22 s 5	0
^{255}104	≈ 4 s	0?
^{256}Es	28 m	
^{256}Fm	157.6 m 13	0
^{256}Md	76 m 4	0
^{256}No	3.3 s 2	0
^{256}Lr	31 s 3	0
^{257}Fm	100.5 d 2	0
^{257}Md	5.2 h 5	0
^{257}No	25 s 2	0
^{257}104	4.8 s 3	0
^{258}Md	55 d 4	0
^{258}Lr	4.2 s 6	0
^{259}No	58 m 5	0
^{259}Lr	5.4 s 8	0
^{259}104	3.2 s 8	0
^{260}Lr	180 s 30	0
^{260}105	1.6 s 3	0
^{261}104	65 s 10	0
^{261}105	1.8 s 4	0
^{262}105	40 s 10	0

APPENDIX I.B

NUCLEAR LEVELS WITH $T_{1/2} \geq 1$ s FOR $A \geq 207$

Ordered by $T_{1/2}$

I.B.2

nuclear levels from ENSDF: A≥207, $T_{1/2}$≥1 s: 31 March 1979

$T_{1/2}$	Nucleus	$T_{1/2}$	Nucleus
1.04 s 5	^{224}Th	2.20 m 7	^{209}Tl
1.1 s 2	^{246}Fm	2.2 m 1	^{223}Ac
1.17 m 3	^{234}Pa	2.3 m 1	^{238}Pa
1.2 s 2	^{215}Th	2.3 m 8	^{252}Md
1.3 s 2	^{207}Ra	2.4 m 2	^{227}Fr
1.33 s 11	^{207}Tl	2.6 m 2	^{234}Am
1.4 s 4	^{208}Ra	2.6 m 7	^{249}Fm
1.6 s 3	^{260}105	2.67 m 20	^{224}Fr
1.8 s 3	^{225}Pa	2.74 m 6	^{213}Ra
1.8 s 1	^{250}Fm	180 s 30	^{260}Lr
1.8 s 4	^{261}105	3.07 m 2	^{208}Tl
≈ 2 s	^{218}At	3.10 m 2	^{211}Fr
2.3 s 3	^{252}No	3.05 m	^{218}Po
2.46 s 3	^{214}Ra	3.1 m 2	^{255}No
2.8 s 2	^{207}Po	3.18 m 6	^{210}Fr
3.2 s 8	^{259}104	3.68 m 44	^{242}Cf
3.3 s 2	^{256}No	3.9 m	^{225}Fr
3.7 s 2	^{210}Ra	4.0 m 2	^{229}Ra
3.96 s 1	^{219}Rn	4.0 m 2	^{229}Np
≈ 4 s	^{255}104	4.0 m 5	^{251}Md
4.2 s 5	^{222}Ac	4.5 m	^{225}Rn
4.2 s 13	^{245}Fm	4.6 m 3	^{230}Np
4.2 s 6	^{258}Lr	4.77 m 2	^{207}Tl
4.6 s 2	^{209}Ra	4.8 m 1	^{221}Fr
4.8 s 3	^{257}104	4.8 m 3	^{247}Es
5.4 s 8	^{259}Lr	6.0 m 5	^{226}Rn
7 s 3	^{248}Md	6.9 m 2	^{235}Th
8.2 s 2	^{214}Ac	7.4 m 6	^{215}Bi
9.2 s 23	^{247}Fm	7.4 m 2	^{240}Np
< 10 s	^{217}Po	7.5 m 1	^{231}Ac
13 s 2	^{211}Ra	7.7 m 5	^{246}Es
14 s 2	^{212}Ra	8.0 m 5	^{225}Th
14.8 s 1	^{207}Fr	8.7 m 2	^{237}Pa
21 s 2	^{243}Es	9.1 m 2	^{236}Pa
22 s 5	^{255}Lr	9.3 m 2	^{207}Rn
24 s 4	^{249}Md	10 m 3	^{254}Md
25 s 2	^{257}No	10.2 m 3	^{213}Pb
25.2 s 6	^{211}Po	10.7 m 5	^{243}Cf
27.4 s 3	^{220}Fr	14.4 m 4	^{222}Fr
28 s 2	^{221}Ra	14.7 m 3	^{232}Np
31 s 3	^{256}Lr	16.0 m 2	^{241}Np
34.7 s 3	^{213}Fr	19.3 m 5	^{212}Fr
35 s 5	^{232}Ac	19.4 m 6	^{244}Cf
35 s 4	^{247}Fm	19.9 m 4	^{214}Bi
36 s 3	^{248}Fm	20.9 m 4	^{233}Pu
37 s 4	^{244}Es	21.8 m 4	^{223}Fr
38.0 s 5	^{222}Ra	22.3 m 1	^{233}Th
39 s 1	^{226}Fr	22 m 3	^{247}Am
40 s 10	^{262}105	23.50 m 5	^{239}U
45.1 s 6	^{212}Po	24 m 2	^{212}Rn
48 s 1	^{226}Fr	24.35 m 13	^{208}Rn
50.0 s 3	^{209}Fr	24.1 m 2	^{235}Pa
50 s 20	^{229}Fr	25 m 2	^{221}Rn
52 s 6	^{250}Md	≈ 25 m	^{235}U
0.9 m 1	^{219}At	25.0 m 2	^{246}Am
55.6 s 1	^{220}Rn	25.3 m 10	^{235}Pu
55 s 5	^{254}No	≈ 26 m	^{244}Am
59.0 s 20	^{208}Fr	26.8 m	^{214}Pb
60 s 5	^{227}Np	27 m 4	^{246}Es
1.06 m 15	^{240}Cf	27 m 2	^{255}Md
66 s 3	^{222}Ac	28 m 8	^{254}Md
1.1 m 3	^{227}U	28 m	^{256}Es
65 s 10	^{261}104	28.5 m 10	^{209}Rn
1.30 m 3	^{210}Tl	30 m 3	^{250}Fm
80 s 10	^{230}Ac	30.9 m	^{226}Th
1.33 m 15	^{245}Es	34.1 m 7	^{232}Pu
1.4 m 3	^{232}Am	36.1 m 2	^{211}Pb
1.7 m 3	^{253}No	36.2 m 1	^{233}Np
1.8 m 2	^{226}Pa	37.1 m 15	^{236}Th
2.14 m 2	^{211}Bi	38.3 m 3	^{227}Pa

Continued on next page

nuclear levels from ENSDF: A≥207, $T_{1/2}$≥1 s: 31 March 1979 continued

$T_{1/2}$	Nucleus
39 m 3	^{246}Am
42.2 m 5	^{227}Ra
43 m 5	^{223}Rn
43.6 m 8	^{245}Cf
45.65 m 5	^{213}Bi
48.8 m 2	^{231}Np
57.0 m 17	^{251}Bk
58 m 3	^{229}U
58 m 5	^{259}No
60.55 m 4	^{212}Bi
62.7 m 5	^{229}Ac
64.15 m 3	^{249}Cm
65 m 3	^{240}Np
73.0 m 10	^{237}Am
76 m 4	^{256}Md
93 m 3	^{230}Ra
1.63 h 3	^{208}At
98 m 2	^{238}Am
1.7 h 1	^{249}Es
107 m 3	^{224}Rn
1.80 h 4	^{207}At
2.05 h 1	^{245}Am
2.1 h 2	^{250}Es
2.4 h 1	^{238}Cm
2.5 h 1	^{210}Rn
157.6 m 13	^{256}Fm
2.9 h 2	^{224}Ac
≈ 3 h	^{239}Cm
3.15 h 4	^{247}Cf
3.253 h 14	^{209}Pb
3.222 h 5	^{250}Bk
3.240 h 2	^{254}Fm
3.4 h	^{241}Np
4.35 h 15	^{244}Bk
4.5 h 2	^{243}Bk
4.956 h 3	^{243}Pu
5.2 h 5	^{257}Md
5.41 h 5	^{209}At
5.30 h 8	^{251}Fm
350 m 4	^{207}Po
6.13 h	^{228}Ac
6.70 h 5	^{234}Pa
7.214 h 7	^{211}At
8.1 h 4	^{210}At
8.3 h 2	^{250}Es
8.8 h 1	^{234}Pu
10.1 h 1	^{244}Am
10.5 h 1	^{245}Pu
10.64 h 1	^{212}Pb
11.9 h 1	^{239}Am
14.1 h 2	^{240}U
14.6 h 2	^{211}Rn
16.02 h 2	^{242}Am
18 h	^{248}Bk
20.07 h 7	^{255}Fm
22 h 1	^{228}Pa
22.5 h 4	^{236}Np
22.7 h 7	^{252}Fm
25.52 h 1	^{231}Th
29 h	^{226}Ac
1.31 d 2	^{232}Pa
33 h 1	^{251}Es
1.4 d 4	^{229}Pa
35.7 h 5	^{246}Cf
39.3 h 2	^{254}Es
1.83 d 15	^{246}Bk
< 2 d	^{252}Cm
2.117 d 2	^{238}Np
50.8 h 3	^{240}Am
2.355 d 4	^{239}Np
3.00 d 12	^{253}Fm
3.66 d 4	^{224}Ra
3.8235 d 3	^{222}Rn
4.2 d 1	^{231}U

$T_{1/2}$	Nucleus
4.4 d 1	^{234}Np
5.012 d 9	^{210}Bi
4.94 d 3	^{245}Bk
6.75 d 1	^{237}U
10.0 d 1	^{225}Ac
10.85 d 2	^{246}Pu
11.434 d 2	^{223}Ra
14.8 d 2	^{225}Ra
17.4 d 5	^{230}Pa
17.81 d 8	^{253}Cf
18.718 d 5	^{227}Th
20.47 d 3	^{253}Es
20.8 d	^{230}U
24.10 d 3	^{234}Th
27.0 d 1	^{233}Pa
27 d 1	^{240}Cm
32.8 d 2	^{241}Cm
39.8 d 12	^{255}Es
45.3 d 2	^{237}Pu
55 d 4	^{258}Md
60.5 d 2	^{254}Cf
100.5 d 2	^{257}Fm
138.378 d 7	^{210}Po
162.8 d 4	^{242}Cm
275.7 d 5	^{254}Es
320 d 6	^{249}Bk
333.5 d 28	^{248}Cf
350 d 50	^{252}Es
396.2 d 12	^{235}Np
1.91313 y 88	^{229}Th
2.638 y 10	^{252}Cf
2.851 y 8	^{236}Pu
2.898 y 2	^{208}Po
5.75 y 3	^{228}Ra
> 9 y	^{248}Bk
13.08 y 9	^{250}Cf
14.4 y 2	^{241}Pu
18.11 y 2	^{244}Cm
21.773 y 3	^{227}Ac
22.3 y 2	^{210}Pb
28.5 y 2	^{243}Cm
38 y 3	^{207}Bi
72 y 2	^{232}U
87.74 y 4	^{238}Pu
102 y 5	^{209}Po
152 y 7	^{242}Am
351 y 2	^{249}Cf
432.2 y 5	^{241}Am
898 y 44	^{251}Cf
1380 y 250	^{247}Bk
1600 y 7	^{226}Ra
4730 y 100	^{246}Cm
6537 y 10	^{240}Pu
≈ 6900 y	^{250}Cm
7340 y 160	^{229}Th
7380 y 40	^{243}Am
8500 y 100	^{245}Cm
24110 y 100	^{239}Pu
32760 y 110	^{231}Pa
7.7×10^{4} y 3	^{230}Th
115000 y 12000	^{236}Np
1.592×10^{5} y 2	^{233}U
2.445×10^{5} y 10	^{234}U
3.39×10^{5} y 3	^{248}Cm
3.68×10^{5} y 4	^{208}Bi
3.763×10^{5} y 20	^{242}Pu
2.14×10^{6} y 1	^{237}Np
3.5×10^{6} y 2	^{210}Bi
1.56×10^{7} y 5	^{247}Cm
2.3416×10^{7} y 39	^{236}U
8.26×10^{7} y 9	^{244}Pu
703.8×10^{6} y 5	^{235}U
4.468×10^{9} y 3	^{238}U
14.05×10^{9} y 6	^{232}Th

APPENDIX II.A

STRONG γ-RADIATIONS ($I_\gamma \geq 1\%$) FROM RADIOACTIVITY, $A \geq 207$

Ordered by Z, A of Parent Nucleus

II.A.2

strong γ-rays (Iγ≥1%) from nuclei with A>208. From ENSDF: 31 March 1979

Parent	Eγ	Iγ	Parent T1/2
^{206}Hg	304.8	27	8.15 m 10
	649.5	2.3	8.15 m 10
^{208}Tl	277.35 6	6.79 30	3.07 m 2
	510.80 8	21.6 9	3.07 m 2
	583.14 20	85.8 20	3.07 m 2
	763.13 8	1.64 9	3.07 m 2
	860.37 8	12.0 4	3.07 m 2
	2614.6 1	99.790	3.07 m 2
^{209}Tl	117 1	81 13	2.20 m 7
	467 2	81 13	2.20 m 7
	1566 4	98 13	2.20 m 7
^{209}At	90.8 1	1.84 20	5.41 h 5
	104.2 1	2.4 4	5.41 h 5
	195.0 1	22.6 10	5.41 h 5
	233.6 1	0.96 6	5.41 h 5
	239.1 1	12.4 5	5.41 h 5
	545.0 1	91.0	5.41 h 5
	551.0 1	4.91 18	5.41 h 5
	552.5 2	1.55 18	5.41 h 5
	666.1 1	1.87 6	5.41 h 5
	781.9 1	83.5 22	5.41 h 5
	790.2 1	63.5 18	5.41 h 5
	863.9 1	2.07 8	5.41 h 5
	903.0 1	3.65 10	5.41 h 5
	1103.4 1	5.40 17	5.41 h 5
	1147.6 1	1.36 9	5.41 h 5
	1170.6 1	3.09 9	5.41 h 5
	1175.3 1	1.91 9	5.41 h 5
	1217.2 1	1.11 5	5.41 h 5
	1262.6 1	1.89 6	5.41 h 5
	1581.6 1	1.79 6	5.41 h 5
^{209}Rn	279.20 10	1.12 12	28.5 m 10
	337.45 4	14.7 6	28.5 m 10
	386.43	≤ 2.1	28.5 m 10
	386.43	≤ 2.1	28.5 m 10
	408.32 4	51.0 21	28.5 m 10
	461.41 7	1.46 9	28.5 m 10
	577.10 8	0.99 7	28.5 m 10
	672.82 4	3.32 14	28.5 m 10
	684.90 10	1.18 15	28.5 m 10
	689.26 5	9.8 4	28.5 m 10
	745.78 4	23.1 9	28.5 m 10
	794.72 7	3.41 25	28.5 m 10
	855.76 5	4.94 29	28.5 m 10
	1037.93 6	4.22 25	28.5 m 10
	1054.53 7	1.6 1	28.5 m 10
	*1065.55 7	1.7 1	28.5 m 10
	1394.42 9	0.99 5	28.5 m 10
^{210}Pb	46.503 15	4.05 8	22.3 y 2
^{210}Bi	265.7 2	51.0 26	3.0×10^6 y 1
	304.8 3	27.5 15	3.0×10^6 y 1
	649.8 10	2.86 15	3.0×10^6 y 1
^{211}Pb	404.84 4	3.83 11	36.1 m 2
	426.99 4	1.72 8	36.1 m 2
	831.83 4	3.81 11	36.1 m 2
^{211}Bi	351.0 1	12.76 20	2.14 m 2
^{211}Rn	168.7 1	6.8 4	14.6 h 2
	250.2 1	6.1 4	14.6 h 2
	370.5 1	1.38 10	14.6 h 2
	416.4 1	3.54 21	14.6 h 2
	442.2 1	23.4 15	14.6 h 2
	674.1 1	46.0	14.6 h 2
	678.4 1	29.4 16	14.6 h 2
	853.4 1	4.69 27	14.6 h 2
	866.0 1	8.0 5	14.6 h 2
	934.7 1	3.72 21	14.6 h 2
	946.7 1	5.1 14	14.6 h 2
	947.4 1	16.5 19	14.6 h 2
	992.5	≈ 1.4	14.6 h 2
	1126.7 1	22.5 15	14.6 h 2
	1181.3 1	1.47 10	14.6 h 2
	1362.9 1	33.1 21	14.6 h 2
^{211}Rn	1538.8 2	4.8 5	14.6 h 2
^{212}Pb	238.626 5	44.6 10	10.64 h 1
	300.09 2	3.4 1	10.64 h 1
^{212}Bi	39.857 5	1.088 15	60.55 m 4
	727.17 4	11.83 26	60.55 m 4
	785.42 6	1.99 7	60.55 m 4
	1078.62 10	0.97 5	60.55 m 4
	1620.56 7	2.7 1	60.55 m 4
^{213}Bi	439.7 4	27.3 24	45.65 m 5
^{214}Pb	53.226 14	1.10 5	26.8 m
	241.91 3	7.46 16	26.8 m
	295.17 2	19.2 4	26.8 m
	351.900 28	37.1 8	26.8 m
	785.910 20	1.09 4	26.8 m
^{214}Bi	609.318 20	46	19.9 m 4
	665.453 22	1.56 6	19.9 m 4
	768.361 18	4.88 12	19.9 m 4
	806.174 18	1.23 4	19.9 m 4
	934.052 20	3.16 8	19.9 m 4
	1120.276 22	15.0 4	19.9 m 4
	1155.19 2	1.69 6	19.9 m 4
	1238.11 3	5.92 12	19.9 m 4
	1280.96 2	1.47 6	19.9 m 4
	1377.65 3	4.02 11	19.9 m 4
	1401.50 4	1.39 5	19.9 m 4
	1407.98 4	2.48 6	19.9 m 4
	1509.19 4	2.19 7	19.9 m 4
	1661.28 6	1.15 4	19.9 m 4
	1729.60 5	3.05 8	19.9 m 4
	1764.51 5	15.9 4	19.9 m 4
	1847.44 5	2.12 8	19.9 m 4
	2118.54 8	1.21 4	19.9 m 4
	2204.12 7	4.99 12	19.9 m 4
	2447.71 10	1.55 3	19.9 m 4
^{219}Rn	271.23 5	9.9 11	3.96 s 1
	401.78 8	6.6 4	3.96 s 1
^{220}Fr	45	2.3	27.4 s 3
	106	1.7	27.4 s 3
	154	1	27.4 s 3
	161.5	1.5	27.4 s 3
^{220}Ra	465 4	1	23 ms 5
^{221}Fr	217.6 2	12.5 4	4.8 m 1
^{222}Ra	324.22 5	2.77 8	38.0 s 5
^{223}Fr	50.2 10	≈ 34	21.8 m 4
	79.77 6	9.2 14	21.8 m 4
	100.3 1	≤ 1.0	21.8 m 4
	205.0 1	0.95 24	21.8 m 4
	234.9 2	3.4	21.8 m 4
^{223}Ra	122.31 6	1.19 2	11.434 d 2
	144.20 4	3.26 7	11.434 d 2
	154.19 3	5.59 10	11.434 d 2
	269.41 3	13.6 3	11.434 d 2
	323.89 4	3.90 9	11.434 d 2
	338.32 6	2.78 7	11.434 d 2
	444.94 5	1.27 6	11.434 d 2
^{224}Ra	241.0 1	3.9 11	3.66 d 4
^{224}Ac	133	19.71	2.9 h 2
	217	44	2.9 h 2
^{224}Th	177 2	9 2	1.04 s 5
^{225}Ra	40.0 10	29	14.8 d 2
^{225}Ac	99.7 1	3.5 19	10.0 d 1
^{226}Ra	185.99 4	3.28 3	1600 y 7
^{226}Ac	158.05 15	17.3 18	29 h
	185.60 15	4.7 7	29 h
	230.00 10	26.7	29 h
	253.5 2	5.6 9	29 h
^{226}Th	111.12 3	3.29 20	30.9 m
^{227}Ra	27.36 1	17.4	42.2 m 5
	258.40 10	2.0	42.2 m 5
	273.16 8	0.96	42.2 m 5
	277.39 10	2.9	42.2 m 5
	283.67 6	3.4	42.2 m 5

Continued on next page (footnotes at end of table)

strong γ-rays (Iγ≥1%) from nuclei with A>208. From ENSDF: 31 March 1979 continued

Parent	Eγ	Iγ	Parent T1/2
^{227}Ra	300.08 6	5.1	42.2 m 5
	302.67 6	4.8	42.2 m 5
	330.07 6	3.0	42.2 m 5
	407.97 6	2.4	42.2 m 5
	486.98 10	2.5	42.2 m 5
	501.4 1	1.05	42.2 m 5
	516.2 2	1.5	42.2 m 5
	611.4 2	1.3	42.2 m 5
^{227}Th	50.20 10	8.5 3	18.718 d 5
	79.77 6	2.1 1	18.718 d 5
	94.00 6	1.40 12	18.718 d 5
	210.65 8	1.13 8	18.718 d 5
	236.00 8	11.2 6	18.718 d 5
	256.25 5	6.8 5	18.718 d 5
	286.15 6	1.58 5	18.718 d 5
	299.90 10	2.0 2	18.718 d 5
	304.44 13	1.05 13	18.718 d 5
	329.82 10	2.75 16	18.718 d 5
	334.40 14	1.0 1	18.718 d 5
^{227}Pa	≈ 50	< 1.7	38.3 m 3
	65	5.3	38.3 m 3
	67	1.0	38.3 m 3
	110	1.7	38.3 m 3
^{228}Ac	99.45 8	1.4 6	6.13 h
	129.1 3	2 1	6.13 h
	154.2 3	1.0 3	6.13 h
	209.4 3	4.6 15	6.13 h
	270.3 3	3.8 9	6.13 h
	328.0 3	3.4 8	6.13 h
	338.4 3	12.0 29	6.13 h
	409.4 5	2.2 4	6.13 h
	463.0 3	4.6 8	6.13 h
	562.3 5	0.99 20	6.13 h
	755.2 5	1.10 23	6.13 h
	772.1 5	1.6 3	6.13 h
	794.8 3	4.8 8	6.13 h
	835.6 5	1.8 3	6.13 h
	840.2 5	0.99 17	6.13 h
	911.07 3	29	6.13 h
	964.6 5	5.5 9	6.13 h
	968.9 5	17.5 30	6.13 h
	1459.2 5	1.04 21	6.13 h
	1495.8 5	1.05 18	6.13 h
	1587.9 4	3.7 8	6.13 h
	1630.4 4	1.95 27	6.13 h
^{228}Th	84.40 5	1.2 4	1.9131 y 9
^{228}Pa	129.22 10	2.85 15	22 h 1
	209.28 10	1.67 15	22 h 1
	270.23 10	2.10 10	22 h 1
	281.87 10	1.23 7	22 h 1
	327.64 10	≈ 2.1	22 h 1
	327.64 10	≈ 1.9	22 h 1
	332.36 10	1.57 14	22 h 1
	338.32 10	5.10 30	22 h 1
	341.1 3	1.54 12	22 h 1
	409.51 10	6.0	22 h 1
	463.00 10	13.2 6	22 h 1
	581.4 2	1.02 24	22 h 1
	755.18 10	1.26 8	22 h 1
	772.17 10	1.19 7	22 h 1
	794.7 2	2.00 9	22 h 1
	830.5 3	1.9 1	22 h 1
	835.5 3	2.72 14	22 h 1
	840.0 4	1.02 6	22 h 1
	870.1 4	1.06 6	22 h 1
	894.3 5	2.6 9	22 h 1
	904.5 3	2.88 24	22 h 1
	911.23 10	16.0 7	22 h 1
	×945.6 8	1.8 6	22 h 1
	964.6 3	10.1 12	22 h 1
	969.11 10	13.2 24	22 h 1
	975.0 3	1.56 9	22 h 1
	1588.0 2	2.43 11	22 h 1
^{228}Pa	1887.0 2	1.56 9	22 h 1
^{229}Th	31.3 2	4.1	7340 y 160
	86.44 5	(3.1)	7340 y 160
	124.5 1	(1.2)	7340 y 160
	137.03 6	1.6	7340 y 160
	148.3 2	(1.4)	7340 y 160
	156.48 4	(1.1)	7340 y 160
	193.63 6	4.6	7340 y 160
	210.97 10	3.3	7340 y 160
^{230}Pa	397.8 2	1.82 16	17.4 d 5
	443.75 5	5.3 5	17.4 d 5
	454.95 5	6.1 4	17.4 d 5
	508.20 5	3.47 29	17.4 d 5
	518.50 10	1.92 17	17.4 d 5
	571.10 10	1.05 9	17.4 d 5
	728.23 7	1.84 15	17.4 d 5
	781.35 5	1.44 11	17.4 d 5
	898.65 10	5.7 5	17.4 d 5
	918.50 10	8.0 7	17.4 d 5
	951.95 10	28.3 20	17.4 d 5
	956.3 3	1.55 29	17.4 d 5
	1009.6 2	1.05 9	17.4 d 5
	1026.05 10	1.42 12	17.4 d 5
^{231}Th	25.64 2	14.8 10	25.52 h 1
	84.21 2	6.5 4	25.52 h 1
^{231}Pa	27.36 1	9	3.276×10^4 y 11
	283.67 6	1.6 3	3.276×10^4 y 11
	300.08 6	2.3 5	3.276×10^4 y 11
	302.67 6	2.3 5	3.276×10^4 y 11
	302.67 6	2.3 5	3.276×10^4 y 11
	330.07	1.3 3	3.276×10^4 y 11
^{231}U	25.64	12	4.2 d 1
	84.18	7	4.2 d 1
^{231}Np	×263.8 3	2.84 10	48.8 m 2
	×348.4 3	3.63 20	48.8 m 2
	370.9 3	9.8	48.8 m 2
	420.7 4	1.05 11	48.8 m 2
	×484.7 5	1.6 3	48.8 m 2
	737.8 3	1.23 7	48.8 m 2
^{232}Pa	105.47 5	1.65 19	1.31 d
	108.96 5	2.81 29	1.31 d
	150.1 1	10.8 5	1.31 d
	183.9 1	1.26 29	1.31 d
	387.9 1	6.97 29	1.31 d
	421.9 2	2.52 19	1.31 d
	453.6 1	8.62 20	1.31 d
	472.4 1	4.16 19	1.31 d
	515.6 1	5.52 20	1.31 d
	563.2 1	3.68 19	1.31 d
	581.5 1	6.00 29	1.31 d
	819.2 2	7.45 10	1.31 d
	864.0 5	1.94 19	1.31 d
	867.0 3	5.81 20	1.31 d
	894.3 1	19.8 3	1.31 d
	969.3 1	41.6 19	1.31 d
^{232}Np	223.6 4	2.24 27	14.7 m 3
	282.0 4	19.8 22	14.7 m 3
	327.3 3	52	14.7 m 3
	×377.0 3	1.25 16	14.7 m 3
	755.0 4	4.2 5	14.7 m 3
	814.8 4	4.1 5	14.7 m 3
	819.5 4	33 4	14.7 m 3
	864.3 5	20.3 22	14.7 m 3
	867.2 6	24.4 28	14.7 m 3
	941.6 4	1.6 3	14.7 m 3
	1037.4 5	3.3 4	14.7 m 3
	1085.4 4	0.99 11	14.7 m 3
	1126.0 4	1.46 21	14.7 m 3
^{233}Th	29.36 4	2.5	22.3 m 1
	86.50 5	2.7	22.3 m 1
	459.2 2	1.4	22.3 m 1
^{233}Pa	75.28 1	1.1 1	27.0 d 1
	86.59 1	1.76 24	27.0 d 1

Continued on next page (footnotes at end of table)

strong γ-rays (Iγ≥1%) from nuclei with A>208. From ENSDF: 31 March 1979 continued

Parent	Eγ	Iγ	Parent T1/2
^{233}Pa	300.12 3	6.2 4	27.0 d 1
	311.98 3	36	27.0 d 1
	340.50 4	4.2 5	27.0 d 1
	398.62 8	1.19 16	27.0 d 1
	415.76 4	1.51 17	27.0 d 1
^{234}Th	63.29 2	(3.8)	24.10 d 3
	92.38 1	2.72 21	24.10 d 3
	92.80 2	2.69 21	24.10 d 3
^{234}Pa	63.0 2	3.2 2	6.70 h 5
	125.4 3	1.0 3	6.70 h 5
	131.2 2	20.0	6.70 h 5
	152.7 1	6.7 5	6.70 h 5
	186.0 2	2.0 3	6.70 h 5
	200.6 3	1.1 3	6.70 h 5
	203.0 3	1.2 2	6.70 h 5
	226.4 4	5.9	6.70 h 5
	227.2 2	5.5	6.70 h 5
	248.9 2	2.8 3	6.70 h 5
	272.1 2	1.0	6.70 h 5
	293.7 3	3.9 3	6.70 h 5
	369.8 4	2.9 3	6.70 h 5
	372.4 4	1.3 2	6.70 h 5
	458.8 3	1.5 1	6.70 h 5
	506.8 5	1.6 3	6.70 h 5
	513.7 5	1.3 2	6.70 h 5
	565.9 10	1.4 3	6.70 h 5
	568.7 5	3.0	6.70 h 5
	569.5 5	10.7	6.70 h 5
	574 1	≈ 2	6.70 h 5
	x664.8 10	1.3 4	6.70 h 5
	666.7 6	1.6 4	6.70 h 5
	669.9 5	1.4 4	6.70 h 5
	692.7 5	1.5 5	6.70 h 5
	699.0 5	4.6 3	6.70 h 5
	706.1 3	3.1 6	6.70 h 5
	733.0 5	8.6 8	6.70 h 5
	738.0 8	1.0 4	6.70 h 5
	742.81 3	2.4 7	6.70 h 5
	755.6 10	1.4 7	6.70 h 5
	780.7 6	1.1 4	6.70 h 5
	786.27 3	1.4 4	6.70 h 5
	x793.6 10	1.5	6.70 h 5
	796.3 5	3.8 5	6.70 h 5
	805.8 5	3.3 5	6.70 h 5
	819.6 6	2.6 5	6.70 h 5
	x824.0 8	< 1.5	6.70 h 5
	826.3 6	4.0 8	6.70 h 5
	831.6 8	5.5 7	6.70 h 5
	876.4 8	4 2	6.70 h 5
	880.5	4	6.70 h 5
	880.51 4	9	6.70 h 5
	883.24 4	12 4	6.70 h 5
	899.0 5	4.1 8	6.70 h 5
	925 1	2.9	6.70 h 5
	926.0 8	11 2	6.70 h 5
	927.1 8	9 2	6.70 h 5
	946.00 3	12 6	6.70 h 5
	949	8	6.70 h 5
	978.8 10	1.4 7	6.70 h 5
	980.5 5	≈ 2	6.70 h 5
	980.5 5	≈ 3	6.70 h 5
	984.0 10	1.9 6	6.70 h 5
	1353.3 6	1.7 5	6.70 h 5
	1394.1 5	3.0 9	6.70 h 5
	1452.7 10	1.0 2	6.70 h 5
	1668.5 10	1.2 2	6.70 h 5
	1694.6 8	1.2 5	6.70 h 5
^{234}Np	451.0 4	1.32 22	4.4 d 1
	743.1 4	5.1 7	4.4 d 1
	786.4 4	2.9 5	4.4 d 1
	1001.6 6	1.5 3	4.4 d 1
	1194.1 5	5.5 7	4.4 d 1
	1237.3 6	2.3 3	4.4 d 1
^{234}Np	1392.2 7	2.1 4	4.4 d 1
	1435.7 6	6.2 8	4.4 d 1
	1527.5 6	11.7 15	4.4 d 1
	1558.7 6	10	4.4 d 1
	1570.7 6	5.5 7	4.4 d 1
	1602.2 6	9.6 14	4.4 d 1
^{235}U	109.14 2	1.5 2	703.8×10^{6} y 5
	143.76 2	10.5 8	703.8×10^{6} y 5
	163.35 2	4.7 4	703.8×10^{6} y 5
	185.715 5	54	703.8×10^{6} y 5
	202.12 2	1.0 1	703.8×10^{6} y 5
	205.311 10	4.7 4	703.8×10^{6} y 5
^{235}Pu	49.1 1	2.4 4	25.3 m 6
^{236}Pa	642.0	30	9.1 m 2
	687.2	8	9.1 m 2
	x1559.8	1.9	9.1 m 2
	1762.6	5	9.1 m 2
	1808.0	2.0	9.1 m 2
	2041.2	1.6	9.1 m 2
^{236}Np	104	7	115000 y 12000
	160.2 6	28	115000 y 12000
	642.4 1	0.99	22.5 h 4
^{237}Pa	310.1 2	1.73 24	8.7 m 2
	498.7 2	2.4 3	8.7 m 2
	529.4 2	14.8 15	8.7 m 2
	540.7 2	9.3 9	8.7 m 2
	554.9 2	1.53 17	8.7 m 2
	853.7 2	34	8.7 m 2
	865.0 2	15.50 14	8.7 m 2
^{237}U	26.348 10	2.2 3	6.75 d 1
	59.543 15	33 5	6.75 d 1
	64.83 2	1.16 17	6.75 d 1
	164.61 2	1.83 20	6.75 d 1
	208.005 23	22	6.75 d 1
	332.36 4	1.20 14	6.75 d 1
^{237}Np	29.373 10	14.0 25	2.14×10^{6} y 1
	86.503 20	12.6	2.14×10^{6} y 1
^{237}Pu	59.5	3.25 16	45.3 d 2
^{237}Am	280.23 2	47 5	73.0 m 10
	321.0 1	1.40 16	73.0 m 10
	425.8 1	1.94 21	73.0 m 10
	438.4 1	8.3 8	73.0 m 10
	473.5 1	4.3 5	73.0 m 10
	655.3 2	1.30 17	73.0 m 10
	908.8 2	2.60 28	73.0 m 10
^{238}Np	923.98 2	2.48 13	2.117 d 2
	984.45 2	23.8	2.117 d 2
	1025.87 2	8.2 5	2.117 d 2
	1028.54 2	17 1	2.117 d 2
^{238}Am	357.7 1	2.10 27	98 m 2
	561.0 1	10.9 13	98 m 2
	605.1 1	7.6 9	98 m 2
	918.7 1	23.0 28	98 m 2
	941.4 1	2.24 28	98 m 2
	962.8 1	28	98 m 2
	1266.2 3	1.68 21	98 m 2
	1577.3 3	2.9 4	98 m 2
	1636.6 3	1.26 18	98 m 2
^{239}U	43.534 3	4.5 5	23.54 m 5
	74.670 3	50	23.54 m 5
^{239}Np	61.480 4	0.96 14	2.355 d 4
	106.13 1	22.7 13	2.355 d 4
	209.75 1	3.24 24	2.355 d 4
	228.19 1	10.7 6	2.355 d 4
	277.60 3	14.1	2.355 d 4
	315.88 4	1.59 11	2.355 d 4
	334.30 5	2.03 18	2.355 d 4
^{239}Am	181.715 10	1.08 12	11.9 h 1
	209.8 1	3.5 4	11.9 h 1
	226.383 12	3.3 4	11.9 h 1
	228.184 12	11.3 13	11.9 h 1
	277.604 16	15.0 17	11.9 h 1
^{240}U	44.10 7	1.69 20	14.1 h 2

Continued on next page (footnotes at end of table)

strong γ-rays (Iγ≥1%) from nuclei with A>208. From ENSDF: 31 March 1979 continued

Parent	Eγ	Iγ	Parent T1/2
^{240}Np	147.2	1.5	65 m 3
	152.2 1	9.0	65 m 3
	x175.0	6.5	65 m 3
	x182.6	1.0	65 m 3
	192.7 3	7.3	65 m 3
	251.46 7	0.96 8	7.4 m 2
	263.35 7	1.1 1	7.4 m 2
	270.8 3	9	65 m 3
	302.98 7	1.12 8	7.4 m 2
	307.0	1.5	65 m 3
	448.2 3	18	65 m 3
	x462.2	1.5	65 m 3
	467.4	2.2	65 m 3
	507.2 1	2.0	65 m 3
	554.60 7	22.4 16	7.4 m 2
	566.4 2	29	65 m 3
	597.40 7	12.5 9	7.4 m 2
	601.1	22	65 m 3
	606.1 1	1.7	65 m 3
	758.62 8	1.19 8	7.4 m 2
	817.88 11	1.24 9	7.4 m 2
	x847.0	5.0	65 m 3
	867.4 2	9.0	65 m 3
	x884.9	4.0	65 m 3
	890.6	1.2	65 m 3
	896.5 5	14	65 m 3
	915.2	1.5	65 m 3
	915.98 9	1.04 8	7.4 m 2
	938.04 10	1.29 8	7.4 m 2
	958.7	2.5	65 m 3
	973.9 2	23	65 m 3
	988	5.0	65 m 3
	x1074.4	1.0	65 m 3
	1167.6 6	5.0	65 m 3
	1496.9 1	1.3 1	7.4 m 2
^{240}Am	98.9 1	1.5 2	50.8 h 3
	888.80 5	25.1 4	50.8 h 3
	987.76 6	73.2 10	50.8 h 3
^{241}Am	26.345 1	2.4 1	432.2 y 5
	59.537 1	35.9 6	432.2 y 5
^{241}Cm	132.413 7	3.86 25	32.8 d 2
	165.049 8	2.97 23	32.8 d 2
	205.879 13	2.67 18	32.8 d 2
	430.634 20	4.06 26	32.8 d 2
	463.273 20	1.23 9	32.8 d 2
	471.805 20	71 4	32.8 d 2
	636.88 3	1.53 13	32.8 d 2
^{243}Pu	84.0 2	23.0	4.956 h 3
^{243}Am	43.53 15	5.5 5	7380 y 40
	74.67 15	66	7380 y 40
^{243}Cm	209.76 1	3.2 1	28.5 y
	228.19 1	10.58 30	28.5 y
	277.63 1	14.0 4	28.5 y
^{245}Pu	280.29 20	1.32 18	10.5 h 1
	308.11 20	5.0 7	10.5 h 1
	327.31 20	26 4	10.5 h 1
	348.73 20	0.99 14	10.5 h 1
	376.58 20	3.3 5	10.5 h 1
	491.50 20	2.8 4	10.5 h 1
	560.03 20	5.6 7	10.5 h 1
	630.04 20	2.8 4	10.5 h 1
	799.87 20	1.62 23	10.5 h 1
	840.56 20	1.32 18	10.5 h 1
	910.46 20	1.43 19	10.5 h 1
	938.4 2	1.04 20	10.5 h 1
	957.59 20	1.01 14	10.5 h 1
	987.60 20	1.36 19	10.5 h 1
	1018.33 20	1.06 17	10.5 h 1
^{245}Am	252.7 2	6.1	2.05 h
^{245}Cm	133 1	4.9 5	8500 y 100
	174 1	5	8500 y 100
^{245}Bk	252.85 5	29.1 26	4.94 d 3
	380.8 1	2.40 23	4.94 d 3
^{246}Pu	27.58 2	4.2 15	10.85 d 2
	43.81 2	30 10	10.85 d 2
^{246}Pu	179.94 2	12 4	10.85 d 2
	223.75 2	20 10	10.85 d 2
^{246}Am	99.2 2	4.8 12	39 m 3
	127.4 5	≤ 3.2	39 m 3
	127.4 5	≤ 3.2	39 m 3
	153.5 5	25 4	39 m 3
	205 1	36 5	39 m 3
	629 1	2.7 6	39 m 3
	679 1	53	39 m 3
	686 2	≈ 2.1	39 m 3
	734.46 4	1.20 7	25.0 m 2
	756 1	13.3 16	39 m 3
	781 1	4.0 6	39 m 3
	798.83 4	25.6 16	25.0 m 2
	833.62 4	1.87 13	25.0 m 2
	839 2	≈ 2.1	39 m 3
	986.06 4	0.99 6	25.0 m 2
	1036.03 4	13.3 9	25.0 m 2
	1062.07 4	17.7 12	25.0 m 2
	1078.90 4	28.9 19	25.0 m 2
	1085.13 7	1.59 19	25.0 m 2
^{246}Bk	734.5 5	3.2 8	1.83 d 15
	800.0 5	70	1.83 d 15
	834.5 5	5.6 13	1.83 d 15
	1037 1	2.0 5	1.83 d 15
	1063 1	3.6 8	1.83 d 15
	1079 1	3.5 9	1.83 d 15
	1082 1	(6)	1.83 d 15
	1124 1	5.3 12	1.83 d 15
^{247}Am	226 2	5.8 20	22 m 3
	285 2	23	22 m 3
^{247}Cm	278.0 8	3.4 7	1.56×10^{7} y 5
	287.5 7	2.0 3	1.56×10^{7} y 5
	346.0 8	≈ 1.3	1.56×10^{7} y 5
	402.4 5	72 6	1.56×10^{7} y 5
^{247}Bk	84 3	≈ 40	1380 y 250
	265 10	≈ 30	1380 y 250
^{249}Cm	634.31 6	1.50 10	64.15 m 3
^{249}Cf	252.88 8	2.73 11	350.6 y 21
	333.44 5	15.5 5	350.6 y 21
	387.95 5	66.0	350.6 y 21
^{249}Es	375.1 1	3.28 30	1.7 h 1
	379.5 1	40.4 25	1.7 h 1
	789.7 1	1.14 9	1.7 h 1
	813.2 1	9.1 6	1.7 h 1
	1218.5 1	1.5 1	1.7 h 1
^{250}Bk	889.98 15	1.64 5	3.222 h 5
	929.28 15	1.37 4	3.222 h 5
	988.96 15	45.1 5	3.222 h 5
	1028.58 15	4.39 11	3.222 h 5
	1031.76 15	35.1	3.222 h 5
^{250}Es	989.0 6	16.3 14	2.1 h 2
	1032.0 6	14	2.1 h 2
^{251}Cf	176.6 1	17.7 15	898 y 44
	227.0 10	6.3 11	898 y 44
	285.0 2	1.4 3	898 y 44
^{251}Es	177.6 3	2.388	33 h 1
^{251}Fm	425.4 1	0.97 13	5.30 h 7
^{252}Es	102.33 5	1.73 25	350 d 50
	139.03 5	12.7 19	350 d 50
	785.1 1	16.8 24	350 d 50
	800.0 1	1.37 20	350 d 50
	924.1 1	2.2 3	350 d 50
^{253}Fm	271.8 4	2.6	3.00 d 12
^{254}Es	63.0 20	2.0 2	275.5 d 5
	584.318 45	2.8 6	39.3 h 2
	648.800 45	28 6	39.3 h 2
	688.681 45	12.3 26	39.3 h 2
	693.783 45	24 5	39.3 h 2
^{255}No	187.2 2	5.5 25	3.1 m 2
^{257}Fm	62.8 10	< 1.5	100.5 d 2
	179.7 6	6.4 11	100.5 d 2
	241.4 7	7.5 12	100.5 d 2

x γ-ray not placed in level scheme.

APPENDIX II.B

STRONG γ-RADIATIONS ($I_\gamma \geq 1\%$) FROM RADIOACTIVITY, $A \geq 207$

Ordered by γ-Ray Energy

II.B.2

strong γ-rays (Iγ≥1%) from nuclei with A>208. From ENSDF: 31 March 1979

Eγ	Iγ	Parent	Parent T1/2
25.64	12	^{231}U	4.2 d 1
25.64 2	14.8 10	^{231}Th	25.52 h 1
26.348 10	2.2 3	^{237}U	6.75 d 1
26.345 1	2.4 1	^{241}Am	432.2 y 5
27.36 1	9	^{231}Pa	3.276×10^4 y 11
	17.4	^{227}Ra	42.2 m 5
27.58 2	4.2 15	^{246}Pu	10.85 d 2
29.36 4	2.5	^{233}Th	22.3 m 1
29.373 10	14.0 25	^{237}Np	2.14×10^6 y 1
31.3 2	4.1	^{229}Th	7340 y 160
39.857 5	1.088 15	^{212}Bi	60.55 m 4
40.0 10	29	^{225}Ra	14.8 d 2
43.534 3	4.5 5	^{239}U	23.54 m 5
43.53 15	5.5 5	^{243}Am	7380 y 40
43.81 2	30 10	^{246}Pu	10.85 d 2
44.10 7	1.69 20	^{240}U	14.1 h 2
45	2.3	^{220}Fr	27.4 s 3
46.503 15	4.05 8	^{210}Pb	22.3 y 2
49.1 1	2.4 4	^{235}Pu	25.3 m 6
≈ 50	< 1.7	^{227}Pa	38.3 m 3
50.20 10	8.5 3	^{227}Th	18.718 d 5
53.226 14	1.10 5	^{214}Pb	26.8 m
59.5	3.25 16	^{237}Pu	45.3 d 2
59.537 1	35.9 6	^{241}Am	432.2 y 5
59.543 15	33 5	^{237}U	6.75 d 1
61.480 4	0.96 14	^{239}Np	2.355 d 4
62.8 10	< 1.5	^{257}Fm	100.5 d 2
63.0 20	2.0 2	^{254}Es	275.5 d 5
63.0 2	3.2 2	^{234}Pa	6.70 h 5
63.29 2	(3.8)	^{234}Th	24.10 d 3
64.83 2	1.16 17	^{237}U	6.75 d 1
65	5.3	^{227}Pa	38.3 m 3
67	1.0	^{227}Pa	38.3 m 3
74.670 3	50	^{239}U	23.54 m 5
74.67 15	66	^{243}Am	7380 y 40
75.28 1	1.1 1	^{233}Pa	27.0 d 1
79.77 6	2.1 1	^{227}Th	18.718 d 5
	9.2 14	^{223}Fr	21.8 m 4
84 3	≈ 40	^{247}Bk	1380 y 250
84.0 2	23.0	^{243}Pu	4.956 h 3
84.18	7	^{231}U	4.2 d 1
84.21 2	6.5 4	^{231}Th	25.52 h 1
84.40 5	1.2 4	^{228}Th	1.9131 y 9
86.44 5	(3.1)	^{229}Th	7340 y 160
86.50 5	2.7	^{233}Th	22.3 m 1
86.503 20	12.6	^{237}Np	2.14×10^6 y 1
86.59 1	1.76 24	^{233}Pa	27.0 d 1
90.8 1	1.84 20	^{209}At	5.41 h 5
92.38 1	2.72 21	^{234}Th	24.10 d 3
92.80 2	2.69 21	^{234}Th	24.10 d 3
94.00 6	1.40 12	^{227}Th	18.718 d 5
98.9 1	1.5 2	^{240}Am	50.8 h 3
99.2 2	4.8 12	^{246}Am	39 m 3
99.45 8	1.4 6	^{228}Ac	6.13 h
99.7 1	3.5 19	^{225}Ac	10.0 d 1
100.3 1	≤ 1.0	^{223}Fr	21.8 m 4
102.33 5	1.73 25	^{252}Es	350 d 50
104	7	^{236}Np	115000 y 12000
104.2 1	2.4 4	^{209}At	5.41 h 5
105.47 5	1.65 19	^{232}Pa	1.31 d
106	1.7	^{220}Fr	27.4 s 3
106.13 1	22.7 13	^{239}Np	2.355 d 4
108.96 5	2.81 29	^{232}Pa	1.31 d
109.14 2	1.5 2	^{235}U	703.8×10^6 y 5
110	1.7	^{227}Pa	38.3 m 3
111.12 3	3.29 20	^{226}Th	30.9 m
117 1	81 13	^{209}Tl	2.20 m 7
122.31 6	1.19 2	^{223}Ra	11.434 d 2
124.5 1	(1.2)	^{229}Th	7340 y 160
125.4 3	1.0 3	^{234}Pa	6.70 h 5
127.4 5	≤ 3.2	^{246}Am	39 m 3
	≤ 3.2	^{246}Am	39 m 3
129.1 3	2 1	^{228}Ac	6.13 h
129.22 10	2.85 15	^{228}Pa	22 h 1
131.2 2	20.0	^{234}Pa	6.70 h 5
132.413 7	3.86 25	^{241}Cm	32.8 d 2
133 1	4.9 5	^{245}Cm	8500 y 100
133	19.71	^{224}Ac	2.9 h 2
137.03 6	1.6	^{229}Th	7340 y 160
139.03 5	12.7 19	^{252}Es	350 d 50
143.76 2	10.5 8	^{235}U	703.8×10^6 y 5
144.20 4	3.26 7	^{223}Ra	11.434 d 2
147.2	1.5	^{240}Np	65 m 3
148.3 2	(1.4)	^{229}Th	7340 y 160
150.1 1	10.8 5	^{232}Pa	1.31 d
152.2 1	9.0	^{240}Np	65 m 3
152.7 1	6.7 5	^{234}Pa	6.70 h 5
153.5 5	25 4	^{246}Am	39 m 3
154	1	^{220}Fr	27.4 s 3
154.19 3	5.59 10	^{223}Ra	11.434 d 2
154.2 3	1.0 3	^{228}Ac	6.13 h
156.48 4	(1.1)	^{229}Th	7340 y 160
158.05 15	17.3 18	^{224}Ac	29 h
160.2 6	28	^{236}Np	115000 y 12000
161.5	1.5	^{220}Fr	27.4 s 3
163.35 2	4.7 4	^{235}U	703.8×10^6 y 5
164.61 2	1.83 20	^{237}U	6.75 d 1
165.049 8	2.97 23	^{241}Cm	32.8 d 2
168.7 1	6.8 4	^{211}Rn	14.6 h 2
174 1	5	^{245}Cm	8500 y 100
×175.0	6.5	^{240}Np	65 m 3
176.6 1	17.7 15	^{251}Cf	898 y 44
177 2	9 2	^{224}Th	1.04 s 5
177.6 3	2.388	^{251}Es	33 h 1
179.7 6	6.4 11	^{257}Fm	100.5 d 2
179.94 2	12 4	^{246}Pu	10.85 d 2
181.715 10	1.08 12	^{239}Am	11.9 h 1
×182.6	1.0	^{240}Np	65 m 3
183.9 1	1.26 29	^{232}Pa	1.31 d
185.60 15	4.7 7	^{226}Ac	29 h
185.715 5	54	^{235}U	703.8×10^6 y 5
185.99 4	3.28 3	^{226}Ra	1600 y 7
186.0 2	2.0 3	^{234}Pa	6.70 h 5
187.2 2	5.5 25	^{255}No	3.1 m 2
192.7 3	7.3	^{240}Np	65 m 3
193.63 6	4.6	^{229}Th	7340 y 160
195.0 1	22.6 10	^{209}At	5.41 h 5
200.6 3	1.1 3	^{234}Pa	6.70 h 5
202.12 2	1.0 1	^{235}U	703.8×10^6 y 5
203.0 3	1.2 2	^{234}Pa	6.70 h 5
205 1	36 5	^{246}Am	39 m 3
205.0 1	0.95 24	^{223}Fr	21.8 m 4
205.311 10	4.7 4	^{235}U	703.8×10^6 y 5
205.879 13	2.67 18	^{241}Cm	32.8 d 2
208.005 23	22	^{237}U	6.75 d 1
209.28 10	1.67 15	^{228}Pa	22 h 1
209.4 3	4.6 15	^{228}Ac	6.13 h
209.75 1	3.24 24	^{239}Np	2.355 d 4
209.76 1	3.2 1	^{243}Cm	28.5 y
209.8 1	3.5 4	^{239}Am	11.9 h 1
210.65 8	1.13 8	^{227}Th	18.718 d 5
210.97 10	3.3	^{229}Th	7340 y 160
217	44	^{224}Ac	2.9 h 2
217.6 2	12.5 4	^{221}Fr	4.8 m 1
223.6 4	2.24 27	^{232}Np	14.7 m 3
223.75 2	20 10	^{246}Pu	10.85 d 2
226 2	5.8 20	^{247}Am	22 m 3
226.383 12	3.3 4	^{239}Am	11.9 h 1
226.4 4	5.9	^{234}Pa	6.70 h 5
227.0 10	6.3 11	^{251}Cf	898 y 44
227.2 2	5.5	^{234}Pa	6.70 h 5
228.184 12	11.3 13	^{239}Am	11.9 h 1
228.19 1	10.58 30	^{243}Cm	28.5 y
	10.7 6	^{239}Np	2.355 d 4
230.00 10	26.7	^{226}Ac	29 h
233.6 1	0.96 6	^{209}At	5.41 h 5

Continued on next page (footnotes at end of table)

strong γ-rays (Iγ≥1%) from nuclei with A>208. From ENSDF: 31 March 1979 continued

Eγ	Iγ	Parent	Parent T1/2
234.9 2	3.4	^{223}Fr	21.8 m 4
236.00 8	11.2 6	^{227}Th	18.718 d 5
238.626 5	44.6 10	^{212}Pb	10.64 h 1
239.1 1	12.4 5	^{209}At	5.41 h 5
241.0 1	3.9 11	^{224}Ra	3.66 d 4
241.4 7	7.5 12	^{257}Fm	100.5 d 2
241.91 3	7.46 16	^{214}Pb	26.8 m
248.9 2	2.8 3	^{234}Pa	6.70 h 5
250.2 1	6.1 4	^{211}Rn	14.6 h 2
251.46 7	0.96 8	^{240}Np	7.4 m 2
252.7 2	6.1	^{245}Am	2.05 h
252.85 5	29.1 26	^{245}Bk	4.94 d 3
252.88 8	2.73 11	^{249}Cf	350.6 y 21
253.5 2	5.6 9	^{226}Ac	29 h
256.25 5	6.8 5	^{227}Th	18.718 d 5
258.40 10	2.0	^{227}Ra	42.2 m 5
263.35 7	1.1 1	^{240}Np	7.4 m 2
x263.8 3	2.84 10	^{231}Np	48.8 m 2
265 10	≈ 30	^{247}Bk	1380 y 250
265.7 2	51.0 26	^{210}Bi	3.0×10^{6} y 1
269.41 3	13.6 3	^{223}Ra	11.434 d 2
270.23 10	2.10 10	^{228}Pa	22 h 1
270.3 3	3.8 9	^{226}Ac	6.13 h
270.8 3	9	^{240}Np	65 m 3
271.23 5	9.9 11	^{219}Rn	3.96 s 1
271.8 4	2.6	^{253}Fm	3.00 d 12
272.1 2	1.0	^{234}Pa	6.70 h 5
273.16 8	0.96	^{227}Ra	42.2 m 5
277.35 6	6.79 30	^{208}Tl	3.07 m 2
277.39 10	2.9	^{227}Ra	42.2 m 5
277.60 3	14.1	^{239}Np	2.355 d 4
277.604 16	15.0 17	^{239}Am	11.9 h 1
277.63 1	14.0 4	^{243}Cm	28.5 y
278.0 8	3.4 7	^{247}Cm	1.56×10^{7} y 5
279.20 10	1.12 12	^{209}Rn	28.5 m 10
280.23 2	47 5	^{237}Am	73.0 m 10
280.29 20	1.32 18	^{245}Pu	10.5 h 1
281.87 10	1.23 7	^{228}Pa	22 h 1
282.0 4	19.8 22	^{232}Np	14.7 m 3
283.67 6	1.6 3	^{231}Pa	3.276×10^{4} y 11
	3.4	^{227}Ra	42.2 m 5
285 2	23	^{247}Am	22 m 3
285.0 2	1.4 3	^{251}Cf	898 y 44
286.15 6	1.58 5	^{227}Th	18.718 d 5
287.5 7	2.0 3	^{247}Cm	1.56×10^{7} y 5
293.7 3	3.9 3	^{234}Pa	6.70 h 5
295.17 2	19.2 4	^{214}Pb	26.8 m
299.90 10	2.0 2	^{227}Th	18.718 d 5
300.08 6	2.3 5	^{231}Pa	3.276×10^{4} y 11
	5.1	^{227}Ra	42.2 m 5
300.09 2	3.4 1	^{212}Pb	10.64 h 1
300.12 3	6.2 4	^{233}Pa	27.0 d 1
302.67 6	2.3 5	^{231}Pa	3.276×10^{4} y 11
	2.3 5	^{231}Pa	3.276×10^{4} y 11
	4.8	^{227}Ra	42.2 m 5
302.98 7	1.12 8	^{240}Np	7.4 m 2
304.44 13	1.05 13	^{227}Th	18.718 d 5
304.8	27	^{206}Hg	8.15 m 10
304.8 3	27.5 15	^{210}Bi	3.0×10^{6} y 1
307.0	1.5	^{240}Np	65 m 3
308.11 20	5.0 7	^{245}Pu	10.5 h 1
310.1 2	1.73 24	^{237}Pa	8.7 m 2
311.98 3	36	^{233}Pa	27.0 d 1
315.88 4	1.59 11	^{239}Np	2.355 d 4
321.0 1	1.40 16	^{237}Am	73.0 m 10
323.89 4	3.90 9	^{223}Ra	11.434 d 2
324.22 5	2.77 8	^{222}Ra	38.0 s 5
327.3 3	52	^{232}Np	14.7 m 3
327.31 20	26 4	^{245}Pu	10.5 h 1
327.64 10	≈ 1.9	^{228}Pa	22 h 1
	≈ 2.1	^{228}Pa	22 h 1
328.0 3	3.4 8	^{228}Ac	6.13 h
329.82 10	2.75 16	^{227}Th	18.718 d 5
330.07	1.3 3	^{231}Pa	3.276×10^{4} y 11
330.07 6	3.0	^{227}Ra	42.2 m 5
332.36 4	1.20 14	^{237}U	6.75 d 1
332.36 10	1.57 14	^{228}Pa	22 h 1
333.44 5	15.5 5	^{249}Cf	350.6 y 21
334.30 5	2.03 18	^{239}Np	2.355 d 4
334.40 14	1.0 1	^{227}Th	18.718 d 5
337.45 4	14.7 6	^{209}Rn	28.5 m 10
338.32 6	2.78 7	^{223}Ra	11.434 d 2
338.32 10	5.10 30	^{228}Pa	22 h 1
338.4 3	12.0 29	^{228}Ac	6.13 h
340.50 4	4.2 5	^{233}Pa	27.0 d 1
341.1 3	1.54 12	^{228}Pa	22 h 1
346.0 8	≈ 1.3	^{247}Cm	1.56×10^{7} y 5
x348.4 3	3.63 20	^{231}Np	48.8 m 2
348.73 20	0.99 14	^{245}Pu	10.5 h 1
351.0 1	12.76 20	^{211}Bi	2.14 m 2
351.900 28	37.1 8	^{214}Pb	26.8 m
357.7 1	2.10 27	^{238}Am	98 m 2
369.8 4	2.9 3	^{234}Pa	6.70 h 5
370.5 1	1.38 10	^{211}Rn	14.6 h 2
370.9 3	9.8	^{231}Np	48.8 m 2
372.4 4	1.3 2	^{234}Pa	6.70 h 5
375.1 1	3.28 30	^{249}Es	1.7 h 1
376.58 20	3.3 5	^{245}Pu	10.5 h 1
x377.0 3	1.25 16	^{232}Np	14.7 m 3
379.5 1	40.4 25	^{249}Es	1.7 h 1
380.8 1	2.40 23	^{245}Bk	4.94 d 3
386.43	≤ 2.1	^{209}Rn	28.5 m 10
	≤ 2.1	^{209}Rn	28.5 m 10
387.9 1	6.97 29	^{232}Pa	1.31 d
387.95 5	66.0	^{249}Cf	350.6 y 21
397.8 2	1.82 16	^{230}Pa	17.4 d 5
398.62 8	1.19 16	^{233}Pa	27.0 d 1
401.78 8	6.6 4	^{219}Rn	3.96 s 1
402.4 5	72 6	^{247}Cm	1.56×10^{7} y 5
404.84 4	3.83 11	^{211}Pb	36.1 m 2
407.97 6	2.4	^{227}Ra	42.2 m 5
408.32 4	51.0 21	^{209}Rn	28.5 m 10
409.4 5	2.2 4	^{226}Ac	6.13 h
409.51 10	6.0	^{228}Pa	22 h 1
415.76 4	1.51 17	^{233}Pa	27.0 d 1
416.4 1	3.54 21	^{211}Rn	14.6 h 2
420.7 4	1.05 11	^{231}Np	48.8 m 2
421.9 2	2.52 19	^{232}Pa	1.31 d
425.4 1	0.97 13	^{251}Fm	5.30 h 7
425.8 1	1.94 21	^{237}Am	73.0 m 10
426.99 4	1.72 8	^{211}Pb	36.1 m 2
430.634 20	4.06 26	^{241}Cm	32.8 d 2
438.4 1	8.3 8	^{237}Am	73.0 m 10
439.7 4	27.3 24	^{213}Bi	45.65 m 5
442.2 1	23.4 15	^{211}Rn	14.6 h 2
443.75 5	5.3 5	^{230}Pa	17.4 d 5
444.94 5	1.27 6	^{223}Ra	11.434 d 2
448.2 3	18	^{240}Np	65 m 3
451.0 4	1.32 22	^{234}Np	4.4 d 1
453.6 1	8.62 20	^{232}Pa	1.31 d
454.95 5	6.1 4	^{230}Pa	17.4 d 5
458.8 3	1.5 1	^{234}Pa	6.70 h 5
459.2 2	1.4	^{233}Th	22.3 m 1
461.41 7	1.46 9	^{209}Rn	28.5 m 10
x462.2	1.5	^{240}Np	65 m 3
463.0 3	4.6 8	^{226}Ac	6.13 h
463.00 10	13.2 6	^{228}Pa	22 h 1
463.273 20	1.23 9	^{241}Cm	32.8 d 2
465 4	1	^{220}Ra	23 ms 5
467 2	81 13	^{209}Tl	2.20 m 7
467.4	2.2	^{240}Np	65 m 3
471.805 20	71 4	^{241}Cm	32.8 d 2
472.4 1	4.16 19	^{232}Pa	1.31 d
473.5 1	4.3 5	^{237}Am	73.0 m 10
x484.7 5	1.6 3	^{231}Np	48.8 m 2
486.98 10	2.5	^{227}Ra	42.2 m 5

Continued on next page (footnotes at end of table)

strong γ-rays (Iγ≥1%) from nuclei with A>208. From ENSDF: 31 March 1979 continued

Eγ	Iγ	Parent	Parent T1/2
491.50 20	2.8 4	^{245}Pu	10.5 h 1
498.7 2	2.4 3	^{237}Pa	8.7 m 2
501.4 1	1.05	^{227}Ra	42.2 m 5
506.8 5	1.6 3	^{234}Pa	6.70 h 5
507.2 1	2.0	^{240}Np	65 m 3
508.20 5	3.47 29	^{230}Pa	17.4 d 5
510.80 8	21.6 9	^{206}Tl	3.07 m 2
513.7 5	1.3 2	^{234}Pa	6.70 h 5
515.6 1	5.52 20	^{232}Pa	1.31 d
516.2 2	1.5	^{227}Ra	42.2 m 5
518.50 10	1.92 17	^{230}Pa	17.4 d 5
529.4 2	14.8 15	^{237}Pa	8.7 m 2
540.7 2	9.3 9	^{237}Pa	8.7 m 2
545.0 1	91.0	^{209}At	5.41 h 5
551.0 1	4.91 18	^{209}At	5.41 h 5
552.5 2	1.55 18	^{209}At	5.41 h 5
554.60 7	22.4 16	^{240}Np	7.4 m 2
554.9 2	1.53 17	^{237}Pa	8.7 m 2
560.03 20	5.6 7	^{245}Pu	10.5 h 1
561.0 1	10.9 13	^{238}Am	98 m 2
562.3 5	0.99 20	^{228}Ac	6.13 h
563.2 1	3.68 19	^{232}Pa	1.31 d
565.9 10	1.4 3	^{234}Pa	6.70 h 5
566.4 2	29	^{240}Np	65 m 3
568.7 5	3.0	^{234}Pa	6.70 h 5
569.5 5	10.7	^{234}Pa	6.70 h 5
571.10 10	1.05 9	^{230}Pa	17.4 d 5
574 1	≈ 2	^{234}Pa	6.70 h 5
577.10 8	0.99 7	^{209}Rn	28.5 m 10
581.4 2	1.02 24	^{228}Pa	22 h 1
581.5 1	6.00 29	^{232}Pa	1.31 d
583.14 20	85.8 20	^{208}Tl	3.07 m 2
584.318 45	2.8 6	^{254}Es	39.3 h 2
597.40 7	12.5 9	^{240}Np	7.4 m 2
601.1	22	^{240}Np	65 m 3
605.1 1	7.6 9	^{238}Am	98 m 2
606.1 1	1.7	^{240}Np	65 m 3
609.318 20	46	^{214}Bi	19.9 m 4
611.4 2	1.3	^{227}Ra	42.2 m 5
629 1	2.7 6	^{246}Am	39 m 3
630.04 20	2.8 4	^{245}Pu	10.5 h 1
634.31 6	1.50 10	^{249}Cm	64.15 m 3
636.88 3	1.53 13	^{241}Cm	32.8 d 2
642.0	30	^{236}Pa	9.1 m 2
642.4 1	0.99	^{236}Np	22.5 h 4
648.800 45	28 6	^{254}Es	39.3 h 2
649.5	2.3	^{206}Hg	8.15 m 10
649.8 10	2.86 15	^{210}Bi	3.0×10^{6} y 1
655.3 2	1.30 17	^{237}Am	73.0 m 10
×664.8 10	1.3 4	^{234}Pa	6.70 h 5
665.453 22	1.56 6	^{214}Bi	19.9 m 4
666.1 1	1.87 6	^{209}At	5.41 h 5
666.7 6	1.6 4	^{234}Pa	6.70 h 5
669.9 5	1.4 4	^{234}Pa	6.70 h 5
672.82 4	3.32 14	^{209}Rn	28.5 m 10
674.1 1	46.0	^{211}Rn	14.6 h 2
678.4 1	29.4 16	^{211}Rn	14.6 h 2
679 1	53	^{246}Am	39 m 3
684.90 10	1.18 15	^{209}Rn	28.5 m 10
686 2	≈ 2.1	^{246}Am	39 m 3
687.2	8	^{236}Pa	9.1 m 2
688.681 45	12.3 26	^{254}Es	39.3 h 2
689.26 5	9.8 4	^{209}Rn	28.5 m 10
692.7 5	1.5 5	^{234}Pa	6.70 h 5
693.783 45	24 5	^{254}Es	39.3 h 2
699.0 5	4.6 3	^{234}Pa	6.70 h 5
706.1 3	3.1 6	^{234}Pa	6.70 h 5
727.17 4	11.83 26	^{212}Bi	60.55 m 4
728.23 7	1.84 15	^{230}Pa	17.4 d 5
733.0 5	8.6 8	^{234}Pa	6.70 h 5
734.46 4	1.20 7	^{246}Am	25.0 m 2
734.5 5	3.2 8	^{246}Bk	1.83 d 15
737.8 3	1.23 7	^{231}Np	48.8 m 2
738.0 8	1.0 4	^{234}Pa	6.70 h 5
742.81 3	2.4 7	^{234}Pa	6.70 h 5
743.1 4	5.1 7	^{234}Np	4.4 d 1
745.78 4	23.1 9	^{209}Rn	28.5 m 10
755.0 4	4.2 5	^{232}Np	14.7 m 3
755.18 10	1.26 8	^{228}Pa	22 h 1
755.2 5	1.10 23	^{228}Ac	6.13 h
755.6 10	1.4 7	^{234}Pa	6.70 h 5
756 1	13.3 16	^{246}Am	39 m 3
758.62 8	1.19 8	^{240}Np	7.4 m 2
763.13 8	1.64 9	^{206}Tl	3.07 m 2
768.361 18	4.88 12	^{214}Bi	19.9 m 4
772.1 5	1.6 3	^{228}Ac	6.13 h
772.17 10	1.19 7	^{228}Pa	22 h 1
780.7 6	1.1 4	^{234}Pa	6.70 h 5
781 1	4.0 6	^{246}Am	39 m 3
781.35 5	1.44 11	^{230}Pa	17.4 d 5
781.9 1	83.5 22	^{209}At	5.41 h 5
785.1 1	16.8 24	^{252}Es	350 d 50
785.42 6	1.99 7	^{212}Bi	60.55 m 4
785.910 20	1.09 4	^{214}Pb	26.8 m
786.27 3	1.4 4	^{234}Pa	6.70 h 5
786.4 4	2.9 5	^{234}Np	4.4 d 1
789.7 1	1.14 9	^{249}Es	1.7 h 1
790.2 1	63.5 18	^{209}At	5.41 h 5
×793.6 10	1.5	^{234}Pa	6.70 h 5
794.7 2	2.00 9	^{228}Pa	22 h 1
794.72 7	3.41 25	^{209}Rn	28.5 m 10
794.8 3	4.8 8	^{228}Ac	6.13 h
796.3 5	3.8 5	^{234}Pa	6.70 h 5
798.83 4	25.6 16	^{246}Am	25.0 m 2
799.87 20	1.62 23	^{245}Pu	10.5 h 1
800.0 1	1.37 20	^{252}Es	350 d 50
800.0 5	70	^{246}Bk	1.83 d 15
805.8 5	3.3 5	^{234}Pa	6.70 h 5
806.174 18	1.23 4	^{214}Bi	19.9 m 4
813.2 1	9.1 6	^{249}Es	1.7 h 1
814.8 4	4.1 5	^{232}Np	14.7 m 3
817.88 11	1.24 9	^{240}Np	7.4 m 2
819.2 2	7.45 10	^{232}Pa	1.31 d
819.5 4	33 4	^{232}Np	14.7 m 3
819.6 6	2.6 5	^{234}Pa	6.70 h 5
×824.0 8	< 1.5	^{234}Pa	6.70 h 5
826.3 6	4.0 8	^{234}Pa	6.70 h 5
830.5 3	1.9 1	^{228}Pa	22 h 1
831.6 8	5.5 7	^{234}Pa	6.70 h 5
831.83 4	3.81 11	^{211}Pb	36.1 m 2
833.62 4	1.87 13	^{246}Am	25.0 m 2
834.5 5	5.6 13	^{246}Bk	1.83 d 15
835.5 3	2.72 14	^{228}Pa	22 h 1
835.6 5	1.8 3	^{228}Ac	6.13 h
839 2	≈ 2.1	^{246}Am	39 m 3
840.0 4	1.02 6	^{228}Pa	22 h 1
840.2 5	0.99 17	^{228}Ac	6.13 h
840.56 20	1.32 18	^{245}Pu	10.5 h 1
×847.0	5.0	^{240}Np	65 m 3
853.4 1	4.69 27	^{211}Rn	14.6 h 2
853.7 2	34	^{237}Pa	8.7 m 2
855.76 5	4.94 29	^{209}Rn	28.5 m 10
860.37 8	12.0 4	^{208}Tl	3.07 m 2
863.9 1	2.07 8	^{209}At	5.41 h 5
864.0 5	1.94 19	^{232}Pa	1.31 d
864.3 5	20.3 22	^{232}Np	14.7 m 3
865.0 2	15.50 14	^{237}Pa	8.7 m 2
866.0 1	8.0 5	^{211}Rn	14.6 h 2
867.0 3	5.81 20	^{232}Pa	1.31 d
867.2 6	24.4 28	^{232}Np	14.7 m 3
867.4 2	9.0	^{240}Np	65 m 3
870.1 4	1.06 6	^{228}Pa	22 h 1
876.4 8	4 2	^{234}Pa	6.70 h 5
880.5	4	^{234}Pa	6.70 h 5
880.51 4	9	^{234}Pa	6.70 h 5
883.24 4	12 4	^{234}Pa	6.70 h 5

Continued on next page (footnotes at end of table)

strong γ-rays (Iγ≥1%) from nuclei with A>208. From ENSDF: 31 March 1979 continued

Eγ	Iγ	Parent	Parent T1/2
x884.9	4.0	^{240}Np	65 m 3
888.80 5	25.1 4	^{240}Am	50.8 h 3
889.98 15	1.64 5	^{250}Bk	3.222 h 5
890.6	1.2	^{240}Np	65 m 3
894.3 5	2.6 9	^{228}Pa	22 h 1
894.3 1	19.8 3	^{232}Pa	1.31 d
896.5 5	14	^{240}Np	65 m 3
898.65 10	5.7 5	^{230}Pa	17.4 d 5
899.0 5	4.1 8	^{234}Pa	6.70 h 5
903.0 1	3.65 10	^{209}At	5.41 h 5
904.5 3	2.88 24	^{228}Pa	22 h 1
908.8 2	2.60 28	^{237}Am	73.0 m 10
910.46 20	1.43 19	^{245}Pu	10.5 h 1
911.07 3	29	^{228}Ac	6.13 h
911.23 10	16.0 7	^{228}Pa	22 h 1
915.2	1.5	^{240}Np	65 m 3
915.98 9	1.04 8	^{240}Np	7.4 m 2
918.50 10	8.0 7	^{230}Pa	17.4 d 5
918.7 1	23.0 28	^{238}Am	98 m 2
923.98 2	2.48 13	^{238}Np	2.117 d 2
924.1 1	2.2 3	^{252}Es	350 d 50
925 1	2.9	^{234}Pa	6.70 h 5
926.0 8	11 2	^{234}Pa	6.70 h 5
927.1 8	9 2	^{234}Pa	6.70 h 5
929.28 15	1.37 4	^{250}Bk	3.222 h 5
934.052 20	3.16 8	^{214}Bi	19.9 m 4
934.7 1	3.72 21	^{211}Rn	14.6 h 2
938.04 10	1.29 8	^{240}Np	7.4 m 2
938.4 2	1.04 20	^{245}Pu	10.5 h 1
941.4 1	2.24 28	^{238}Am	98 m 2
941.6 4	1.6 3	^{232}Np	14.7 m 3
x945.6 8	1.8 6	^{228}Pa	22 h 1
946.00 3	12 6	^{234}Pa	6.70 h 5
946.7 1	5.1 14	^{211}Rn	14.6 h 2
947.4 1	16.5 19	^{211}Rn	14.6 h 2
949	8	^{234}Pa	6.70 h 5
951.95 10	28.3 20	^{230}Pa	17.4 d 5
956.3 3	1.55 29	^{230}Pa	17.4 d 5
957.59 20	1.01 14	^{245}Pu	10.5 h 1
958.7	2.5	^{240}Np	65 m 3
962.8 1	28	^{238}Am	98 m 2
964.6 5	5.5 9	^{228}Ac	6.13 h
964.6 3	10.1 12	^{228}Pa	22 h 1
968.9 5	17.5 30	^{228}Ac	6.13 h
969.11 10	13.2 24	^{228}Pa	22 h 1
969.3 1	41.6 19	^{232}Pa	1.31 d
973.9 2	23	^{240}Np	65 m 3
975.0 3	1.56 9	^{228}Pa	22 h 1
978.8 10	1.4 7	^{234}Pa	6.70 h 5
980.5 5	* 2	^{234}Pa	6.70 h 5
	* 3	^{234}Pa	6.70 h 5
984.0 10	1.9 6	^{234}Pa	6.70 h 5
984.45 2	23.8	^{238}Np	2.117 d 2
986.06 4	0.99 6	^{246}Am	25.0 m 2
987.60 20	1.36 19	^{245}Pu	10.5 h 1
987.76 6	73.2 10	^{240}Am	50.8 h 3
988	5.0	^{240}Np	65 m 3
988.96 15	45.1 5	^{250}Bk	3.222 h 5
989.0 6	16.3 14	^{250}Es	2.1 h 2
992.5	* 1.4	^{211}Rn	14.6 h 2
1001.6 6	1.5 3	^{234}Np	4.4 d 1
1009.6 2	1.05 9	^{230}Pa	17.4 d 5
1018.33 20	1.06 17	^{245}Pu	10.5 h 1
1025.87 2	8.2 5	^{238}Np	2.117 d 2
1026.05 10	1.42 12	^{230}Pa	17.4 d 5
1028.54 2	17 1	^{238}Np	2.117 d 2
1028.58 15	4.39 11	^{250}Bk	3.222 h 5
1031.76 15	35.1	^{250}Bk	3.222 h 5
1032.0 6	14	^{250}Es	2.1 h 2
1036.03 4	13.3 9	^{246}Am	25.0 m 2
1037 1	2.0 5	^{246}Bk	1.83 d 15
1037.4 5	3.3 4	^{232}Np	14.7 m 3
1037.93 6	4.22 25	^{209}Rn	28.5 m 10
1054.53 7	1.6 1	^{209}Rn	28.5 m 10
1062.07 4	17.7 12	^{246}Am	25.0 m 2
1063 1	3.6 8	^{246}Bk	1.83 d 15
x1065.55 7	1.7 1	^{209}Rn	28.5 m 10
x1074.4	1.0	^{240}Np	65 m 3
1078.62 10	0.97 5	^{212}Bi	60.55 m 4
1078.90 4	28.9 19	^{246}Am	25.0 m 2
1079 1	3.5 9	^{246}Bk	1.83 d 15
1082 1	(6)	^{246}Bk	1.83 d 15
1085.13 7	1.59 19	^{246}Am	25.0 m 2
1085.4 4	0.99 11	^{232}Np	14.7 m 3
1103.4 1	5.40 17	^{209}At	5.41 h 5
1120.276 22	15.0 4	^{214}Bi	19.9 m 4
1124 1	5.3 12	^{246}Bk	1.83 d 15
1126.0 4	1.46 21	^{232}Np	14.7 m 3
1126.7 1	22.5 15	^{211}Rn	14.6 h 2
1147.6 1	1.36 9	^{209}At	5.41 h 5
1155.19 2	1.69 6	^{214}Bi	19.9 m 4
1167.6 6	5.0	^{240}Np	65 m 3
1170.6 1	3.09 9	^{209}At	5.41 h 5
1175.3 1	1.91 9	^{209}At	5.41 h 5
1181.3 1	1.47 10	^{211}Rn	14.6 h 2
1194.1 5	5.5 7	^{234}Np	4.4 d 1
1217.2 1	1.11 5	^{209}At	5.41 h 5
1218.5 1	1.5 1	^{249}Es	1.7 h 1
1237.3 6	2.3 3	^{234}Np	4.4 d 1
1238.11 3	5.92 12	^{214}Bi	19.9 m 4
1262.6 1	1.89 6	^{209}At	5.41 h 5
1266.2 3	1.68 21	^{238}Am	98 m 2
1280.96 2	1.47 6	^{214}Bi	19.9 m 4
1353.3 6	1.7 5	^{234}Pa	6.70 h 5
1362.9 1	33.1 21	^{211}Rn	14.6 h 2
1377.65 3	4.02 11	^{214}Bi	19.9 m 4
1392.2 7	2.1 4	^{234}Np	4.4 d 1
1394.1 5	3.0 9	^{234}Pa	6.70 h 5
1394.42 9	0.99 5	^{209}Rn	28.5 m 10
1401.50 4	1.39 5	^{214}Bi	19.9 m 4
1407.98 4	2.48 6	^{214}Bi	19.9 m 4
1435.7 6	6.2 8	^{234}Np	4.4 d 1
1452.7 10	1.0 2	^{234}Pa	6.70 h 5
1459.2 5	1.04 21	^{228}Ac	6.13 h
1495.8 5	1.05 18	^{228}Ac	6.13 h
1496.9 1	1.3 1	^{240}Np	7.4 m 2
1509.19 4	2.19 7	^{214}Bi	19.9 m 4
1527.5 6	11.7 15	^{234}Np	4.4 d 1
1538.8 2	4.8 5	^{211}Rn	14.6 h 2
1558.7 6	10	^{234}Np	4.4 d 1
x1559.8	1.9	^{236}Pa	9.1 m 2
1566 4	98 13	^{209}Tl	2.20 m 7
1570.7 6	5.5 7	^{234}Np	4.4 d 1
1577.3 3	2.9 4	^{238}Am	98 m 2
1581.6 1	1.79 6	^{209}At	5.41 h 5
1587.9 4	3.7 8	^{228}Ac	6.13 h
1588.0 2	2.43 11	^{228}Pa	22 h 1
1602.2 6	9.6 14	^{234}Np	4.4 d 1
1620.56 7	2.7 1	^{212}Bi	60.55 m 4
1630.4 4	1.95 27	^{228}Ac	6.13 h
1636.6 3	1.26 18	^{238}Am	98 m 2
1661.28 6	1.15 4	^{214}Bi	19.9 m 4
1668.5 10	1.2 2	^{234}Pa	6.70 h 5
1694.6 8	1.2 5	^{234}Pa	6.70 h 5
1729.60 5	3.05 8	^{214}Bi	19.9 m 4
1762.6	5	^{236}Pa	9.1 m 2
1764.51 5	15.9 4	^{214}Bi	19.9 m 4
1808.0	2.0	^{236}Pa	9.1 m 2
1847.44 5	2.12 8	^{214}Bi	19.9 m 4
1887.0 2	1.56 9	^{228}Pa	22 h 1
2041.2	1.6	^{236}Pa	9.1 m 2
2118.54 8	1.21 4	^{214}Bi	19.9 m 4
2204.12 7	4.99 12	^{214}Bi	19.9 m 4
2447.71 10	1.55 3	^{214}Bi	19.9 m 4
2614.6 1	99.790	^{208}Tl	3.07 m 2

x γ-ray not placed in level scheme.

APPENDIX III.A

STRONG α-RADIATIONS ($I_\alpha \geq 1\%$) FROM RADIOACTIVITY, $A \geq 207$

Ordered by Z, A of Parent Nucleus

III.A.2

strong (Iα≥1%) α-rays from nuclei with A>208. From ENSDF: 31 March 1979

Parent	Eα	Iα	Parent T1/2
^{209}Po	4882 3	≤ 99.2	102 y 5
^{209}At	5647 2	4.1	5.41 h 5
^{209}Rn	6039 3	16.9 20	28.5 m 10
^{209}Fr	6646 5	89.0	50.0 s 3
^{209}Ra	7008 5	≤ 100	4.6 s 2
^{209}Ac	7585 15	100	0.10 s 5
^{210}Bi	4568 5	4.8	3.0×10^{6} y 1
	4908 10	39.4 10	3.0×10^{6} y 1
	4946 9	55.0 11	3.0×10^{6} y 1
^{210}Po	5304.51 7	100	138.378 d 7
^{210}Rn	6041 2	≈ 96.0	2.5 h 1
^{211}Bi	6278.8 6	15.96 20	2.14 m 2
	6623.1 6	83.77 20	2.14 m 2
^{211}Po	7270 15	90.87 15	25.2 s 6
	7450.4 16	98.92 3	0.516 s 3
	7990 15	1.657 30	25.2 s 6
	8885 10	7.03 14	25.2 s 6
^{211}At	5867 2	41.70	7.214 h 7
^{211}Rn	5784 2	16.4 7	14.6 h 2
	5851 2	8.8 4	14.6 h 2
^{211}Fr	6534 5	70	3.10 m 2
^{211}Ra	6912 5	93	13 s 2
^{211}Ac	7480 8	99.8	0.25 s 5
^{212}Bi	6050.77 7	25.22 8	60.55 m 4
	6090.06 8	9.63 7	60.55 m 4
^{212}Po	8784.8 3	100	3.05×10^{-7} s 5
^{213}Bi	5870 5	2.00 11	45.63 m 4
^{213}Po	8376 3	99.996 1	4.2 μs 8
^{213}At	9080 12	100	0.11 μs 2
^{213}Rn	7550 15	1	25.0 ms 2
	8088 8	99	25.0 ms 2
^{213}Fr	6775 2	99.1	34.6 s 2
^{213}Ra	6520 3	4.8 9	2.74 m 6
	6623 5	39.2 29	2.74 m 6
	6730 5	36.0 28	2.74 m 6
^{214}Po	7687.09 6	99.9896 6	164.3 μs 20
^{214}At	8819 4	99	short
^{214}Rn	9037 10	100	0.27 μs 2
^{214}Fr	7605 8	≈ 1.0	5.0 ms 2
	7708 5	≈ 1.1	3.35 ms 5
	7937 8	≈ 1.0	5.0 ms 2
	8358 5	4.7 5	5.0 ms 2
	8426 5	93.0 2	5.0 ms 2
	8477 5	50.9 20	3.35 ms 5
	8546 5	46.0 20	3.35 ms 5
^{214}Ra	7136 5	99.9	2.46 s 3
^{214}Ac	7000 15	3.6 9	8.2 s 2
	7082 5	39.2 22	8.2 s 2
	7214 5	46.3 24	8.2 s 2
^{214}Th	7680 10	100	125 ms 25
^{215}Po	7386.4 8	≈ 100	0.001780 s 4
^{215}At	8026 4	≈ 100	0.10 ms 2
^{215}Rn	8674 8	100	2.30 μs 10
^{215}Fr	9360 8	≈ 100	0.09 μs 1
^{215}Ra	7883 6	2.8 4	1.59 ms 9
	8172 6	1.35 40	1.59 ms 9
	8700 4	95.9 10	1.59 ms 9
^{215}Ac	7604 5	99.910	0.17 s 1
^{215}Th	7333 10	7.9 30	1.2 s 2
	7395 8	51.2 30	1.2 s 2
	7524 8	39.4 30	1.2 s 2
^{216}Po	6778.5 5	99.9979 4	0.15 s 1
^{216}At	7697	2.1	0.30 ms 3
	7800 3	97	0.30 ms 3
^{216}Rn	8050 10	(100)	45 μs 5
^{216}Fr	9005 10	100	0.70 μs 2
^{216}Ra	9349 8	100	182 ns 10
^{216}Ac	8198 8	1.7	0.33 ms 2
	8283 8	2.5	0.33 ms 2
	8990 20	10	≈ 0.33 ms
	9028 5	49.2	0.33 ms 2
	9070 8	90	≈ 0.33 ms

Continued on next page

Parent	Eα	Iα	Parent T1/2
^{216}Ac	9106 5	46.2	0.33 ms 2
^{216}Th	7921 8	(100)	0.028 s 2
^{217}At	7067 2	99.92 2	0.0323 s 4
^{218}Po	6002.55 9	99.9789	3.05 m
^{218}At	6654 5	6	≈ 2 s
	6694 3	90	≈ 2 s
	6757 5	3.6	≈ 2 s
^{218}Rn	7133 2	99.8 1	35 ms 5
^{218}Fr	7542 15	1	0.7 ms 6
	7572 10	5	0.7 ms 6
	7867 2	93	0.7 ms 6
^{218}Ra	8390 8	100	14 μs 2
^{218}Ac	9205 15	100	0.27 μs 4
^{218}Th	9665 10	100	109 ns 13
^{219}At	6275 50	97	0.9 m 1
^{219}Rn	6424.7	7.5 5	3.96 s 1
	6552.8	12.2 7	3.96 s 1
	6819.3 3	80.9 10	3.96 s 1
^{219}Fr	7313.2 20	98.6	21 ms 1
^{219}Ra	7680 10	65 5	10 ms 3
	7982 9	35 2	10 ms 3
^{219}Ac	8664 10	≈ 100	7 μs 2
^{219}Th	9340 20	100	1.05 μs 3
^{220}Rn	6288.29 10	99.93 2	55.6 s 1
^{220}Fr	6413 2	1.25	27.4 s 3
	6482 3	1.3	27.4 s 3
	6527 3	3.0	27.4 s 3
	6535 3	2.5	27.4 s 3
	6582 2	9.8	27.4 s 3
	6630 3	6.5	27.4 s 3
	6642 2	12.2	27.4 s 3
	6686 2	61.3	27.4 s 3
(^{220}Ra)	(6998)	(1%)	(23 ms 5)
^{220}Ra	7455 10	99%	23 ms 5
^{220}Th	8790 20	90	9.7 μs 6
^{221}Fr	6125 2	15.1 2	4.8 m 1
	6242 2	1.35 6	4.8 m 1
	6339.8 17	83.4 8	4.8 m 1
^{222}Rn	5489.66 30	99.92 1	3.8235 d 3
^{222}Ra	6235 4	3.05 5	38.0 s 5
	6556 5	96.9 1	38.0 s 5
^{222}Ac	6460 20	1.8 9	66 s 3
	6710 20	7 4	66 s 3
	6750 20	13 4	66 s 3
	6810 20	24 9	66 s 3
	6840 20	9 4	66 s 3
	6890 20	13 4	66 s 3
	6967 10	6 1	4.2 s 5
	6970 20	7.0 26	66 s 3
	7000 20	13 4	66 s 3
	7013 2	94 1	4.2 s 5
^{222}Th	7982 8	100	2.8 ms 3
^{222}Pa	≈ 8180	≈ 50	5.7 ms 5
	≈ 8330	≈ 20	5.7 ms 5
	≈ 8540	≈ 30	5.7 ms 5
^{223}Ra	5433.6 5	2.27 20	11.434 d 2
	5501.6 10	1.00 15	11.434 d 2
	5540.0 10	9.16 30	11.434 d 2
	5606.9 3	24.2 4	11.434 d 2
	5716.4 3	52.5 8	11.434 d 2
	5747.2 4	9.50 58	11.434 d 2
^{223}Ac	6473.0 15	3.07 30	2.2 m 1
	6528.4 15	3.07 30	2.2 m 1
^{223}Ac	6563.0 10	13 1	2.2 m 1
	6646.0 10	44 4	2.2 m 1
	6660.9 10	31.5 30	2.2 m 1
^{223}Th	7287 10	60 10	0.66 s 1
	7317 10	40 10	0.66 s 1
^{223}Pa	8006 10	55 5	6.5 ms 10
	8196 10	45 5	6.5 ms 10
^{224}Ra	5449	4.9 4	3.66 d 4
	5685.56 20	95.1 4	3.66 d 4

strong (Iα≥1%) α-rays from nuclei with A>208. From ENSDF: 31 March 1979 continued

Parent	Eα	Iα	Parent T1/2
^{224}Ac	6056.0 7	2.2	2.9 h 2
	6137.9 7	2.6	2.9 h 2
	6203.2 7	1.2	2.9 h 2
	6210.0 7	2.0	2.9 h 2
^{224}Th	6770	1.2 4	1.04 s 5
	7000 10	19 3	1.04 s 5
	7170 10	79 3	1.04 s 5
^{225}Ac	5579 2	1.2 1	10.0 d 1
	5608 3	1.1 1	10.0 d 1
	5637 2	4.35 20	10.0 d 1
	5681 1	1.3 2	10.0 d 1
	5723 2	3.2 4	10.0 d 1
	5731 2	10.1	10.0 d 1
	5790.6	8.6	10.0 d 1
	5792.5	18.1 20	10.0 d 1
	5829 1	50.65	10.0 d 1
^{226}Ra	4601.9 5	5.55 5	1600 y 7
	4784.50 25	94.45 5	1600 y 7
^{226}Th	6099.5 50	1.27 5	30.9 m
	6234.0 50	22.8 2	30.9 m
	6337.5 50	75.5 3	30.9 m
^{226}Pa	6823 10	34	1.8 m 2
	6863 10	38	1.8 m 2
^{226}U	7430 30	100	0.5 s 2
^{227}Th	5668.0 15	2.06 12	18.718 d 5
	5693.0 16	1.50 10	18.718 d 5
	5700.8 16	3.63 20	18.718 d 5
	5709.0 16	8.2 3	18.718 d 5
	5713.2 16	4.89 20	18.718 d 5
	5757.06 15	20.3 10	18.718 d 5
	5807.5 15	1.27 2	18.718 d 5
	5866.6 15	2.42 10	18.718 d 5
	5959.7 15	3.00 15	18.718 d 5
	5977.92 10	23.4 10	18.718 d 5
	6008.8 15	2.90 15	18.718 d 5
	6038.21 15	24.5 10	18.718 d 5
^{227}Pa	6356	7	38.3 m 3
	6376	2.2	38.3 m 3
	6401	8	38.3 m 3
	6415	13	38.3 m 3
	6423	10	38.3 m 3
	6465 5	43	38.3 m 3
^{228}Th	5340.54 15	26.7 2	1.9131 y 9
	5423.33 22	72.7	1.9131 y 9
^{228}U	6590	28	9.1 m 2
	6684 10	67	9.1 m 2
^{229}Th	4797.8 12	1.27	7340 y 160
	4814.6 12	9.30 8	7340 y 160
	≈ 4837	4.8	7340 y 160
	4845.3 12	56.2 2	7340 y 160
	4901.0 12	10.20 8	7340 y 160
	4967.5 12	5.97 6	7340 y 160
	4978.5 12	3.17 4	7340 y 160
	≈ 5050	5.2	7340 y 160
	≈ 5052	1.6	7340 y 160
^{229}U	6297 3	2.20 20	58 m 3
	6332 3	4.0 4	58 m 3
	6360 3	12.8 4	58 m 3
^{229}Np	6890 20	50	4.0 m 2
^{230}Th	4621.0 15	23.4 1	7.7×10^{4} y 2
	4687.5 15	76.3 3	7.7×10^{4} y 2
^{230}U	5817.7 7	32.0 2	20.8 d
	5888.5 7	67.4 4	20.8 d
^{231}Pa	4680 2	1.5	3.276×10^{4} y 11
	4712 2	1	3.276×10^{4} y 11
	4736 2	8.4	3.276×10^{4} y 11
	4851 2	1.4	3.276×10^{4} y 11
	4933 2	3.0	3.276×10^{4} y 11
	4950	22.8	3.276×10^{4} y 11
	4984 2	1.4	3.276×10^{4} y 11
	5011 2	25.4	3.276×10^{4} y 11
	5028	20	3.276×10^{4} y 11
	5030.5 20	≈ 2.5	3.276×10^{4} y 11
^{231}Pa	5057.3 20	11.0	3.276×10^{4} y 11
^{231}Np	≈ 6280	(1.6)	48.8 m 2
^{232}Th	3953	23 3	1.405×10^{10} y 6
	4010 5	77 3	1.405×10^{10} y 6
^{232}U	5263.54 9	31.2 4	72 y 2
	5320.30 14	68.6 4	72 y 2
^{232}Pu	6542 10	≈ 8	34.1 m 7
	6600 10	≈ 12	34.1 m 7
^{233}U	4729	1.61	1.592×10^{5} y 2
	4783.5 12	13.2 2	1.592×10^{5} y 2
	4824.2 12	84.4 5	1.592×10^{5} y 2
^{234}U	4723.7 20	27.5 15	2.445×10^{5} y 10
	4775.8 20	72.5 20	2.445×10^{5} y 10
^{234}Pu	6151	1	8.8 h 1
	6202 5	4.1	8.8 h 1
^{235}U	4217 3	5.7 6	703.8×10^{6} y 5
	4325	4.6 5	703.8×10^{6} y 5
	≈ 4344	≈ 1.5	703.8×10^{6} y 5
	4364 5	≈ 11	703.8×10^{6} y 5
	4370 4	≈ 6	703.8×10^{6} y 5
	4396 3	55 3	703.8×10^{6} y 5
	4414 4	2.1 2	703.8×10^{6} y 5
	4502 2	1.7 2	703.8×10^{6} y 5
	4556 2	4.2 3	703.8×10^{6} y 5
	4598 2	5.0 5	703.8×10^{6} y 5
^{236}U	4445 5	26 4	2.3415×10^{7} y 14
	4494 3	74 4	2.3415×10^{7} y 14
^{236}Pu	5721.9 10	31.8 9	2.851 y 8
	5770.1 10	68.1 8	2.851 y 8
^{237}Np	4639.5 20	6.18 12	2.14×10^{6} y 1
	4664.1 20	3.32 10	2.14×10^{6} y 1
	4708.3 20	1.0	2.14×10^{6} y 1
	4766.1 15	8 3	2.14×10^{6} y 1
	4771.1 15	25 6	2.14×10^{6} y 1
	4788.1 15	47 9	2.14×10^{6} y 1
	4803.4 20	1.56	2.14×10^{6} y 1
	4817.4 20	2.5 4	2.14×10^{6} y 1
	4873.1 20	2.6 2	2.14×10^{6} y 1
^{238}U	4147 5	23 4	4.468×10^{9} y 3
	4196 5	77 4	4.468×10^{9} y 3
^{238}Pu	5456.5 4	28.3 6	87.74 y 4
	5499.21 20	71.6 6	87.74 y 4
^{239}Pu	(5105)	10.6 13	24065 y
	(5142)	15.1 2	24065 y
	(5155)	73.2 7	24065 y
^{240}Pu	5123	27.0 3	6537 y 10
	5123.43 23	26.5 4	6537 10
	5168.3	73.0 3	6537 y 10
	5168.30 15	73.4 8	6537 10
^{240}Cm	6247.9 6	28.8 6	27 d 1
	6290.7 6	70.7 6	27 d 1
^{240}Cf	(7546)	(30)	1.06 m 15
	7590 10	(70)	1.06 m 15
^{241}Am	5388 1	1.4 2	432.2 y 5
	5442.98 13	12.8 2	432.2 y 5
	5485.74 12	85.2 8	432.2 y 5
^{242}Pu	4856.3 12	22.4 20	3.763×10^{5} y 20
	4900.6 12	77.5 30	3.763×10^{5} y 20
^{242}Cm	6069.63 12	25.9 5	162.8 d 4
	6112.92 8	74.1 5	162.8 d 4
^{243}Am	5181 1	1.1	7380 y 40
	5233.5 10	10.73 1	7380 y 40
	5275.4 10	87.8 5	7380 y 40
^{243}Cm	5686 3	1.6	28.5 y
	5741.6 10	11	28.5 y
	5784.5 10	73 1	28.5 y
	5993 3	5.6	28.5 y
	6010 3	1.0	28.5 y
	6057 3	4.7	28.5 y
	6067 3	1.5	28.5 y
(^{243}Cf)	≈ 7037	(1.5)	(10.7 m 5)
^{243}Cf	7050 20	≈ 7.0	10.7 m 5
^{243}Es	7890 20	≈ 30	21 s 2

Continued on next page

strong (Iα≥1%) α-rays from nuclei with A>208. From ENSDF: 31 March 1979 continued

Parent	Eα	Iα	Parent T1/2
^{244}Pu	4546 1	19.4 8	8.26×10^{7} y 9
^{244}Pu	4589 1	80.6 8	8.26×10^{7} y 9
^{244}Cm	5762.84 3	23.6 2	18.11 y 2
	5804.96 5	76.4 2	18.11 y 2
^{244}Cf	7168 5	25 3	19.4 m 6
	7210 5	75 3	19.4 m 6
^{244}Es	7570 20	≈ 4.0	37 s 4
^{245}Cm	5303.8 10	5.0 1	8500 y 100
	5362.0 7	93.2 5	8500 y 100
^{246}Cm	5343 3	21 1	4730 y 100
	5386 3	79 1	4730 y 100
^{246}Cf	6719 2	21.89 20	35.7 h 5
	6758 2	77.88 20	35.7 h 5
^{246}Es	7350 20	≈ 9.9	7.7 m 5
^{246}Fm	8240 20	74 syst	1.1 s 2
^{247}Cm	4818 4	4.7 3	1.56×10^{7} y 5
	4868 4	71.0 10	1.56×10^{7} y 5
	4941 4	1.6 2	1.56×10^{7} y 5
	4983 4	2.0 2	1.56×10^{7} y 5
	5145 4	1.2 2	1.56×10^{7} y 5
	5210 4	5.7 5	1.56×10^{7} y 5
	5265 4	13.8 7	1.56×10^{7} y 5
^{247}Bk	5456 5	1.5 2	1380 y 250
	5501 5	7 1	1380 y 250
	5531 5	45 2	1380 y 250
	5654 5	5.5 6	1380 y 250
	5688 5	13 1	1380 y 250
	5710 5	17 1	1380 y 250
	5754 5	4.3 4	1380 y 250
	5794 5	5.5 5	1380 y 250
^{247}Fm	7870 50	≈ 35	35 s 4
	7930 50	≈ 15	35 s 4
^{248}Cm	5034 2	16.6 12	3.39×10^{5} y 3
	5078 2	75.1 12	3.39×10^{5} y 3
^{248}Cf	≈ 6220	17.0 5	333.5 d 28
	6260 30	83.0 5	333.5 d 28
^{248}Fm	7830 20	20	36 s 3
	7870 20	80	36 s 3
^{248}Md	8320 20	≈ 15	7 s 3
	8360 30	≈ 5	7 s 3
^{249}Cf	5759.7 10	3.66	350.6 y 21
	5813.5 10	84.4	350.6 y 21
	5849.5 10	1.04	350.6 y 21
	5903.4 10	2.79	350.6 y 21
	5946.2 10	4.0	350.6 y 21
	6139.5 7	1.11	350.6 y 21
	6194.0 7	2.17	350.6 y 21
^{249}Md	8030 20	20	24 s 4
^{250}Cf	5989.1 6	16.2 12	13.08 y 9
	6030.8 6	83.4 12	13.08 y 9
^{250}Fm	7430 30	(72)	30 m 3
^{250}Md	7750 20	≈ 4.2	52 s 6
	7820 30	≈ 1.8	52 s 6
^{251}Cf	5566 2	1.5 2	898 y 44
	5632 1	4.5 10	898 y 44
^{251}Cf	5648 1	3.5 13	898 y 44
	5677 1	35 1	898 y 44
	5738 7	1.0 3	898 y 44
	5762 3	3.8 4	898 y 44
	5793 1	2.0 3	898 y 44
	5814 4	4.2 4	898 y 44
	5852 1	27 1	898 y 44
	6014 3	11.6 5	898 y 44
	6074 3	2.7 3	898 y 44
^{251}Fm	6834 2	1.65 17	5.30 h 7
^{251}No	8600 20	80	0.8 s 3
	8680 20	20	0.8 s 3
^{252}Cf	6075.7 5	15.21 29	2.638 y 10
	6118.3 5	81.60 29	2.638 y 10
^{252}Es	6482 3	1.71 11	350 d 50
^{252}Es	6562 3	10.6 6	350 d 50
	6632 3	63 3	350 d 50
^{252}No	8410 20	(60)	2.3 s 3
^{253}Es	6592 2	6.6 1	20.47 d 3
	6632.73 5	89.8 2	20.47 d 3
^{253}Fm	6676 3	2.78 26	3.00 d 12
	6847 3	1.01 10	3.00 d 12
	6901 4	1.18 11	3.00 d 12
	6943 3	5.1 4	3.00 d 12
^{254}Es	6358.6 20	2.6 3	275.7 d 5
	6415.8 20	1.8 1	275.7 d 5
	6428.8 20	93.1 10	275.7 d 5
^{254}Fm	7147	14 1	3.240 h 2
	7189 5	85 1	3.240 h 2
^{254}No	8100 20	(85)	55 s 5
^{255}Es	6299.5 15	7	39.8 d 12
^{255}Fm	6963 2	5.04 6	20.07 h 7
	7022 2	93.4 3	20.07 h 7
^{255}Md	7326 5	≈ 8.0	27 m 2
^{255}No	7620? 10	2.8 4	3.1 m 2
	7717 11	2.4 4	3.1 m 2
	7771 7	8.9 7	3.1 m 2
	7879 11	4.2 4	3.1 m 2
	7927 7	11.9 2	3.1 m 2
	8007 11	6.3 11	3.1 m 2
	8077 9	11.9 6	3.1 m 2
	8121 6	45.5 13	3.1 m 2
	8266 8	5 1	3.1 m 2
	8312 9	1.9 1	3.1 m 2
^{255}Lr	8350 20	≈ 35	22 s 5
	8370 20	≈ 35	22 s 5
^{256}Fm	6915 5	(7.3)	157.6 m 13
^{256}Md	7140 7	1.49 20	76 m 4
	7210 7	5.9 5	76 m 4
^{256}Lr	8320 20	6.4 16	31 s 3
	8390 20	18 4	31 s 3
	8430 20	27 3	31 s 3
	8480 20	10.4 24	31 s 3
	8520 20	15.2 24	31 s 3
	8640 20	2.4 16	31 s 3
^{257}Fm	6441 4	2.00 30	100.5 d 2
	6519 2	93 1	100.5 d 2
	6696 3	3.19 30	100.5 d 2
^{257}Md	7064 5	≈ 10	5.2 h 5
^{257}No	8220 20	55 3	25 s 2
	8270 20	26 2	25 s 2
	8320 20	19 2	25 s 2
^{257}Lr	8810 20	16.2 17	0.6 s 1
	8870 20	68.9 17	0.6 s 1
^{257}104	8700	≈ 12	4.8 s 3
	8780	≈ 16	4.8 s 3
	8950	≈ 25	4.8 s 3
	9000 20	≈ 29	4.8 s 3
^{258}Md	6716 5	72 10	55 d 4
	6790 10	28 6	55 d 4
^{259}No	7455 10	13 4	58 m 5
	7500 10	39 10	58 m 5
	7533 10	23 8	58 m 5
	7605 10	14 5	58 m 5
	7685 10	11 4	58 m 5
^{259}Lr	8450 20	≈ 90	5.4 s 8
^{259}104	8770	≈ 48	3.2 s 8
	8860	≈ 32	3.2 s 8
^{260}Lr	8030 20	≈ 6000	180 s 30
^{260}105	9041 14	48 5	1.52 s 13
	9060 20	50	1.6 s 3
	9074 14	25 3	1.52 s 13
	9100 20	23	1.6 s 3
	9120 17	17 3	1.52 s 13
	9140 20	18	1.6 s 3

APPENDIX III.B

STRONG α-RADIATIONS ($I_\alpha \geq 1\%$) FROM RADIOACTIVITY, $A \geq 207$

Ordered by α-Energy

III.B.2

strong ($I_\alpha \geq 1\%$) α-rays from nuclei with A>208. From ENSDF: 31 March 1979

Eα	Iα	Parent	Parent T1/2	Eα	Iα	Parent	Parent T1/2
3953	23 3	^{232}Th	1.405×10^{10} y 6	(5155)	73.2 7	^{239}Pu	24065 y
4010 5	77 3	^{232}Th	1.405×10^{10} y 6	5168.3	73.0 3	^{240}Pu	6537 y 10
4147 5	23 4	^{238}U	4.468×10^{9} y 3	5168.30 15	73.4 8	^{240}Pu	6537 y 10
4196 5	77 4	^{238}U	4.468×10^{9} y 3	5181 1	1.1	^{243}Am	7380 y 40
4217 3	5.7 6	^{235}U	703.8×10^{6} y 5	5210 4	5.7 5	^{247}Cm	1.56×10^{7} y 5
4325	4.6 5	^{235}U	703.8×10^{6} y 5	5233.5 10	10.73 1	^{243}Am	7380 y 40
≈ 4344	≈ 1.5	^{235}U	703.8×10^{6} y 5	5263.54 9	31.2 4	^{232}U	72 y 2
4364 5	≈ 11	^{235}U	703.8×10^{6} y 5	5265 4	13.8 7	^{247}Cm	1.56×10^{7} y 5
4370 4	≈ 6	^{235}U	703.8×10^{6} y 5	5275.4 10	87.8 5	^{243}Am	7380 y 40
4396 3	55 3	^{235}U	703.8×10^{6} y 5	5303.8 10	5.0 1	^{245}Cm	8500 y 100
4414 4	2.1 2	^{235}U	703.8×10^{6} y 5	5304.51 7	100	^{210}Po	138.378 d 7
4445 5	26 4	^{236}U	2.3415×10^{7} y 14	5320.30 14	68.6 4	^{232}U	72 y 2
4494 3	74 4	^{236}U	2.3415×10^{7} y 14	5340.54 15	26.7 2	^{228}Th	1.9131 y 9
4502 2	1.7 2	^{235}U	703.8×10^{6} y 5	5343 3	21 1	^{246}Cm	4730 y 100
4546 1	19.4 8	^{244}Pu	8.26×10^{7} y 9	5362.0 7	93.2 5	^{245}Cm	8500 y 100
4556 2	4.2 3	^{235}U	703.8×10^{6} y 5	5386 3	79 1	^{246}Cm	4730 y 100
4568 5	4.8	^{210}Bi	3.0×10^{6} y 1	5388 1	1.4 2	^{241}Am	432.2 y 5
4589 1	80.6 8	^{244}Pu	8.26×10^{7} y 9	5423.33 22	72.7	^{228}Th	1.9131 y 9
4598 2	5.0 5	^{235}U	703.8×10^{6} y 5	5433.6 5	2.27 20	^{223}Ra	11.434 d 2
4601.9 5	5.55 5	^{226}Ra	1600 y 7	5442.98 13	12.8 2	^{241}Am	432.2 y 5
4621.0 15	23.4 1	^{230}Th	7.7×10^{4} y 2	5449	4.9 4	^{224}Ra	3.66 d 4
4639.5 20	6.18 12	^{237}Np	2.14×10^{6} y 1	5456 5	1.5 2	^{247}Bk	1380 y 250
4664.1 20	3.32 10	^{237}Np	2.14×10^{6} y 1	5456.5 4	28.3 6	^{238}Pu	87.74 y 4
4680 2	1.5	^{231}Pa	3.276×10^{4} y 11	5485.74 12	85.2 8	^{241}Am	432.2 y 5
4687.5 15	76.3 3	^{230}Th	7.7×10^{4} y 2	5489.66 30	99.92 1	^{222}Rn	3.8235 d 3
4708.3 20	1.0	^{237}Np	2.14×10^{6} y 1	5499.21 20	71.6 6	^{238}Pu	87.74 y 4
4712 2	1	^{231}Pa	3.276×10^{4} y 11	5501 5	7 1	^{247}Bk	1380 y 250
4723.7 20	27.5 15	^{234}U	2.445×10^{5} y 10	5501.6 10	1.00 15	^{223}Ra	11.434 d 2
4729	1.61	^{233}U	1.592×10^{5} y 2	5531 5	45 2	^{247}Bk	1380 y 250
4736 2	8.4	^{231}Pa	3.276×10^{4} y 11	5540.0 10	9.16 30	^{223}Ra	11.434 d 2
4766.1 15	8 3	^{237}Np	2.14×10^{6} y 1	5566 2	1.5 2	^{251}Cf	898 y 44
4771.1 15	25 6	^{237}Np	2.14×10^{6} y 1	5579 2	1.2 1	^{225}Ac	10.0 d 1
4775.8 20	72.5 20	^{234}U	2.445×10^{5} y 10	5606.9 3	24.2 4	^{223}Ra	11.434 d 2
4783.5 12	13.2 2	^{233}U	1.592×10^{5} y 2	5608 3	1.1 1	^{225}Ac	10.0 d 1
4784.50 25	94.45 5	^{226}Ra	1600 y 7	5632 1	4.5 10	^{251}Cf	898 y 44
4788.1 15	47 9	^{237}Np	2.14×10^{6} y 1	5637 2	4.35 20	^{225}Ac	10.0 d 1
4797.8 12	1.27	^{229}Th	7340 y 160	5647 2	4.1	^{209}At	5.41 h 5
4803.4 20	1.56	^{237}Np	2.14×10^{6} y 1	5648 1	3.5 13	^{251}Cf	898 y 44
4814.6 12	9.30 8	^{229}Th	7340 y 160	5654 5	5.5 6	^{247}Bk	1380 y 250
4817.4 20	2.5 4	^{237}Np	2.14×10^{6} y 1	5668.0 15	2.06 12	^{227}Th	18.718 d 5
4818 4	4.7 3	^{247}Cm	1.56×10^{7} y 5	5677 1	35 1	^{251}Cf	898 y 44
4824.2 12	84.4 5	^{233}U	1.592×10^{5} y 2	5681 1	1.3 2	^{225}Ac	10.0 d 1
≈ 4837	4.8	^{229}Th	7340 y 160	5685.56 20	95.1 4	^{224}Ra	3.66 d 4
4845.3 12	56.2 2	^{229}Th	7340 y 160	5686 3	1.6	^{243}Cm	28.5 y
4851 2	1.4	^{231}Pa	3.276×10^{4} y 11	5688 5	13 1	^{247}Bk	1380 y 250
4856.3 12	22.4 20	^{242}Pu	3.763×10^{5} y 20	5693.0 16	1.50 10	^{227}Th	18.718 d 5
4868 4	71.0 10	^{247}Cm	1.56×10^{7} y 5	5700.8 16	3.63 20	^{227}Th	18.718 d 5
4873.1 20	2.6 2	^{237}Np	2.14×10^{6} y 1	5709.0 16	8.2 3	^{227}Th	18.718 d 5
4882 3	≤ 99.2	^{209}Po	102 y 5	5710 5	17 1	^{247}Bk	1380 y 250
4900.6 12	77.5 30	^{242}Pu	3.763×10^{5} y 20	5713.2 16	4.89 20	^{227}Th	18.718 d 5
4901.0 12	10.20 8	^{229}Th	7340 y 160	5716.4 3	52.5 8	^{223}Ra	11.434 d 2
4908 10	39.4 10	^{210}Bi	3.0×10^{6} y 1	5721.9 10	31.8 9	^{236}Pu	2.851 y 8
4933 2	3.0	^{231}Pa	3.276×10^{4} y 11	5723 2	3.2 4	^{225}Ac	10.0 d 1
4941 4	1.6 2	^{247}Cm	1.56×10^{7} y 5	5731 2	10.1	^{225}Ac	10.0 d 1
4946 9	55.0 11	^{210}Bi	3.0×10^{6} y 1	5738 7	1.0 3	^{251}Cf	898 y 44
4950	22.8	^{231}Pa	3.276×10^{4} y 11	5741.6 10	11	^{243}Cm	28.5 y
4967.5 12	5.97 6	^{229}Th	7340 y 160	5747.2 4	9.50 58	^{223}Ra	11.434 d 2
4978.5 12	3.17 4	^{229}Th	7340 y 160	5754 5	4.3 4	^{247}Bk	1380 y 250
4983 4	2.0 2	^{247}Cm	1.56×10^{7} y 5	5757.06 15	20.3 10	^{227}Th	18.718 d 5
4984 2	1.4	^{231}Pa	3.276×10^{4} y 11	5759.7 10	3.66	^{249}Cf	350.6 y 21
5011 2	25.4	^{231}Pa	3.276×10^{4} y 11	5762 3	3.8 4	^{251}Cf	898 y 44
5028	20	^{231}Pa	3.276×10^{4} y 11	5762.84 3	23.6 2	^{244}Cm	18.11 y 2
5030.5 20	≈ 2.5	^{231}Pa	3.276×10^{4} y 11	5770.1 10	68.1 8	^{236}Pu	2.851 y 8
5034 2	16.6 12	^{240}Cm	3.39×10^{5} y 3	5784 2	16.4 7	^{211}Rn	14.6 h 2
≈ 5050	5.2	^{229}Th	7340 y 160	5784.5 10	73 1	^{243}Cm	28.5 y
≈ 5052	1.6	^{229}Th	7340 y 160	5790.6	8.6	^{225}Ac	10.0 d 1
5057.3 20	11.0	^{231}Pa	3.276×10^{4} y 11	5792.5	18.1 20	^{225}Ac	10.0 d 1
5078 2	75.1 12	^{240}Cm	3.39×10^{5} y 3	5793 1	2.0 3	^{251}Cf	898 y 44
(5105)	10.6 13	^{239}Pu	24065 y	5794 5	5.5 5	^{247}Bk	1380 y 250
5123	27.0 3	^{240}Pu	6537 y 10	5804.96 5	76.4 2	^{244}Cm	18.11 y 2
5123.43 23	26.5 4	^{240}Pu	6537 y 10	5807.5 15	1.27 2	^{227}Th	18.718 d 5
(5142)	15.1 2	^{239}Pu	24065 y	5813.5 10	84.4	^{249}Cf	350.6 y 21
5145 4	1.2 2	^{247}Cm	1.56×10^{7} y 5	5814 4	4.2 4	^{251}Cf	898 y 44

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strong (Iα≥1%) α-rays from nuclei with A>208. From ENSDF: 31 March 1979 continued

Eα	Iα	Parent	Parent T1/2
5817.7 7	32.0 2	^{230}U	20.8 d
5829 1	50.65	^{225}Ac	10.0 d 1
5849.5 10	1.04	^{249}Cf	350.6 y 21
5851 2	8.8 4	^{211}Rn	14.6 h 2
5852 1	27 1	^{251}Cf	898 y 44
5866.6 15	2.42 10	^{227}Th	18.718 d 5
5867 2	41.70	^{211}At	7.214 h 7
5870 5	2.00 11	^{213}Bi	45.63 m 4
5886.5 7	67.4 4	^{230}U	20.8 d
5903.4 10	2.79	^{249}Cf	350.6 y 21
5946.2 10	4.0	^{249}Cf	350.6 y 21
5959.7 15	3.00 15	^{227}Th	18.718 d 5
5977.92 10	23.4 10	^{227}Th	18.718 d 5
5989.1 6	16.2 12	^{250}Cf	13.08 y 9
5993 3	5.6	^{243}Cm	28.5 y
6002.55 9	99.9789	^{218}Po	3.05 m
6008.8 15	2.90 15	^{227}Th	18.718 d 5
6010 3	1.0	^{243}Cm	28.5 y
6014 3	11.6 5	^{251}Cf	898 y 44
6030.8 6	83.4 12	^{250}Cf	13.08 y 9
6038.21 15	24.5 10	^{227}Th	18.718 d 5
6039 3	16.9 20	^{209}Rn	28.5 m 10
6041 2	≈ 96.0	^{210}Rn	2.5 h 1
6050.77 7	25.22 8	^{212}Bi	60.55 m 4
6056.0 7	2.2	^{224}Ac	2.9 h 2
6057 3	4.7	^{243}Cm	28.5 y
6067 3	1.5	^{243}Cm	28.5 y
6069.63 12	25.9 5	^{242}Cm	162.8 d 4
6074 3	2.7 3	^{251}Cf	898 y 44
6075.7 5	15.21 29	^{252}Cf	2.638 y 10
6090.06 8	9.63 7	^{212}Bi	60.55 m 4
6099.5 50	1.27 5	^{226}Th	30.9 m
6112.92 8	74.1 5	^{242}Cm	162.8 d 4
6118.3 5	81.60 29	^{252}Cf	2.638 y 10
6125 2	15.1 2	^{221}Fr	4.8 m 1
6137.9 7	2.6	^{224}Ac	2.9 h 2
6139.5 7	1.11	^{249}Cf	350.6 y 21
6151	1	^{234}Pu	8.8 h 1
6194.0 7	2.17	^{249}Cf	350.6 y 21
6202 5	4.1	^{234}Pu	8.8 h 1
6203.2 7	1.2	^{224}Ac	2.9 h 2
6210.0 7	2.0	^{224}Ac	2.9 h 2
≈ 6220	17.0 5	^{248}Cf	333.5 d 28
6234.0 50	22.8 2	^{226}Th	30.9 m
6235 4	3.05 5	^{222}Ra	38.0 s 5
6242 2	1.35 6	^{221}Fr	4.8 m 1
6247.9 6	28.8 6	^{240}Cm	27 d 1
6260 30	83.0 5	^{248}Cf	333.5 d 28
6275 50	97	^{219}At	0.9 m 1
6278.8 6	15.96 20	^{211}Bi	2.14 m 2
≈ 6280	(1.6)	^{231}Np	48.8 m 2
6288.29 10	99.93 2	^{220}Rn	55.6 s 1
6290.7 6	70.7 6	^{240}Cm	27 d 1
6297 3	2.20 20	^{229}U	58 m 3
6299.5 15	7	^{255}Es	39.8 d 12
6332.3	4.0 4	^{229}U	58 m 3
6337.5 50	75.5 3	^{226}Th	30.9 m
6339.8 17	83.4 8	^{221}Fr	4.8 m 1
6356	7	^{227}Pa	38.3 m 3
6358.6 20	2.6 3	^{254}Es	275.7 d 5
6360 3	12.8 4	^{229}U	58 m 3
6376	2.2	^{227}Pa	38.3 m 3
6401	8	^{227}Pa	38.3 m 3
6413 2	1.25	^{220}Fr	27.4 s 3
6415	13	^{227}Pa	38.3 m 3
6415.8 20	1.8 1	^{254}Es	275.7 d 5
6423	10	^{227}Pa	38.3 m 3
6424.7	7.5 5	^{219}Rn	3.96 s 1
6428.8 20	93.1 10	^{254}Es	275.7 d 5
6441 4	2.00 30	^{257}Fm	100.5 d 2
6460 20	1.8 9	^{222}Ac	66 s 3
6465 5	43	^{227}Pa	38.3 m 3
6473.0 15	3.07 30	^{223}Ac	2.2 m 1
6482 3	1.3	^{220}Fr	27.4 s 3
	1.71 11	^{252}Es	350 d 50
6519 2	93 1	^{257}Fm	100.5 d 2
6520 3	4.8 9	^{213}Ra	2.74 m 6
6527 3	3.0	^{220}Fr	27.4 s 3
6528.4 15	3.07 30	^{223}Ac	2.2 m 1
6534 5	70	^{211}Fr	3.10 m 2
6535 3	2.5	^{220}Fr	27.4 s 3
6542 10	≈ 8	^{232}Pu	34.1 m 7
6552.8	12.2 7	^{219}Rn	3.96 s 1
6556 5	96.9 1	^{222}Ra	38.0 s 5
6562 3	10.6 6	^{252}Es	350 d 50
6563.0 10	13 1	^{223}Ac	2.2 m 1
6582 2	9.8	^{220}Fr	27.4 s 3
6590	28	^{228}U	9.1 m 2
6592 2	6.6 1	^{253}Es	20.47 d 3
6600 10	≈ 12	^{232}Pu	34.1 m 7
6623 5	39.2 29	^{213}Ra	2.74 m 6
6623.1 6	83.77 20	^{211}Bi	2.14 m 2
6630 3	6.5	^{220}Fr	27.4 s 3
6632 3	63 3	^{252}Es	350 d 50
6632.73 5	89.8 2	^{253}Es	20.47 d 3
6642 2	12.2	^{220}Fr	27.4 s 3
6646 5	89.0	^{209}Fr	50.0 s 3
6646.0 10	44 4	^{223}Ac	2.2 m 1
6654 5	6	^{218}At	≈ 2 s
6660.9 10	31.5 30	^{223}Ac	2.2 m 1
6676 3	2.78 26	^{253}Fm	3.00 d 12
6684 10	67	^{228}U	9.1 m 2
6686 2	61.3	^{220}Fr	27.4 s 3
6694 3	90	^{218}At	≈ 2 s
6696 3	3.19 30	^{257}Fm	100.5 d 2
6710 20	7 4	^{222}Ac	66 s 3
6716 5	72 10	^{258}Md	55 d 4
6719 2	21.89 20	^{246}Cf	35.7 h 5
6730 5	36.0 28	^{213}Ra	2.74 m 6
6750 20	13 4	^{222}Ac	66 s 3
6757 5	3.6	^{218}At	≈ 2 s
6758 2	77.88 20	^{246}Cf	35.7 h 5
6770	1.2 4	^{224}Th	1.04 s 5
6775 2	99.1	^{213}Fr	34.6 s 2
6778.5 5	99.9979 4	^{216}Po	0.15 s 1
6790 10	28 6	^{258}Md	55 d 4
6810 20	24 9	^{222}Ac	66 s 3
6819.3 3	80.9 10	^{219}Rn	3.96 s 1
6823 10	34	^{226}Pa	1.8 m 2
6834 2	1.65 17	^{251}Fm	5.30 h 7
6840 20	9 4	^{222}Ac	66 s 3
6847 3	1.01 10	^{253}Fm	3.00 d 12
6863 10	38	^{226}Pa	1.8 m 2
6890 20	13 4	^{222}Ac	66 s 3
	50	^{229}Np	4.0 m 2
6901 4	1.18 11	^{253}Fm	3.00 d 12
6912 5	93	^{211}Ra	13 s 2
6915 5	(7.3)	^{256}Fm	157.6 m 13
6943 3	5.1 4	^{253}Fm	3.00 d 12
6963 2	5.04 6	^{255}Fm	20.07 h 7
6967 10	6 1	^{222}Ac	4.2 s 5
6970 20	7.0 26	^{222}Ac	66 s 3
(6998)	(1%)	(^{220}Ra)	(23 ms 5)
7000 15	3.6 9	^{214}Ac	8.2 s 2
7000 20	13 4	^{222}Ac	66 s 3
7000 10	19 3	^{224}Th	1.04 s 5
7008 5	≤ 100	^{209}Ra	4.6 s 2
7013 2	94 1	^{222}Ac	4.2 s 5
7022 2	93.4 3	^{255}Fm	20.07 h 7
≈ 7037	(1.5)	(^{243}Cf)	(10.7 m 5)
7050 20	≈ 7.0	^{243}Cf	10.7 m 5
7064 5	≈ 10	^{257}Md	5.2 h 5
7067 2	99.92 2	^{217}At	0.0323 s 4
7082 5	39.2 22	^{214}Ac	8.2 s 2
7133 2	99.8 1	^{216}Rn	35 ms 5
7136 5	99.9	^{214}Ra	2.46 s 3

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strong (Iα≥1%) α-rays from nuclei with A>208. From ENSDF: 31 March 1979 continued

Eα	Iα	Parent	Parent T1/2
7140 7	1.49 20	^{256}Md	76 m 4
7147	14 1	^{254}Fm	3.240 h 2
7168 5	25 3	^{244}Cf	19.4 m 6
7170 10	79 3	^{224}Th	1.04 s 5
7189 5	85 1	^{254}Fm	3.240 h 2
7210 7	5.9 5	^{256}Md	76 m 4
7210 5	75 3	^{244}Cf	19.4 m 6
7214 5	46.3 24	^{214}Ac	8.2 s 2
7270 15	90.87 15	^{211}Po	25.2 s 6
7287 10	60 10	^{223}Th	0.66 s 1
7313.2 20	98.6	^{219}Fr	21 ms 1
7317 10	40 10	^{223}Th	0.66 s 1
7326 5	≈ 8.0	^{255}Md	27 m 2
7333 10	7.9 30	^{215}Th	1.2 s 2
7335 5	≈ 10	^{241}Cf	3.78 m 70
7350 20	≈ 9.9	^{246}Es	7.7 m 5
7386.4 8	≈ 100	^{215}Po	0.001780 s 4
7395 8	51.2 30	^{215}Th	1.2 s 2
7430 30	(72)	^{250}Fm	30 m 3
	100	^{226}U	0.5 s 2
7450.4 16	98.92 3	^{211}Po	0.516 s 3
7455 10	13 4	^{259}No	58 m 5
	99%	^{220}Ra	23 ms 5
7480 8	99.8	^{211}Ac	0.25 s 5
7500 10	39 10	^{259}No	58 m 5
7524 8	39.4 30	^{215}Th	1.2 s 2
7533 10	23 8	^{259}No	58 m 5
7542 15	1	^{218}Fr	0.7 ms 6
(7546)	(30)	^{240}Cf	1.06 m 15
7550 15	1	^{213}Rn	25.0 ms 2
7570 20	≈ 4.0	^{244}Es	37 s 4
7572 10	5	^{218}Fr	0.7 ms 6
7585 15	100	^{209}Ac	0.10 s 5
7590 10	(70)	^{240}Cf	1.06 m 15
7604 5	99.910	^{215}Ac	0.17 s 1
7605 8	≈ 1.0	^{214}Fr	5.0 ms 2
7605 10	14 5	^{259}No	58 m 5
7620? 10	2.8 4	^{255}No	3.1 m 2
7680 10	65 5	^{219}Ra	10 ms 3
	100	^{214}Th	125 ms 25
7685 10	11 4	^{259}No	58 m 5
7687.09 6	99.9896 6	^{214}Po	164.3 μs 20
7697	2.1	^{216}At	0.30 ms 3
7708 5	≈ 1.1	^{214}Fr	3.35 ms 5
7717 11	2.4 4	^{255}No	3.1 m 2
7750 20	≈ 4.2	^{250}Md	52 s 6
7771 7	8.9 7	^{255}No	3.1 m 2
7800 3	97	^{216}At	0.30 ms 3
7820 30	≈ 1.8	^{250}Md	52 s 6
7830 20	20	^{248}Fm	36 s 3
7867 2	93	^{218}Fr	0.7 ms 6
7870 50	≈ 35	^{247}Fm	35 s 4
7870 20	80	^{248}Fm	36 s 3
7879 11	4.2 4	^{255}No	3.1 m 2
7883 6	2.8 4	^{215}Ra	1.59 ms 9
7890 20	≈ 30	^{243}Es	21 s 2
7921 8	(100)	^{216}Th	0.028 s 2
7927 7	11.9 2	^{255}No	3.1 m 2
7930 50	≈ 15	^{247}Fm	35 s 4
7937 8	≈ 1.0	^{214}Fr	5.0 ms 2
7982 9	35 2	^{219}Ra	10 ms 3
7982 8	100	^{222}Th	2.8 ms 3
7990 15	1.657 30	^{211}Po	25.2 s 6
8006 10	55 5	^{223}Pa	6.5 ms 10
8007 11	6.3 11	^{255}No	3.1 m 2
8026 4	≈ 100	^{215}At	0.10 ms 2
8030 20	20	^{249}Md	24 s 4
	≈ 6000	^{260}Lr	180 s 30
8050 10	(100)	^{216}Rn	45 μs 5
8077 9	11.9 6	^{255}No	3.1 m 2
8088 8	99	^{213}Rn	25.0 ms 2
8100 20	(85)	^{254}No	55 s 5
8121 6	45.5 13	^{255}No	3.1 m 2
8172 6	1.35 40	^{215}Ra	1.59 ms 9
≈ 8180	≈ 50	^{222}Pa	5.7 ms 5
8196 10	45 5	^{223}Pa	6.5 ms 10
8198 8	1.7	^{216}Ac	0.33 ms 2
8220 20	55 3	^{257}No	25 s 2
8240 20	74 syst	^{246}Fm	1.1 s 2
8266 8	5 1	^{255}No	3.1 m 2
8270 20	26 2	^{257}No	25 s 2
8283 8	2.5	^{216}Ac	0.33 ms 2
8312 9	1.9 1	^{255}No	3.1 m 2
8320 20	6.4 16	^{256}Lr	31 s 3
	≈ 15	^{248}Md	7 s 3
	19 2	^{257}No	25 s 2
≈ 8330	≈ 20	^{222}Pa	5.7 ms 5
8350 20	≈ 35	^{255}Lr	22 s 5
8358 5	4.7 5	^{214}Fr	5.0 ms 2
8360 30	≈ 5	^{248}Md	7 s 3
8370 20	≈ 35	^{255}Lr	22 s 5
8376 3	99.996 1	^{213}Po	4.2 μs 8
8390 20	18 4	^{256}Lr	31 s 3
8390 8	100	^{218}Ra	14 μs 2
8410 20	(60)	^{252}No	2.3 s 3
8426 5	93.0 2	^{214}Fr	5.0 ms 2
8430 20	27 3	^{256}Lr	31 s 3
8450 20	≈ 90	^{259}Lr	5.4 s 8
8477 5	50.9 20	^{214}Fr	3.35 ms 5
8480 20	10.4 24	^{256}Lr	31 s 3
8520 20	15.2 24	^{256}Lr	31 s 3
≈ 8540	≈ 30	^{222}Pa	5.7 ms 5
8546 5	46.0 20	^{214}Fr	3.35 ms 5
8600 20	80	^{251}No	0.8 s 3
8640 20	2.4 16	^{256}Lr	31 s 3
8664 10	≈ 100	^{219}Ac	7 μs 2
8674 8	100	^{215}Rn	2.30 μs 10
8680 20	20	^{251}No	0.8 s 3
8700	≈ 12	^{257}104	4.8 s 3
8700 4	95.9 10	^{215}Ra	1.59 ms 9
8770	≈ 48	^{259}104	3.2 s 8
8780	≈ 16	^{257}104	4.8 s 3
8784.8 3	100	^{212}Po	3.05×10^{-7} s 5
8790 20	90	^{220}Th	9.7 μs 6
8810 20	16.2 17	^{257}Lr	0.6 s 1
8819 4	99	^{214}At	short
8860	≈ 32	^{259}104	3.2 s 8
8870 20	68.9 17	^{257}Lr	0.6 s 1
8885 10	7.03 14	^{211}Po	25.2 s 6
8950	≈ 25	^{257}104	4.8 s 3
8990 20	10	^{216}Ac	≈ 0.33 ms
9000 20	≈ 29	^{257}104	4.8 s 3
9005 10	100	^{216}Fr	0.70 μs 2
9028 5	49.2	^{216}Ac	0.33 ms 2
9037 10	100	^{214}Rn	0.27 μs 2
9041 14	48 5	^{260}105	1.52 s 13
9060 20	50	^{260}105	1.6 s 3
9070 8	90	^{216}Ac	≈ 0.33 ms
9074 14	25 3	^{260}105	1.52 s 13
9080 12	100	^{213}At	0.11 μs 2
9100 20	23	^{260}105	1.6 s 3
9106 5	46.2	^{216}Ac	0.33 ms 2
9120 17	17 3	^{260}105	1.52 s 13
9140 20	18	^{260}105	1.6 s 3
9205 15	100	^{216}Ac	0.27 μs 4
9340 20	100	^{219}Th	1.05 μs 3
9349 8	100	^{216}Ra	182 ns 10
9360 8	≈ 100	^{215}Fr	0.09 μs 1
9665 10	100	^{218}Th	109 ns 13

COORDINATED RESEARCH PROGRAMME ON THE INTERCOMPARISON OF EVALUATIONS OF ACTINIDE NEUTRON NUCLEAR DATA

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Abstract

This report describes the development of the IAEA Coordinated Research Programme (CRP) on the intercomparison of evaluations of actinide neutron nuclear data, and reviews the achievments of this programme since its inception in 1977. Some practical problems and recommendations for the future work of this CRP are proposed.

1. INTRODUCTION

In November 1975, the First Advisory Group Meeting on Transactinium Isotope Nuclear Data (TND), Karlsruhe[1], noting "that transactinium isotopes are becoming more and more important in nuclear technology" and also "that the present knowledge of nuclear data required to evaluate the effects of transactinium isotopes in nuclear technology is not satisfactory", recommended as follows:

General Recommendation

1.1 In view of the above, the meeting recommends that an internationally coordinated effort be implemented, and pursued during the next ten years so as to improve the status of transactinium neutron nuclear data required for nuclear technology. The results from the first phase of this effort should be made available and reviewed after the first three to five years of this effort.

This recommendation of 1975 has special significance, and special urgency, in 1979 in view of the growing emphasis on once-through high-burnup nuclear fuel cycles for lightwater reactors, alternate fuel cycles, safeguards, recycle and reprocessing, breeders, waste disposal and the whole future of nuclear technology. These topics are treated on an international basis by the many groups and sub-groups in the framework of the International Nuclear Fuel Cycle Evaluation (INFCE) program. All these topics need now and will need more and more in the future better measured and better evaluated transactinium nuclear data.

Following discussions and Consultants Meeting in 1976[2,3], the IAEA, in response to the above recommendation, formed two coordinated research projects (CRP): one on the Intercomparison of Evaluations of Actinide Neutron Nuclear Data, the other on the Measurement and Evaluation of Transactinium Isotope Nuclear Decay Data.

This report covers work done, and to be done, in the framework of the first CRP, as well as some of the practical problems for future work.

2. COORDINATED RESEARCH PROGRAMME ON THE INTERCOMPARISON OF TND EVALUATIONS

The CRP on the Intercomparison of TND Evaluations started in October, 1977. Of the nine countries participating in the programme, (France, Fed. Rep. of Germany, India, Israel, Italy, Japan, Romania, U.K., U.S.S.R.) three countries, India, Italy and the U.S.S.R., started in December 1977, Germany started in March 1978 while the five other countries started in October 1977.

The programme includes six Research Agreements and three Research Contracts.

The First Research Coordination Meeting of the Programme was held in Vienna, April 1978[4].

At this stage, and as a result of this programme, an evaluated neutron data file for some twenty actinide isotopes is envisaged to be completed by the end of 1980. The file will be independent of ENDF/B evaluations, but parts of the file would be included in the national libraries of participants, such as UKNDL, KEDAK, JENDL or SOKRATOR.

The tentative list of evaluations to be completed by the end of 1980 in the framework of this programme includes:

Thorium-232, 233
Protactinium-231, 232, 233
Uranium-233, 234, 236, 237, 239
Neptunium-237, 239
Plutonium-236, 238, 240, 241, 242
Americium-241, 242, 242m, 243
Curium-242, 243, 244, 245, 246, 247, 248

This tentative list of 28 nuclides is subject to modifications, but it is probable that the international actinide neutron data file to be ready by the end of 1980 - beginning of 1981 will include 20 nuclides from this list.

According to IAEA Memoranda[4] the known programme, by country, for 1978-1979 (maybe also 1980), is approximately as follows:

France (J. Salvy) - U-237, 239; Np-237, 239; Pu-240, 242, Am-241; to be continued for other U, Pu and Am isotopes.
Germany F.R. (H. Küsters) - Pu-242, Am-241, 242, 243, Cm-244.
India (M.K. Mehta) - Th-232, to be continued for Th-233.
Israel (S. Yiftah) - Cm-244, to be continued for Cm-246.
Italy (E. Menapace) - Pu-241, 242; Am-241, 243; Cm-242, 245, 246, 247, 248.
Japan (T. Fuketa) - Am-243, Cm-244; to be continued for various isotopes of Th, Pa, U, Np, Pu, Am, Cm.
Romania (G. Vasiliu) - Th-233; U-233; Pa-231, 232, 233.
U.K. (J.E. Lynn) - Am-241, 242m, 243; Cm-242, 244; to be continued after 1980 for Cm-245, 247, 248.
U.S.S.R. (L.N. Usachev) - $\overline{\nu}$, fission and capture cross sections of Am-241. To be continued for other Am and Cm isotopes.
U.S.S.R. (V. Konshin) - Pu-242 (10^{-4} eV to 15 MeV).

This approximate programme, as well as the intended programmes for 1980-1981 and the tentative future programmes for 1982-1987*, to conclude the ten-year international actinide effort recommended by the Karlsruhe 1975 TND meeting, have been discussed, coordinated and spelled out, as far as possible, during the CRP Second Coordination Meeting, Aix-en-Provence, April 30 - May 1, 1979. The conclusions and recommendations of the second meeting of the CRP, including the summary of the CRP programme by country and by isotope are to be published in the report of the second CRP meeting, INDC(NDS)-104/L.

In the meantime it can be stated in brief that according to reports submitted by the participating countries to the IAEA, considerable work has already been accomplished in the framework of the TND CRP.

Thus a full evaluation for Th-232 has been completed by the Romanian group[5] including spherical and deformed optical model calculations, while data compilation and operating spherical and deformed optical model elastic and total and statistical theory (n,2n and n,3n) codes for this isotope have been performed by the Indian group for the fast region up to 20 MeV[6].

* See tables in pages 4 and 5 of INDC(NDS)-89, July 1977, and INDC(NDS)-104/L

The French group reported[7]:

(1) An evaluation for the same Th-232 from 0.3 to 2.4 MeV using deformed optical model, statistical theory and double-humped model for fission.

(2) A simultaneous evaluation of Pu-240 and Pu-242 in the energy range 10 keV - 20 MeV, using a deformed optical model. The statistical theory code NCNR has been used for calculating σ_γ and σ_n' from 10 keV to 3 MeV. A statistical model was used for calculating (n,xn) and (n,xnf).

(3) A preliminary full evaluation for Pu-242 between 10^{-5} eV and 20 MeV. This evaluation which is constructed out of the data of (2) plus ENDF/B-IV between 10^{-5} eV and 10 keV, is compared with ENDF/B-IV and ENDL/76.

(4) An empirical relation has been obtained between fission probabilities and σ_f (thermal) for actinides.

The Italian group reported[8] on evaluations of Pu-241, Pu-242, Am-241 and Cm-242 in the resonance region.

The Japanese group reported[9] on evaluations of Am-243, Cm-244 and Cm-242 in the energy range of thermal to 16 MeV. Evaluations of Am-242 and Am-242^m will start in the near future.

The Israeli group reported[10] on the completion of a full evaluation for Cm-244.

The British group reported the completion of a full evaluation for Am-241. Full evaluations of Am-243 and Am-242^m are in progress.

Some preliminary and illustrative intercomparisons are given in another paper[11] prepared for this conference.

3. EIGHTEEN TRANSACTINIUM ELEMENTS AND TWO HUNDRED ISOTOPES

One would like to be able to assess the scope of the above programme compared with the total problem of TND measurements and evaluations.

Actinium being element number 89, 18 transactinium elements are known to date, from 90 to 107. The eighteen transactinium elements include three naturally occurring elements and fifteen man-made elements. These fifteen elements were discovered as a result of irradiation in nuclear reactors, or, from curium (96) to element 107, by bombardment with heavy ions from heavy-ion accelerators. Einsteinium and fermium,

elements 99 and 100, were discovered unexpectedly in 1952 in investigations of the coral bottom of the Bikini atoll after the first hydrogen bomb test.

The last three transactinium elements, hahnium (105) and unnamed elements 106 and 107 were discovered, respectively, in 1970, 1974 and 1976. Hahnium and element 106 were discovered by the following heavy ion reactions:

$$^{249}Cf(^{15}N,4n)^{260}Ha$$
$$^{249}Bk(^{18}O,5n)^{262}Ha$$
$$^{249}Cf(^{18}O,4n)^{263}106$$
$$^{208}Pb(^{54}Cr,3n)^{259}106$$

For element 107 the Dubna group claimed discovery in 1976 on the basis of a spontaneous fission activity.

About 200 isotopes of the 18 transactinium elements are known to date, of which about a third, 72 isotopes, have half-lives higher than one day. Of these 72 isotopes more than half, 39 isotopes, have evaluations of neutron data listed in CINDA 76/77 and its supplements, the last of which, Supplement 5 (CINDA 78) was published in Dec. 1978. This means that we have 33 TND isotopes with $T_{1/2} > 1$ day for which some measured data exist but no evaluation has been done or listed.

Table I summarizes the above data for the 18 transactinium isotopes divided into three groups: thorium to plutonium (90-94), americium to fermium (95-100) and mendelevium to elements 106 and 107, both unnamed (101-107). The table also identifies in the last column those isotopes for which no evaluation exists (or at least none is listed in CINDA).

Compared with a similar table presented in 1975[12], one tends to conclude that a relatively big effort of TND evaluations has been done in the last four years, the number of evaluated isotopes having reached 39 in 1978 compared with 24 in 1975.

Obviously, for a successful neutron nuclear data evaluation to be performed, for any isotope, three conditions must be met:

(a) Motivation based on actual need for specific applications.
(b) Some measurements of neutron reactions in certain energy ranges.
(c) Possibility to supplement measurements, and sometimes to clear up discrepancies, by theory, nuclear model computations and systematics.

The eighteen transactinium elements, together with predicted locations of new elements, are shown on a conventional from of the periodic table in Figure 1[13].

TABLE I

The three groups of transactinium elements

Group	No.	Atomic number	Element	Number of known isotopes	Known isotopes with $T_{1/2}$>1d	No. of isotopes evaluated (CINDA 76/77*)	Isotopes evaluated (CINDA 76/77*)	Isotopes with $T_{1/2}$>1d. No evaluation listed
I	1	90	Thorium (Th)	24	7	1	232	227,228.229 230,231, 234
	2	91	Protactinium (Pa)	18	5	2	231,233	229,230,232
	3	92	Uranium (U)	15	9	7	232,233, 234,235, 236,237, 238	230,231
	4	93	Neptunium (Np)	14	6	3	237,238, 239	234,235,236
	5	94	Plutonium (Pu)	15 (86)	9 (36)	8 (21)	236,237, 238,239, 240,241, 242,244	246
II	6	95	Americium (Am)	14	4	3	241,242, 243	240
	7	96	Curium (Cm)	16	10	8	242,241, 243,244, 245,246, 247,248	240,250
	8	97	Berkelium (Bk)	9	5	1	249	245,246,247, 248
	9	98	Californium (Cf)	16	8	5	249,250, 251,252, 253	246,248,254
	10	99	Einsteinium (Es)	14	5	1	253	251,252,254, 255
	11	100	Fermium (Fm)	16 (85)	3 (35)	(18)		252,253,257

TABLE I (contd.)

Group	No.	Atomic number	Element	Number of known isotopes	Known isotopes with $T_{1/2}$>1d	No. of isotopes evaluated (CINDA 76/77*)	Isotopes evaluated (CINDA 76/77*)	Isotopes with $T_{1/2}$>1d. No evaluation listed.
III	12	101	Mendelevium (Md)	11	1			258
	13	102	Nobelium (No)	10				
	14	103	Lawrencium (Lr)	6				
	15	104	Kurchatovium** (Ku)	9				
	16	105	Hahnium (Ha)	5				
	17	106		1				
	18	107		1 (43)	(1)			
			Totals	214	72	39		33

*CINDA 76/77 + Supplements

**the American name is Rutherfordium (Rf)

Figures in parentheses are group totals

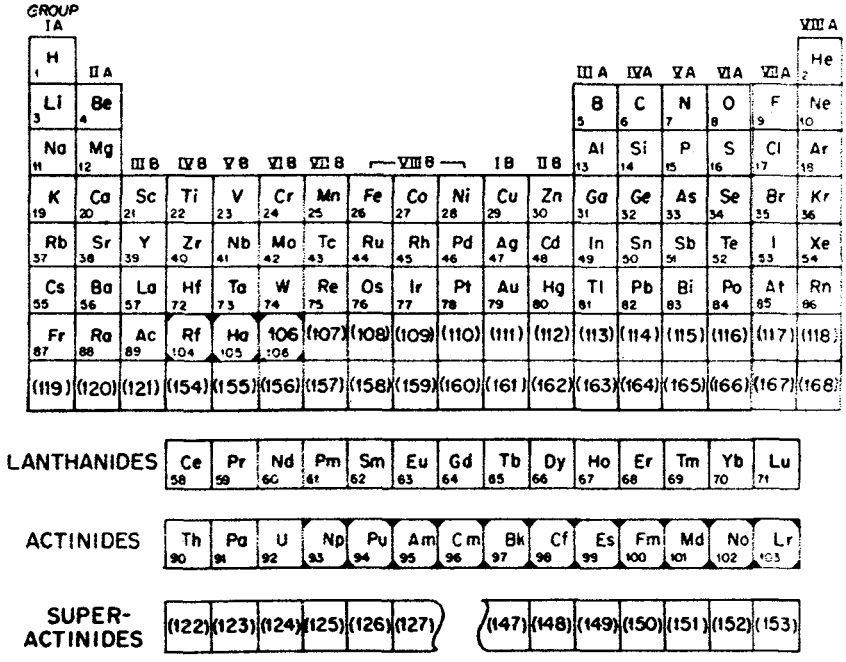

Figure 1. Simple form of periodic table, showing known transactinide and undiscovered in locations predicted with varying degrees of certainty.

4. ACTINIDE EVALUATIONS FOR ENDF/B-V

A relatively large effort of new and revised actinide evaluations has been completed in the U.S. for inclusion in ENDF/B-V. The so-called General Purpose File (GP) will include only evaluations having complete cross section and secondary neutron data. The twenty actinides in the ENDF/B-V GP file are: Th-232, Pa-233, U-233, U-234, U-235, U-236, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Am-241, Am-242^{m}, Am-243, Cm-243, Cm-244, Cm-245, Cm-246.

The Special Purpose Actinide File (the A file) will include other actinides, with less stringent conditions, some of them evaluations of only decay data. The twenty-four actinides in the ENDF/B-V A file are: Th-228, Th-230, Th-231, Th-233, Pa-231, U-232, U-237, Np-238, Pu-236, Pu-237, Pu-243, Pu-244, Am-242, Cm-241, Cm-242, Cm-247, Cm-248, Bk-249, Cf-249, Cf-250, Cf-251, Cf-252, Cf-253, Es-253.

The A file includes also nine actinides for which only decay data evaluations are given. These are: U-239, Np-236, Np-236^{m}, Np-239, Am-240, Am-244, Am-244^{m}, Cm-249, Bk-250.

It has been announced during the CRP coordination meeting that comparative analyses with other actinide files, to emphasize added confidence when evaluations agree, to re-check and clarify areas of disagreements, sometimes by data testing with well-documented benchmarks (which are now non-existent) and in general to improve future versions of all files, will be performed.

Another important step forward which has been announced at the same time is that the U.S.S.R. will perform TND evaluations in ENDF/B format. This again will simplify intercomparison of evaluations.

Some of the actinide experimental data which have become available since the 1975 Karlsruhe TND meeting are listed in a recent (May 1978) paper by Benjamin[14].

Several papers in Nuclear Science and Engineering[15-28] and in Soviet Nuclear Energy[29-32] contain new actinide experimental data. A report by Mann and Schenter[33] summarizes some of the actinide evaluations for ENDF/B-V.

5. SOME PRACTICAL PROBLEMS AND RECOMMENDATIONS FOR FUTURE WORK

It seems to me that the IAEA TND evaluations CRP should try, in the near future, to address itself to the following tasks and problems:

(a) Try to specify the contents of the 1981 IAEA actinide library and the contributors to the file* and outline a feasible time table.

(b) Up to now we already have in the framework of the CRP both full evaluations and partial evaluations. Since this situation is likely to continue in the future, it is proposed to open two IAEA TND files:

1) INDL/A/FE, to include full evaluations, that is evaluations of all neutron reactions data for the full energy range (10^{-3} eV to 15-20 MeV)

2) INDL/A/PE, to include partial evaluations.

(c) It is proposed to open the two IAEA files in the near future and to incorporate in the files the evaluations that have already been submitted. The files may thus include at this first stage two, or sometimes even more, evaluations of the same nuclide.

(d) Specify the methodology of intercomparison(11) of two or more evaluations for the same nuclide in the framework of the CRP.

(e) Look into the problem of testing the evaluations. Reactor irradiation benchmarks are clearly needed. One would use the evaluated data as input to actinide depletion and production calculations codes or irradiation experiments in systems with known spectra and compare the calculated results with the experimental benchmarks, thus testing both input data and computing codes.

(f) Perform intercomparisons and testing of the evaluations, if feasible, and try, at this second stage, by mutual consent, to consolidate the INDL/A/FE and INDL/A/PE to version II of the files where if possible only one consistent evaluation for each nuclide is included.

(g) Outline the future programme, 1982-1987.

(h) Perform intercomparisons of evaluations in the IAEA INDL/A/FE and INDC/A/PE with those in ENDF/B-V actinides GP file and A file.

(i) Try to identify, at several stages, areas where TND measurements would improve considerably the evaluated files, clarify discrepancies and help resolve differences in judgement in the evaluations.

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* As a specific example, the Israeli group with the consent of the Karlsruhe group, in cooperation with whom part of the work has been performed, could propose to include in the file its evaluations of Np-237, Pu-238, Cm-244, Cm-246, and may be Pu-240, Pu-241, Pu-242.

A tentative timetable for future work in the framework of the IAEA TND evaluations CRP follows:

1979: Open IAEA two files INDL/A/FE and INDL/A/PE and include terminated evaluations submitted to IAEA.
Concentrated evaluation work on nuclides chosen for inclusion in the IAEA actinides library.
Start intercomparison with ENDF/B-V.
Coordination meeting for stock-taking, exchange of information and preliminary intercomparison - Spring 1980.

1980: Terminate above evaluations.
Intercomparison and possibly some testing.
Coordination meeting - Spring 1981. Finalize IAEA INDL/A/FE and INDL/A/PE and outline future work.

1981: Assemble, consolidate and make available, on a larger scale, the IAEA actinide library.
Perform sensitivity studies and benchmark testing. Analyse differences in evaluations and feedback to evaluations.
Recommendations for TND measurements.

The above recommendations and tentative timetable have been endorsed by the participants of the Aix-en-Provence coordination CRP meeting.

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REPORT ON THE NOVEMBER 1978 NEANDC-SPONSORED WORKSHOP ON THE CROSS-SECTIONS OF THE HEAVIER PLUTONIUM AND AMERICIUM ISOTOPES, COMPLEMENTED BY THE STATUS AND ACCURACY OF EXPERIMENTAL NEUTRON CROSS-SECTION DATA FOR ELEMENTS HIGHER THAN AMERICIUM

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Abstract

A review of NEANDC sponsored meeting on nuclear data of higher plutonium and americium isotopes held at Brookhaven National Laboratory from November 20th to 21st, 1978 is given. It contains a table summarizing cross section experiments on these isotopes, which recently became available. Also the recommendations elaborated during the meeting are presented.

In the second part the status and accuracy of the experimental neutron cross section data of elements heavier than americium are reviewed. For the different isotopes along the main production line for heavy elements an overview is given in tabular form of cross section measurements, type of cross section measured, experimental technique used and approximative accuracy achieved. The values of fission and capture cross sections for thermal neutrons, their accuracies and the corresponding references are also given in form of a table.

1. REPORT ON NEANDC SPONSORED MEETING

1.1. Introduction

The meeting on nuclear data of higher Pu and Am isotopes for reactor applications was held from November 20-21, 1978 at the Brookhaven National Laboratory, Upton NY, USA under the chairmanship of R.E.Chrien. This meeting was visited by twenty to thirty participants, fission and fusion reactor data specialists, data evaluators and measurers. The report on the meeting I am presenting is based to a large extent on the summary report edited by R.E.Chrien (1) which goes back to tape recording of the summary panel session which closed the meeting. The participants in the panel were Phil Young, John Dabbs, R.E. Schenter and myself.

The purpose of this meeting was to assess the present status of measurements of cross sections and other nuclear data for the isotopes of plutonium and americium relevant to reactor applications, and to assess the

present and future needs for those measurements. The idea for the workshop originated within the Nuclear Energy Agency Nuclear Data Committee (NEANDC), which felt that the time was ripe for an assessment in this limited area. This feeling was prompted by several experiments and evaluations which have recently become available.

Clearly, the question of recycling and handling reactor fuel will become of ever-increasing importance as the nuclear power industry matures. Furthermore, as we have seen at this meeting, the design of future reactor systems -both fission breeders and certain fusion reactor concepts- depend in important ways on the knowledge of these cross sections. These nuclides present difficult problems in measurements, because of sample impurities and high radioactivity. They present a severe challenge to the evaluator because of the limited data base. The role of nuclear model calculations is especially important in this context.

The meeting, about which I have to report, was devided into four sessions. Session I dealt with neutron cross section data for the higher Pu and Am isotopes in the resolved resonance region. Session II had the same subject but at high neutron energies, where under high one understood the energy range from 10 keV to 20 MeV. The III. session had the title "Applications and Techniques for Transactinium Cross Section Data". In the fourth session integral data of the higher plutonium and americium isotopes were discussed. My report will follow now the scheme of the meeting.

1.2. Session on resolved resonance region of higher Pu and Am isotpes

A review talk about this subject was given by L.Weston (1) from Oak Ridge for the plutonium isotopes and by J.Browne (1) from Livermore for the americium isotopes. L.Weston gave rather in the beginning of his talk a table with the typical isotopic composition of light water reactor plutonium to judge the importance of the different isotopes. This table, fig.1, I want to show also here. As the table shows, ^{240}Pu and ^{241}Pu can not really regarded as so called minor isotopes. The almost stable isotope ^{244}Pu does not play an important role in reactor applications and was therefore not treated at this meeting.

Total cross section measurements for ^{240}Pu exist in the resonance region and the data seem to be of sufficient accuracy at present, except in the region from 0.01 to 3 eV. Here better data would be needed to determine the low energy resonance parameters accurately. Also scattering cross sections would be of great value in the same energy range.

The capture cross section of ^{240}Pu is measured in several experiments as shown in fig.2 and 3. Weston pointed out that corrobarative measurements

in the range especially from 100 eV to 10 keV would be very wellcome.

^{240}Pu shows a threshold for neutron induced fission. Two recent measurements of the subthreshold fission cross section were presented at the meeting. These are the preliminary results obtained with ORELA from 1 keV to 100 keV by Weston (1), and the results from Wisshak et al. (1) from Karlsruhe in the range from 10 keV to 250 keV. Fig.4 shows a part of the results and compares high resolution measurements with results obtained with less energy resolution.

For ^{241}Pu Weston concluded in his review paper that the fission cross section measurements in the unresolved resonance region are discrepant up to 10 %. Therefore he proposes a careful measurement of the fission cross section of ^{241}Pu in the energy range from 100 eV to 50 keV with an accuracy of better than 3 %. The situation for the fission cross section is demonstrated in Fig.5. The capture cross section measurements of ^{241}Pu in the unresolved resonance region between 100 eV and 10 keV have apparently also not yet reached the requested accuracy.

For the resonance region of the higher plutonium isotopes Weston has put down a wish list for measurements in two priorities :

First Priority :

Total cross section measurements with multiple sample thicknesses of ^{240}Pu and ^{241}Pu from 0.01 to 3 eV to accurately determine the low energy resonance parameters. Scattering cross sections in the same neutron energy region would be of great value.

Second Priority :

1. An accurate (< 3 %) measurement of the average fission cross section in the unresolved resonance region of ^{241}Pu between 100 eV and 50 keV. A better theoretical interpretation of this neutron energy region would also be helpful.

2. Corroborative measurements of capture cross sections, particularly in the neutron energy range from 100 eV to 10 keV. No demands were formulated for ^{242}Pu.

A review about the status of the neutron cross sections in the energy region below 10 keV of the americium isotopes was given by J.Browne. I will report here only the conclusions and suggestions which were made by him : For ^{241}Am there is a good data set available for the total cross section and for the absorption cross section. The discrepancy in the shape and the

magnitude of the fission cross section, if one regards the recent measurements (2,3), is now a small problem. However, it has been deemed important to measure the branching in the neutron capture of ^{241}Am to ^{242} and ^{242m}Am, and to a lesser degree for ^{243}Am leading to ^{244}Am and ^{244m}Am. These values are important for the estimation of the build-up of the curium isotopes under neutron irradiation. For ^{242m}Am a total cross section measurement would be valuable to check the s-wave strength function and the values of the fission widths. An other fission cross section measurement for ^{242m}Am would be valuable to check the data obtained by Browne et al. (4). A capture cross section measurement is suggested to determine Γ_γ for the 0.173 eV resonance. This would be very helpful for calculating more reliably the capture cross section at higher energies.

For ^{243}Am there are several consistent total cross section data sets in the low energy range. The s-wave strength function, the average level spacing and the average capture width obtained from these data sets are also in agreement with each other. The neutron induced fission cross section is measured only in a bomb shot experiment and should be checked by an other experiment.

An absorption cross section measurement would be valuable.

In this session on the resolved resonance region of the higher plutonium and americium isotopes there were several contributed papers which I want to mention only. There are the papers presented by K.Wisshak from KFK Karlsruhe about recent capture cross section measurements for ^{240,242}Pu and for ^{241}Am in the neutron energy range from 10 keV to 250 keV and about fission cross section measurements for ^{240}Pu and for ^{241}Am in the same neutron energy range. These measurements were performed at a Van de Graaff accelerator. For ^{240}Pu a fission cross section measurement performed by S.Cierjacks et al. at the Karlsruhe cyclotron in the energy range from 0.5 to 20 MeV was reported also by Wisshak.

Then we heard about evaluations of ^{241}Am resonance parameters and their consequences for the unresolved region by H.Derrien, E.Fort and D.Lafond. Fig.6, taken from their work, gives a good overview over the experimental cross sections obtained until now for this isotope in the unresolved region. The capture data of Wisshak et al.(5) and of Philipps et al.(6) are recent data and were not used as input to the evaluation.
A preliminary evaluation of ^{242}Pu data for the neutron energy range from 10 keV to 20 MeV was presented by Philis et al. in this session. The fission cross section is based on recent experimental results (8). Direct interactions were considered in the evaluation. All results were brought to ENDF/B-IV format and the data set was complemented by the low energy region of ENDF/B-IV (MAT 1161) data to provide a complete data set in the whole energy range from 10^{-5} eV to 20 MeV.

1.3. *Cross section data for the higher Pu and Am isotopes in the fast neutron energy region*

Also this session was started with a review paper and was then followed by contributions describing recent measurements and evaluations. The review talk was given by B.H.Patrick (1) from Harwell. He examined the status of the total, fission, capture, elastic and inelastic scattering cross section data of the five isotopes ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am and ^{243}Am in the neutron energy range from 10 keV to 20 MeV. To give a visual impression of what is known, I will show as an example only the figures of the ^{240}Pu cross sections which Patrick presented. The status of the cross section in general looks rather similar for the other isotopes. Fig.(7) shows the known experimental cross sections except the fission cross section. For $\sigma_{n,T}$, $\sigma_{n,n}$ and $\sigma_{n,n'}$ only one data set exists. For $\sigma_{n,\gamma}$ two experiments exist which overlap in the range from 10 to 30 keV. The next fig.8 shows the fission cross section measurements of ^{240}Pu, where the cross section ratio with respect to the ^{235}U fission cross section is given. From the first session we learned, that considerable sturcture exists in the subthreshold region. Table 1 is a copy of table 10 of Patricks work and gives the comparison of requirements and status of cross section data in the fast neutron energy region. Some of the requirements for nuclear data for fast reactor applications were set out in the conclusions and recommendations at the working group on fast reactors at the Advisory Group Meeting on Transactinium Isotope Nuclear Data (7) and appropriate extracts are given in table 1. The Advisory Group Meeting did not include the higher Pu isotopes in its comparison table and the requirements for data of these nuclei have been taken from WRENDA 76/77. Patrick, however, warned not to take these table too serious, since the "achieved accuracies" were obtained by inspection of cross section graphs and by educated guesswork and not by a real evaluation. The table shows that the status for fission cross sections is the best compared to others. The capture cross section data, generally speaking, are not yet sufficiently accurate to fulfil the needs and this is clearly the area where further work is required.

Several contributed papers were presented also in this second session. We heard about new measurements of the fission cross section of ^{240}Pu by C.Budtz-Jørgensen and H.-H.Knitter from CBNM and of ^{242}Pu by J.W.Meadows from the Argonne National Laboratory. Both measurements were done in the neutron energy range from some 100 keV to 10 MeV. D.G.Madland and P.G.Young presented an extensive evaluation of (n+^{242}Pu) reactions from 10 keV to 20 MeV. The angle integrated fission and capture cross sections in their evaluation are based upon experimental measurements. Because of lack of experimental data, the remaining cross sections, together with the elastic and inelastic neutron scattering angular distributions to low lying states have been calculated using various reaction models. The results were brought in ENDF/B-V format and were combined with a recent evaluation of data below 10 keV

by the Hanford Engineering Development Laboratory, so that a complete data set, covering the range of 10^{-5} eV to 20 MeV is available. However, the sparsity of experimental cross sections implies large uncertainties in the calculated cross sections. Therefore the data base for this isotope should be improved to validate and improve the evaluation. The authors suggest in particular measurements of the total, differential elastic and inelastic neutron scattering cross sections from some 100 keV to several MeV and to verify in an independent experiment the fission cross section as measured by Behrens et al. (8).

From B.Goel from Karlsruhe we heard about an evaluation of thermal cross sections for ^{241}Am. He recommends values for 2200 m/s cross sections. He contributed also with a second paper about evaluation of high plutonium isotopes for the German nuclear data file KEDAK. Table II of his paper is may be of special interest to this meeting, because it presents the required accuracies of nuclear data for reactivity calculations in the case of a fast reactor. It reflects also the high degree of accuracy which is demanded for the knowledge of the fission cross sections and of ν of the higher plutonium isotopes.

Futhermore we heard about an other evaluation performed at Hanford Engineering Development Laboratory of the higher plutonium and americium isotopes for inclusion in the ENDF/B-V library. This evaluation covers the isotopes ^{242} and ^{244}Pu and the three americium isotopes ^{241,242m,243}Am.

1.4. *Session on applications and techniques for transactinium cross section data*

The applications of actinide data were discussed in review talks by Beaman on reactors, Lemley on safeguards, and Meldner on inertial confinement fusion used for incineration of nuclear wastes. Beaman pointed out the need for ^{241}Am capture and branching ratios for the design of fuel shipping casks and for decay heat calculations after reactor shutdown. The neutron and heat source terms are of considerable importance both for ^{241}Am and for ^{242}Cm.

He further pointed out that the neutron source term was very dependent on how rapidly the fuel is recycled, since the ^{242}Cm can become the dominant source after several years of fuel storage.

Beaman also pointed out the importance of certain cross sections in recycling fuel from thermal and fast reactors and using it as feed material in fast reactor situations. In the former case -(thermal reactor fuel) the ^{240}Pu capture and the ^{241}Pu fission cross section need to be accurately known. In the latter case, the ^{241}Pu is less important because the amount produced is less.

The merits of waste disposal from thorium and uranium based reactors was debated. In the former system, the heavy element production is inhibited because of the need to capture six more neutrons as compared to uranium, hence production of mass numbers greater than 238 is down by ~ 10^6. On the other hand, the hazards from a thorium based system have been shown to exceed those from uranium after a sufficiently long time (10^4 years) because of the undesirable by-products in the thorium decay chain, such as ^{231}Pa. Unfortunately, the thorium wasts are generally not good fuels, in contrast to the Pu isotopes produced in uranium capture processes.

Meldner's talk (9) about burning a very large amount of actinides in a large number of inertial confinement fusion (ICF) implosions showed in what new directions the rapidly-developing fusion technology can lead us. ICF pellet center burnup of reactor waste offers the major advantage of safety, because only milligram quantities of the toxic material need to be present in the fusion chamber compared to the large amount in e.g. blanket burnup. Meldner estimated that one ICF plant could safely consume the wastes of ten power equivalent fission reactors . His contribution also served as an excellent illustration of the need to maintain a measurement program able to meet the yet unforeseen applications that may arise in the future. The cross section demands for this future application lie mainly in the neutron energy region up to 16 MeV and downwards.

At present, the safeguards application area has no important data demands, as Lemley pointed out in his review. Instrumentation development for safeguards applications may prove, at least on the short time scale, to be more important than cross section measurements. Here accurate cross sections are not so much needed as the appropriate instrumentation to monitor and analyze nuclear fuel and waste.

In the review talk about instrumentation for actinide cross section research J.W.Dabbs from Oak Ridge pointed out, that the actinide region has presented us special problems in the measurement of fission cross sections accompanied by very high α-particle background. Experimenters have risen to this challenge by presenting us with design for fission chambers which tend to minimize the longer-range α-particle response. Dabbs of Oak Ridge and myself both discussed these special instruments. Dabbs described the spherical and honeycomb chambers which present the shortest possible path lengths to α's, thus reducing the ionization in the counter gas due to the α-background. I discussed the time evolution of a parallel plate ionization chamber pulse, and how the pulse shape could be appropriately processed to produce both, fast timing and energy information at optimum signal-to-background ratio. In a paper distributed at the meeting (3) also a fission fragment detector with inherent discrimination of alpha background, developed by C.Budtz-Jørgensen and H.-H.Knitter (10), is described.

1.5. Session on integral data

Since I do not feel competent enough in this subject, I will repeat here only what was said in the summary session.
Harker from Idaho Falls stressed the role of integral measurements in relation to the differential cross section measurements.

Integral experiments can serve to distinguish between discrepant data sets or to normalize model calculations where no differential data exist. One difficulty which hampers the use of integral data was pointed out, however. This difficulty is that integral data are not always sufficiently well specified, particularly with regard to flux and spectral conditions. Nevertheless, these data are valuable and are frequently the only source of experimental information.

1.6. Conclusions

Let me show now table 3 which summarizes the new or recent cross section measurements which were presented at this NEANDC Specialists Meeting. It shows that during the last few years a good amount of cross section data for these higher Pu and Am isotopes was obtained. These data have clearly improved our knowledge about these nuclides, which present special difficulties for the experimenters compared to other isotopes.
The following specific and general recommendations were worked out in the meeting :

Specific Recommendations :

1. Neutron total and scattering cross sections are required in the region from 0.01 to 3.0 eV for ^{240}Pu and ^{242}Pu to obtain accurate resonance parameters.

2. An average fission cross section to 3 % accuracy is needed for ^{241}Pu between 0.1 and 50 keV, with a complementary capture measurement to 10 keV.

3. Total cross sections for ^{242m}Am for parameters in the resolved resonance region are desirable.

4. Checks on fission cross sections for ^{242m}Am and ^{243}Am are needed in the resolved resonance region.

5. A thermal capture cross section measurement for ^{242m}Am and an absorption cross section for ^{243}Am are useful.

6. Capture branching ratios for ^{241}Am to the ground and isomeric states of ^{242}Am and to a lesser extent of ^{243}Am are required.

General Recommendations :

1. An improvement in cross section precision for fission above 3 MeV and below threshold is desirable.

2. For capture measurements, at higher energies, an improved precision is required. Present data, except possibly for ^{240} and ^{242}Pu contain error margins a factor two larger than desired.

3. More detailed error information should be included with experimental work.

4. A better justification for measurement requests and a more detailed accuracy specification would be appreciated by experimenters.

5. More accurate measurements of the more easily accessible actinides are needed to provide tests and systematics for nuclear models and their extrapolations.

6. In general good total cross section data, and in some cases scattering data, are needed to constrain the fission and capture data, and to check model calculations.

7. Instrumental developments in the difficult actinide area should be encouraged. It should be noted that such developments can be useful in other areas -for example, in monitoring nuclear materials in safeguards applications.

8. Areas of more exotic application needs such as fusion reactor problems should be communicated to measurers.

9. Integral experimental results should be factored into evaluations as they provide important tests for microscopic data, and in some cases can be decisive in choosing between discrepant data sets.

In conclusion, it can be said that the Specialists Meeting presented us with a reasonably comprehensive picture of the state of measurements on important isotopes above ^{239}Pu and of the needs for such measurements. In at least one instance, that of the disposal of reactor fuel waste by inertial confinement fusion techniques, the cross section community was confronted with a new and extensive set of transactinide cross section needs at high neutron energies.

There may be more such needs which as yet have not been properly assessed, but may become important in the future. Such undefined future needs emphasize the importance of maintaining a measurement program which is capable of supporting future requirements and of developing refined model calculations to provide parameters which cannot yet be measured.

As this point I would like to acknowledge especially R.Chrien for sending me so short time after the NEANDC sponsored meeting on the higher plutonium and americium isotopes for reactor applications the summary of the panel discussions, which was elaborated by him.

2. STATUS AND ACCURACY OF EXPERIMENTAL NEUTRON CROSS SECTION DATA FOR ELEMENTS HIGHER THAN AMERICIUM

2.1. Introduction

At the last "IAEA Advisory Group Meeting on Transactinium Isotope Nuclear Data, held in Karlsruhe in 1975 (10), the status of measured neutron cross sections was reviewed in several review papers, where each of it dealt with a different neutron energy range. If someone wants to have a comprehensive overview of these data till 1975 he should consult these references too.

As sources of information for this review I obtained a bibliography and cross section data from the NEA data bank at Saclay and I asked a literature search from the INIS-ENDS documentation service of the Commission of the European Communities.

The accuracy of the experimentally available neutron cross sections can in a strickt manner only be obtained by proper mathematical evaluation procedures. However, this was not my intention to do, and, therefore the statements about achieved accuracies made here, are obtained only by inspection of cross section graphs. As long as only one cross section measurement in a certain energy range is available, eventual systematic errors are difficult to identify if at all. For these reasons, especially the remarks on accuracy should not be taken as absolute truth.

In fig.9 the according part of the nuclide chart above neptunium is shown. The thick arrows in it show the main production line for the heavy elements by slow neutrons starting at ^{239}Pu. The thinner arrows represent some side branches of the main production line. For this paper only those isotopes were selected which are lying on the main production line for heavy elements or whose half life is longer than about one year. Because of the short half lives, the high specific activity of theseisotopes presents in most cases of cross section measurements severe event detection problems. Therefore special detectors and techniques had to be applied in these measurements. An other aspect is, when one has to judge the experimental results in this heavy element region, that in many cases only small amounts of materials were available. Also their chemical and isotopical purity was in seldom cases such as the experimentalist would have liked it.

In order to review the experimental data a table, table 4, is prepared which summarizes for each isotope the accuracies obtained so far, and it is indicated if resonance parameters were extracted from the experimental information. The experimental method applied and the energy range covered by the experiment is listed too. The last column contains the references. Papers published later than 1975 are underlined to identify what is new since the last meeting. Table 5 summarized the numerical values available for the thermal neutron capture- and fission cross sections.

2.2. *The curium isotopes*

With a half life of larger than about half a year, curium has a family of eight isotopes from ^{242}Cm to ^{248}Cm and the isotope ^{250}Cm.

^{242}Cm (163 d)

As one can see from table 4, only one measurement of the fission cross section exists at 14.5 MeV by Fomushkin et al.(11). The cross section is (3.03 ± 0.30)b. The measurement was performed using glas plate detectors. An other early measurement performed by Hanna et al. (12) gives an upper limit for the fission cross section $\sigma_F \leq 5$ b at "slow" neutron energies.

^{243}Cm (28 a)

On this isotope the earliest fission cross section measurement stems from Hulet et al. (13) who measured it for neutrons with a maxwellian energy distribution in the thermal regin.These authors found a cross section of (690 ± 50)b. A recent measurement by Bemis et al.(14) gave for the 2200 m/s fission and capture cross section values of (609.6 ± 25.9)b and (130.7 ± 9.6)b respectively. They were measured using mass spectrometric methods.

Then we have the bomb shot experiment reported by Seeger (15) made at the Pommard event in 1968. The fission cross section was measured relative to ^{235}U in the neutron energy range from 0.1 to 3.0 MeV. The fission fragments were detected at two angles with respect to the incident neutron beam and the results of two recordings deviate by ± 10 % from the average. Fig.10 shows the results of this experiment. Structures in the cross sections are probably not resolved. Silbert (16) reports about fission cross section measurements on ^{243}Cm made at the Physics-8 bomb shot event. The cross section could be measured in a time-of-flight experiment in the range from 15 eV to 3.0 MeV with a flight path of 240 m. The cross sections are channalized into 1 μsec bins.

Typical uncertainties for each data point are ± 10 % non-systematic and ± 10 % systematic.

Berreth et al.(17) performed total cross section measurements on several curium isotopes using a fast chopper as neutron spectrometer. They used three samples with different isotopic composition containing the curium isotopes 243,244,245 and 246. The ^{243}Cm content ranged only between 0.05 and 1.5 % and therefore it was only possible to extract 15 resonance energies and and the corresponding scattering and fission widths of the resonances under the assumption of 40 meV for the capture widths.

Dabbs et al.(18) have reported about fission cross section measurements on ^{243}Cm at a 10 m flight path at ORELA, using hemispherical ionization chambers for selective suppression of alpha pulses, while permitting a larger than 95 % fission counting effiency. Unfortunately data were not given in the paper and were not available from the NEA data bank.

$^{244}Cm(18\ a)$

For ^{244}Cm there exist two evaluations, one by Benjamin et al. (19) and a very recent and unpublished one by Fuketa et al.(20). From these evaluations more detailed informations can be obtained.

On this isotope three total cross section measurements exist. The earliest total cross section measurement was made by Coté et al.(21) with a fast chopper covering an energy range between 0.01 and 900 eV. They were able to determine resonance parameters of ^{244}Cm in the mentioned range and also some resonance parameters of ^{246}Cm which was contained with a small abundance in the transmission samples. The second transmission experiment is published by Berreth et al.(17). Several samples with rather complex composition were used. The authors could obtain a total cross section curve for ^{244}Cm from 0.01 eV to 1 eV and stated, that this curve may be in error from 0.3 eV to 1 eV. Resonance parameters are obtained in the energy range from 7 eV to 85 eV.

A third total cross section measurement is made by Belanova et al.(22,23) using also a chopper. The experiment yielded resonance parameters between 7 and 171 eV.

There are several fission cross section measurements available. Fomuskin et al.(11) measured also on this isotope a point at 14.5 MeV using glas plate detectors and a ionization chamber. He also determined the fission fragment angular distribution with respect to the incident neutrons. Koontz and Barton (24) measured the fission cross section using a Van de Graaff and solid state detectors at some energies between 1 and 14.5 MeV. No errors are given.

Moore et al.(25) described a fission and capture cross section measurement of curium by the bomb shot method at the Helsinki Conference in 1970. A final analysis of this extensive work is given in ref.(26). The fission

cross section of all the isotopes from ^{244}Cm to ^{248}Cm were measured between 20 eV and 3 MeV using five samples containing each a rather high enreachment for one, two or three isotopes. The capture cross section was measured for the isotopes ^{244}Cm and ^{246}Cm between 20 eV and 10 keV. Resonance analysis was carried out for ^{244}Cm between 20 eV and 1 keV, for ^{246}Cm and ^{248}Cm between 20 eV and 400 eV and for the odd isotopes between 20 eV and 60 eV. To give an impression of the quality of data I show in fig.11 the capture and fission cross section (25) between 200 eV and 1 keV and in fig. 12 between 10 keV and 3 MeV. For such a complex experiment, where all the data including the background runs have to be made at the same and single event, it is especially difficult to evaluate the errors of the measured cross sections. Moreover, the error will depend also strongly from the neutron energy region. This is evident also for the energy resolution. The authors discussed several error sources but do not give an integral error on the cross section results. Therefore, the values for the accuracy which are given in table 4 are only indicative values.

The thermal fission cross section of the curium isotopes 244-248 is measured by Benjamin et al.(27) and Zhuravlev et al.(28). For ^{244}Cm they obtained values of (1.1 $\pm$ 0.5)b and (1.0 $\pm$ 0.2)b respectively. The large error margin of 50 % in the result of ref.(27) is due to the fact, that the small thermal cross section of ^{244}Cm has to be measured in the presence of a small amount of ^{245}Cm, which shows however a fission cross section which is about 2000 times larger than the previous one.

Then Fomushkin et al.(29) measured the fission cross section ratio of the curium isotopes 244 to 248 and of ^{252}Cf with respect to ^{235}U for a fast reactor spectrum which is quite close to a fission neutron spectrum.

The neutron capture cross section of ^{244}Cm for pile neutrons was measured by Stevens et al.(30). It was obtained with a 40 % accuracy from the Cm isotope production in different plutonium samples which were irradiated in a reactor.

^{245}Cm (8500 a)

Also for this isotope a recent and unpublished evaluation of S.Igarasi and T.Nakagawa (31) exists, which gives much more details than I can present here.

There are two total cross section measurements available, which were mentioned already (17,23). Berreth et al.(17) as well as Belonova et al. (23) gave resonance parameters.

For the fission cross section determination at thermal energies there are several measurements (13,27,28,32,33,34,35,36) which may be mentioned

only. The average of all these values is (2000 ± 35)b. The error is calculated from the scattering of the experimental points around the average value giving same weight to all measurements.

The thermal capture cross section was measured in three experiments (30,34,37). The average value, using the errors as given by the authors as weights, is (327.5 ± 31)b.

Then we have again the average fission cross section measurement of Fomushkin et al.(29) for a neutron spectrum close to a fission neutron spectrum.

Dabbs et al.(38) measured the fission cross section in a time-of-flight experiment using a hemispherical ionization chamber for better background suppression at ORELA. Some energies of resonances in ^{245}Cm are reported.

A very recent work of fission cross section measurement is published by Browne et al.(36) in the energy range from 0.01 to 35 eV. Resonance analysis is made and the accuracy of the data points lies between 5 and 10 % about. The data are obtained with the Livermore Linac using a ionization chamber and only micrograms of material at a flight path of 3.6 m. It represents the most complete resonance analysis of this isotope.

Then we have again the work of Moore et al.(25,26) who measured the fission cross section between 20 eV and 3 MeV and performed resonance analysis between 20 eV and 60 eV.
Fig. 13, which is taken from the evaluation of Igarasi et al.(31), shows the fission cross section of ^{245}Cm in the energy range from 100 eV to 15 MeV. It gives you an impression of how the situation looks like for this cross section.

^{246}Cm (4730 a)

Benjamin et al. (19) made an evaluation in 1976 about this isotope. A total cross section measurement using a fast chopper was made by Berreth et al. (17) in the range grom 0.01 to 30 eV. The accuracy of the data is difficult to estimate since the cross sections were obtained from samples having only a small abundance of ^{246}Cm.

Belanova et al.(23) made a transmission experiment also on this isotope and extracted resonance parameters. Cross section curves are not given. The thermal fission cross section is obtained by Benjamin et al. (27) and by Zhuravlev et al. (28). Fission cross sections for neutron energies between 20 eV and 3 MeV are available again from the work of Moore et al. (25,26) with an accuracy of 10-20 %. Resonance analysis was carried out between 20 eV and 400 eV.

Fomushkin et al. (29) made an average fission cross section measurement using fast reactor neutrons with an almost fission neutron like spectrum.

$^{247}Cm(1.56 \cdot 10^{7}\ a)$

The thermal fission cross section of ^{247}Cm is measured in several experiments by Diamond et al.(32), Halperin et al.(33),Zhuravlev et al. (28),Thompson et al.(34), Gavrilov et al.(35), and Benjamin et al. (27). The values are lying between 82 and 120 b. Therefore I indicated in table 4 an error of $\pm$ 20 % for the thermal fission cross section of ^{247}Cm. Then we have again the measurement of the fission cross section from 20 eV to 3.0 MeV obtained in the bom shot experiment by Moore et al. (25,26). At energies above 1 MeV the cross section may bein error, as stated by the authors, because of large corrections due to the presence of the even isotopes 244 and 246-Cm in the samples. Resonance analysis was made only between 20 and 60 eV.

Fomushkin et al.(29) determined also for this isotopes an average fission cross section for a neutron spectrum which is near to that of a fission neutron spectrum.

$^{248}Cm\ (3.39 \cdot 10^{5}\ a)$

For this isotope there is an evaluation available from Benjamin et al. (19), where many details about this isotope can be found. There are thermal fission cross section measurements of Benjamin et al. (27) and Zhuravlev et al.(28) and an average fission cross section measurement of Fomushkin et al. (29) for an almost fission neutron like spectrum. For ^{248} Cm a transmission experiment performed at ORELA is made by Benjamin et al. (39) in the neutron energy range from 0.5 eV to 3 keV. This time-of-flight experiment allowed to make an analysis of 47 resonances to obtain the resonance energies and Breit-Wigner single level parameters.

Moore et al. (25,26) measured the fission cross section also from this isotope in the neutron energy range from 20 eV to 3 MeV, however, only a few resonances could be analysed, which agree fairly well with ref.(39). The fast chopper measurement of Belanova et al. (23) yielded also resonance parameters of some resonances below 100 eV. The neutron widths however, are much larger than the ones of ref. 39.

^{249}Cm (64.2 m) and ^{250}Cm (6900 a)

No direct neutron cross section measurements are available for these isotopes. However, Diamond et al. (40) have shown, that the main source for ^{250}Cm in high flux reactors is the neutron capture of ^{249}Cm, a β-emitter with a half life of 64.2 m and not the α-decay of ^{254}Es. From the isotopic and chemical composition of an irradiated curium sample and the irradiation history they estimated the neutron capture cross section of ^{249}Cm. This is possible since all masses from 249 on are obtained by the β-decay of ^{249}Cm, and all the ^{250}Cm is obtained by the capture process on the same nucleus.

2.3. Berkelium

^{249}Bk (320 days)

For the isotope ^{249}Bk, the results of a transmission experiment is available (41,42) using small sample techniques developed at Oak-Ridge for time-of-flight measurements at the ORELA. The covered energy range is between 0.005 eV and 1 keV. Resonance energies are given. Since ^{249}Bk decays with a half life of 320 days to ^{249}Cf one has always a sample where both isotopes are present. For the large thermal absorption cross section evident from integral measurements the large resonance at 0.197 eV is responsible.

There are several fission cross section measurements available; at thermal energies by Diamond et al. (32) using ion chamber technique in the thermal column of a reactor, measurements across the fission threshold from 0.2 to 1.7 MeV by Vorotnikov et al. (43,44) using glas detector technique. There are also some points in the MeV-range by Fomushkin et al. (45) and the bomb shot experiment as decribed by Silbert (46). This bomb shot experiment covers the energy range from 0.7 to 3.0 MeV. The author claims an accuracy of $\pm$ 6.4 %. The thermal capture cross section is determined by Magnusson et al. (47), Gavrilov et al. (35,48), and Harvey et al. (49).

2.4. Californium

^{249}Cf (351 a)

Since ^{249}Cf is a daughter of ^{249}Bk the total cross section of ^{249}Cf was measured at ORELA (41,42) using the same ^{249}Bk samples only a few months later. Then they contained an appreciable amount of ^{249}Cf. The measurement was made between 13 eV and 1 keV. Then we have several thermal fission cross section measurements (27,33,35,48,50) which report obtained

accuracies between 4 and 10 %. Also for ^{249}Cf there is a bomb shot experiment availabe (51) where for the cross section points an error of ± 6 % is obtained. Resonance parameters are obtained for resonances in the energy range from 15 eV to 70 eV. The energy range below the bomb shot measurements is covered by a time-of-flight experiment made at ORELA (52) from 0.7eV to 16 eV. Then there are some fission cross section measurements using electrostatic generators for neutron production and glas detectors for fission fragment detection (53,54,55) which cover an energy range from 0.5-7 MeV. The capture cross section, at thermal energies is measured from heavier element production experiments by Harvey et al.(49) relative to ^{197}Au and ^{59}Co capture cross section, by Gavrilov et al. (48), and by Halperin et al. (56).

^{250}Cf (13 a)

Here only a crude determination of the capture cross section from heavy element production is available (47).

^{251}Cf (898 a)

Two thermal fission cross section measurements at a reactor exist (50,57). Both give an error of about 6 %, however, their results deviate by 25 % from the common average. Then there is a crude determination of the capture cross section at thermal energies (47), obtained in a heavy element production experiment.

^{252}Cf (2.6a)

The fission cross section of ^{252}Cf is measured in a bomb shot experiment in the energy range from 20 eV to 5 MeV (25,58). Compared to the bomb shot measurements on the Cm-isotopes a renormalization (58) was necessary with respect to a previous evaluation (26) of the same raw data. This gives an additional error of 12 %. Resonance parameters, mostly Γ_f, could be obtained from the experiment in the range from 20 eV to 1 keV.A thermal fission cross section measurement is reported by Halperin et al. (56). Some thermal capture cross section measurements are also known (47,59,60) with an accuracy of about 10 %.

2.5. Einsteinium

^{252}Es (350 d)

For this isotope no neutron cross section measurements were found.

^{254}Es (276 d)

The thermal fission cross section is known from Diamond et al.(32) and from Shuman et al.(61). For the capture cross section an upper limit is given by Harvey et al. (49).

2.6. Summary

Fig. 14 gives an overview over all the measurements of total, fission and capture cross sections available until now. Horizontally the neutron energy is plotted over a range of nine decades from 10^{-2} to 10^{7} eV. For each isotope three fields are foreseen, for each of the cross sections σ_T, σ_F, and σ_c one field. The energy range of a measurement is indicated by a hatched area. In general one can see, that capture cross section measurements in this heavy mass region above americium are very scarce. The thermal neutron capture cross sections are often obtained as by-products in heavy element production experiments and their accuracy is around 30-50 %. At higher neutron energies there are only results from a bomb shot experiment.

Total cross section measurements are also scarce, although the small beam- and sample techniques developed at Oak-Ridge (41) have brought new results.

Fission cross section measurements were performed more frequent, even for isotopes with a rather high specific activity for spontaneous fission. For these latter cases the bomb shot experiments are the only source of information.

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TABLE 1

TABLE X

Comparison of Requirements and Status of Cross-section Data in the Fast Neutron Energy Region

Nuclide	Cross-section	Main Energy Range	Accuracy (%) Reqd.	Achieved	Comment	Needs
Pu-240	(n,γ)	5keV-1MeV	10	10-15		Fast reactors
	(n,f)	5keV-10MeV	5-10	5		"
Pu-241	(n,γ)	5keV-1MeV	10	20	E<250keV	"
	(n,f)	5keV-10MeV	5	5		"
Pu-242	(n,γ)	5keV-1MeV	10	10	E<200keV	"
	(n,γ)	5keV-1MeV	30	10	E<200keV	Actinide recycle
	(n,f)	1keV-10MeV	10	5		
Am-241	(n,γ)	0.5-100keV	5	10		In-core cycle, fuel fabrication, fuel control and Cm-242 production
	(n,f)	1keV-5MeV	15	$\lesssim$10		
Am-243	(n,γ)	0.5-100keV	10	-	+25% from theory	In-core cycle and Cm-244 production
	(n,f)	>500 keV	30	<10		

* Copied from B. H. Patrick (1)

TABLE 2*

Desirable Precisions in the case of Fast Reactor Cross Sections for Reactivity Calculation Problems

(± in %)

Higher Pu isotopes	$\nu\sigma_f-\sigma_a$	σ_c	σ_f	ν
^{240}Pu	8	5	2	1
^{241}Pu	2	8	1.5	0.5
^{242}Pu	50	8	4	4

* copied from B. Goel (1)

TABLE 3 : New measurements referred to at the workshop

Isotope	$\sigma_{n,f}$	$\sigma_{n,\gamma}$	$\sigma_{tot.}$
^{240}Pu	1 keV-100 keV (Oak-Ridge) 10 keV-250 keV (Karlsruhe) 150 keV-10 MeV (Geel) 0.5-20 MeV (Karlsruhe)	10-250 keV (Karlsruhe)	10-375 keV (Karlsruhe)
^{242}Pu	0.4-10 MeV (Argonne)	10-250 keV (Karlsruhe)	10-375 keV (Karlsruhe)
^{241}Am	100eV-5.3 MeV** (Geel) 10 keV-1 MeV (Karlsruhe)	10-250 keV (Karlsruhe)	0.5-25 MeV* (Livermore)
^{242m}Am	0.01 eV-20 MeV (Livermore)		

* A report of recent work by Phillips and Howe (6) was distributed at the meeting.

** A preprint of recent work by H. -H. Knitter and C. Budtz-Jørgensen (3) was distributed at the meeting.

TABLE 4 : Overview of cross section measurements on Cm, Bk and Cf

Isotope	σ_T	σ_F	σ_c	energy range	method	Ref.
^{242}Cm	--	± 10 %	--	14.5 MeV	glas plate det.	11
	--	≤ 5 b	--	"slow"		12
^{243}Cm	--	± 10 %	--	thermal	ioniz. chamber	13
		± 4 %	7.5 %	thermal	mass spectr.	14
	--	± 20 %	--	0.1-3.0 MeV	bomb shot	15
	--	± (10-20)%	--	15eV-3MeV	bomb shot	16
	reson.par.	--	--	1.5-30 eV	chopper	17
^{244}Cm	reson.par	--	--	0.01 eV-900 eV	chopper	21
	15 %	--	--	0.01 eV-1 eV	chopper	17
	reson.par.	--	--	7 eV-85 eV		
	reson.par.	--	--	7 eV-171 eV	chopper	22,23
	--	± 10 %	--	14.5 MeV	glas plate, ioniz.chamber	11
	--	± 20 %	--	1,1.5,3,14.9 MeV	solid state detector	24
	--	± 10 % E < 1 keV	--	20 eV-3.0 MeV	bomb shot	25,26
	--	± 20 % E < 1 keV	--			
	--	reson.par.	--	20 eV-10 keV		
		--	20 %	20 eV-10 keV		
	--	20-50 %	--	thermal	plastic track det., ioniz. chamber	27,28

Isotope	σ_T	σ_F	σ_c	energy range	method	Ref.
	--	± 3 %	--	~fiss.neutr.spectr.	glas detector	29
	--	--	40 %	pile neutrons	Cm pile prod.	30
^{245}Cm	~ 20 %	--	--	0.01-30 eV	chopper	17
	reson.par.	--	--			
	reson.par.	--	--	1-50 eV	chopper	23
	--	< 3 %	--	thermal		13,27,28,32,33,34,35,36
	--	--	10 %	thermal		30,34,37
	--	10 %	--	~fiss.neutr.spectr.	glas detector	29
	--	reson.ener-gies	--	1-20 eV	hemispherical ioniz.chamber	38
	--	5-10 % reson.par.	--	0.01-35 eV	ioniz. chamber	36
	--	10-20 %	--	20 eV-3 MeV	bomb shot	25,26
	--	reson.par.	--	20 eV-60 eV		
^{246}Cm	~ 20 % reson.par.	--	--	0.01-30 eV	chopper	17
	reson.par.	--	--	1-150 eV	chopper	23
	--	30-75 %	--	thermal		27,28
	--	--	30 %	thermal		30
	--	10-20 % reson.par.	--	20 eV-3 MeV 20 eV-400 eV	bomb shot	25,26
	--	10 %	--	~fiss.neutr.spectr.	glas detector	29

Isotope	σ_T	σ_F	σ_c	energy range	method	Ref.
^{247}Cm	--	~20 %	--	thermal		27,28,32,33,34
	--	10% E<1 MeV	--	20 eV-3.0 MeV	bomb shot	25,26
	--	20% E≥1 MeV	--			
	--	reson.par.	--	20 eV-60 eV		
	--	10 %	--	fiss.neutr.spectr.	glas detector	29
	--	--	50 %	thermal		34
^{248}Cm	--	15 %	--	thermal	ioniz.chamber plastic track	27,28
	--	6 %	--	fiss. neutr.spectr.	glas detector	29
	< 10%	--	--	0.5 eV-3 keV	T-O-F, Linac	39
	reson.par.	--	--			
	--	reson.par.	--	20 eV-3.0 MeV	bomb shot	25,26
	--	reson.par.	--	7 eV-100 eV	chopper	22,23
			30 %	thermal	mass spectr.	34
^{249}Cm	--	--	1000 %	reactor spectr.	isotope separation	40
^{249}Bk	reson.par.	--	--	0.005 eV-1 keV	T-O-F ORELA	41,42
	--	10 %	--	0.2-1.7 MeV	glas detector σ_F and $\sigma_F(\theta)$	43,44
	--	15 %	--	thermal	ioniz.chamber	32
	--	--	10 %	pile neutrons	Cf isotope prod.	35,49
	--	± 6.4 %	--	0.7-3 MeV	bomb shot	46
	--	± 10 %	--	MeV-range	glas detector	45

Isotope	σ_T	σ_F	σ_c	energy range	method	Ref.
^{249}Cf	reson.energies	--	--	0.005-1000 eV	T-O-F ORELA	41,42
	--	4-10 %	--	thermal	reactor meas.	27,33,35,48,50
	--	6 %	--	13 eV-3 MeV	bomb shot	51
	--	reson.par.	--	15-70 eV		
		reson.par.	--	0.7 eV-17 eV	T-O-F ORELA	52
	--	5-10 %	--	thermal, 0.5-7 MeV	glas detector	53,54,55
	--	$\sigma_f(\theta),\sigma_f$	--	0.16-1.7 MeV	glas detector	54
	--	--	< 10 %	thermal	heavy elem.prod.	35,48,56
^{250}Cf	--	--	crude	pile neutron spectr.	prod.heavy elem.	47
^{251}Cf	--	~ 25 %	--	thermal	pile reactor	50,57
	--	--	crude	thermal	heavy elem.prod.	47
^{252}Cf	--	~20 %	--	20 eV-5 MeV	bomb shot	25,58
	--	reson.par.	--	20 eV-1 keV		
	--	--	crude	thermal	heavy elem.prod.	44
	--	--	10 %	2200 m/s	activation	56,57
	--	15 %	--	2200 m/s	fiss.track	54

TABLE 5 : *Numerical values of the experimental thermal neutron fission and capture cross section of some Cm, Bk, Cf and Es isotopes*

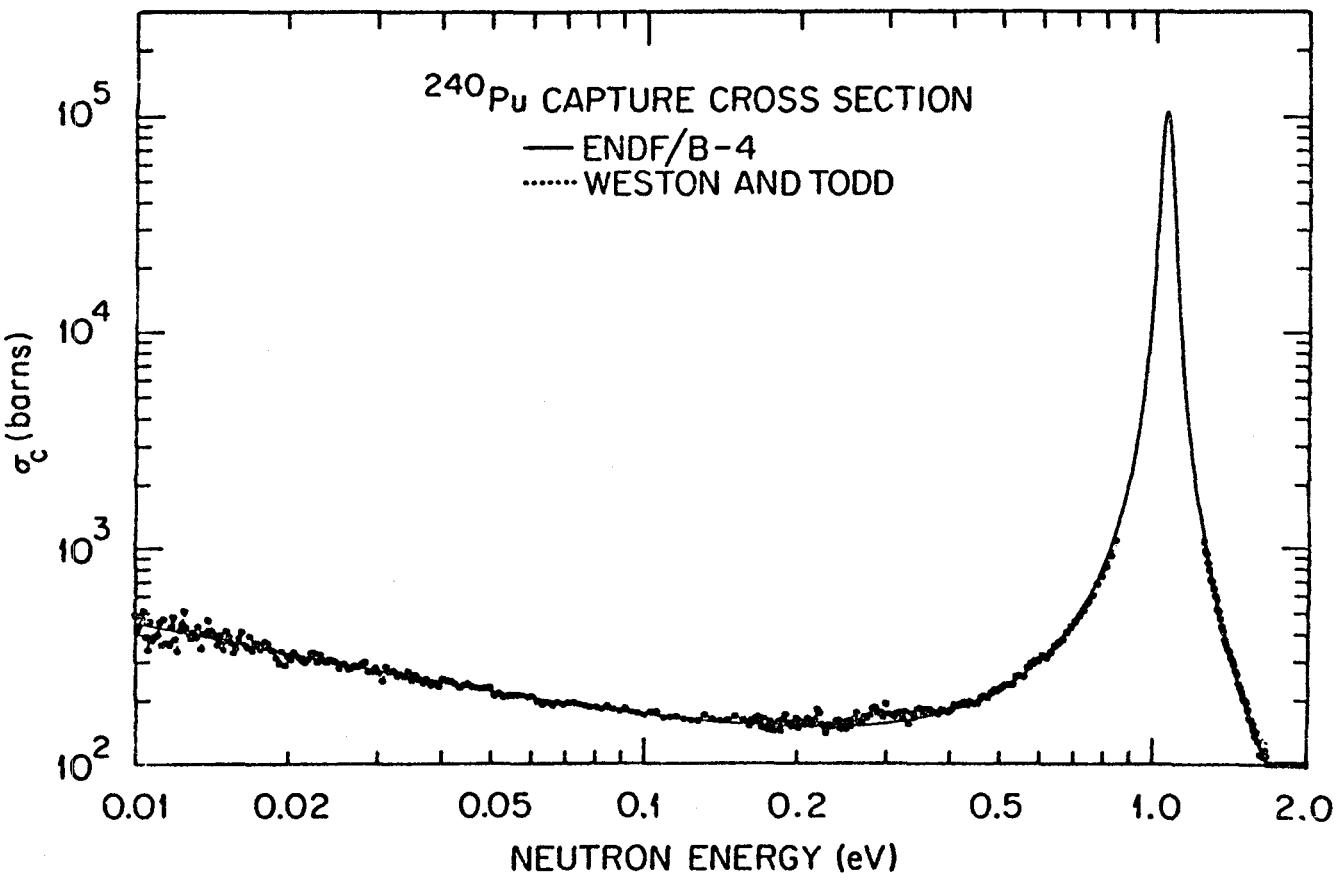
Isotope	σ_F (barn)	Ref.	σ_C (barn)	Ref.
^{242}Cm	5 <	12		
^{243}Cm	690 ± 50	13		
	690,6 ± 25,9	14	130,7 ± 9,6	14
^{244}Cm	690 ± 50	13	25 ± 10	30
	609,6 ± 25,9	14		
^{245}Cm	1880 ± 150	13	200 ± 100	30
	2018 ± 37	27	340 ± 20	37
	2040 ± 80	32		
	2070 ± 150	28		
	1920 ± 180	33		
	2030 ± 200	34	360 ± 50	34
	1900 ± 100	35		
	2143 ± 58	36		
^{246}Cm	0,14 ± 0,05	28	15 ± 10	30
	0,17 ± 27			
^{247}Cm	82 ± 5	27		
	80 ± 7	28		
	100 ± 50	34	60 ± 30	34
	108 ± 5	32		
	120 ± 12	33		
^{248}Cm	0,34 ± 0,07	27	3 ± 1	34
	0,39 ± 0.07	28		
^{249}Cm	1660 ± 50	27	478 ± 25	56
	1690 ± 160	33		
	1735 ± 70	50		
	1610 ± 110	48,35	530 ± 33	48,35
^{251}Cf	3000 ± 260	50		
	4800 ± 250	57		
^{252}Cf	32 ± 4	56	20,6	60
			20,4 ± 2	59
			25	45
^{254}Es	3060 ± 180	32	< 15	49
	2700 ± 600	61		

TYPICAL COMPOSITION OF LWR Pu

59%	^{239}Pu
26%	^{240}Pu
12%	^{241}Pu
3%	^{242}Pu

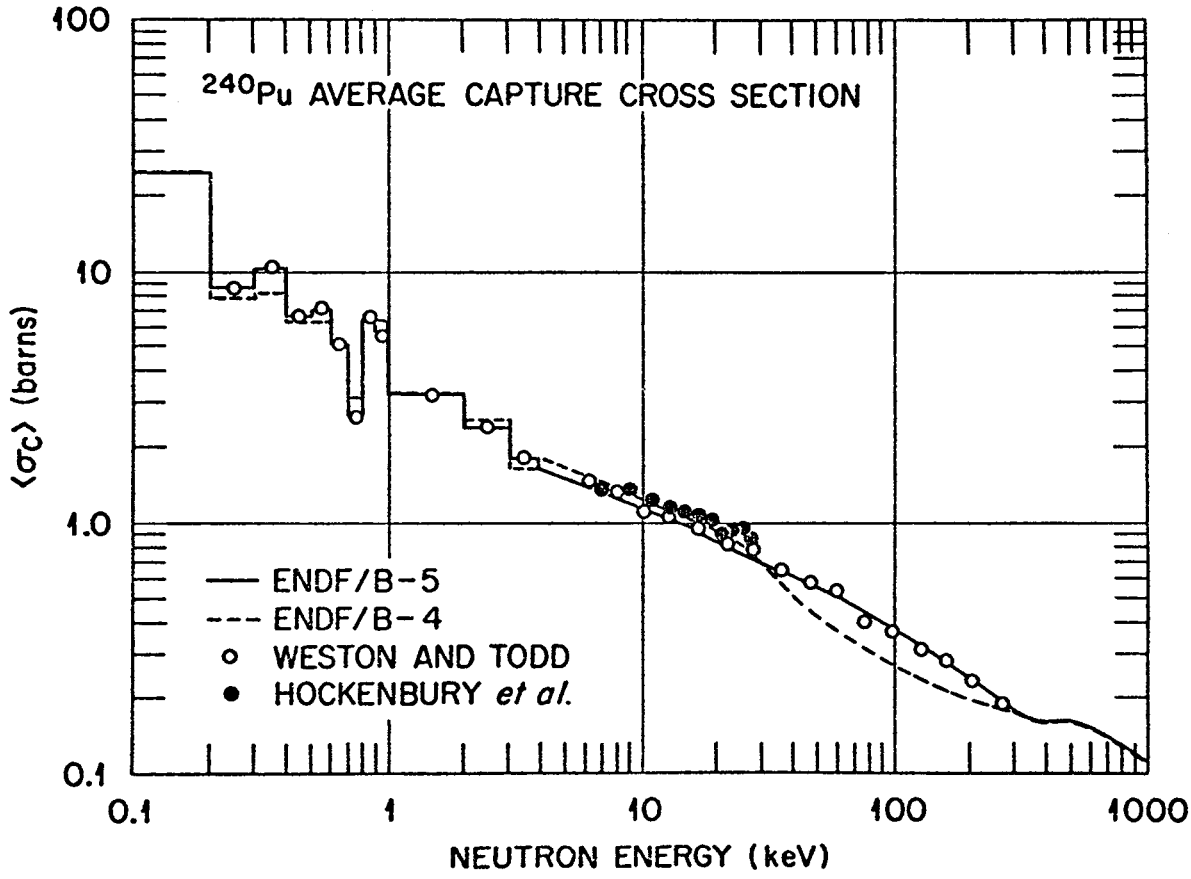
Typical composition of light water reactor plutonium. Figure taken from L.Weston (1)

Fig. 1



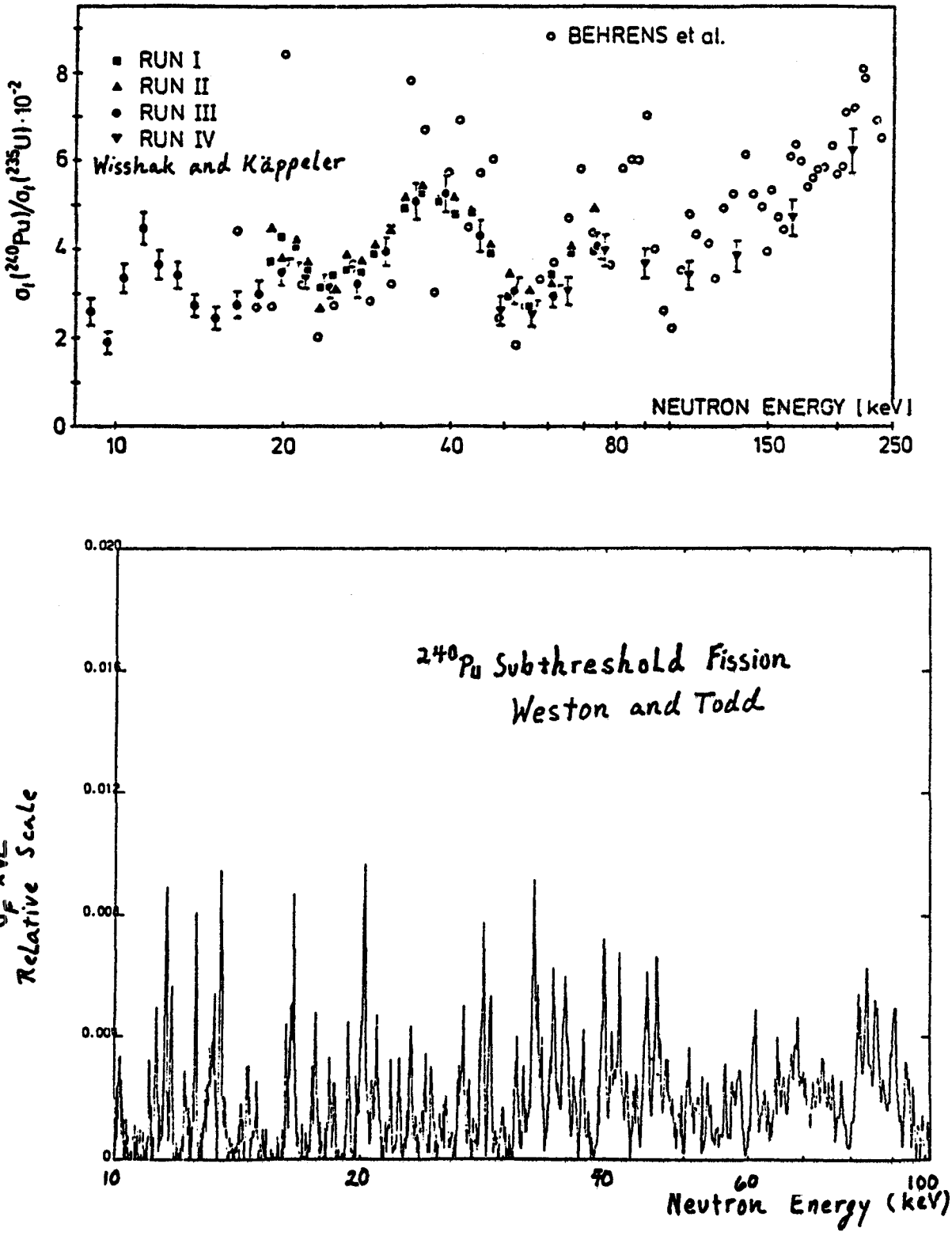
^{240}Pu capture cross section, taken from L.Weston (1)

Fig. 2



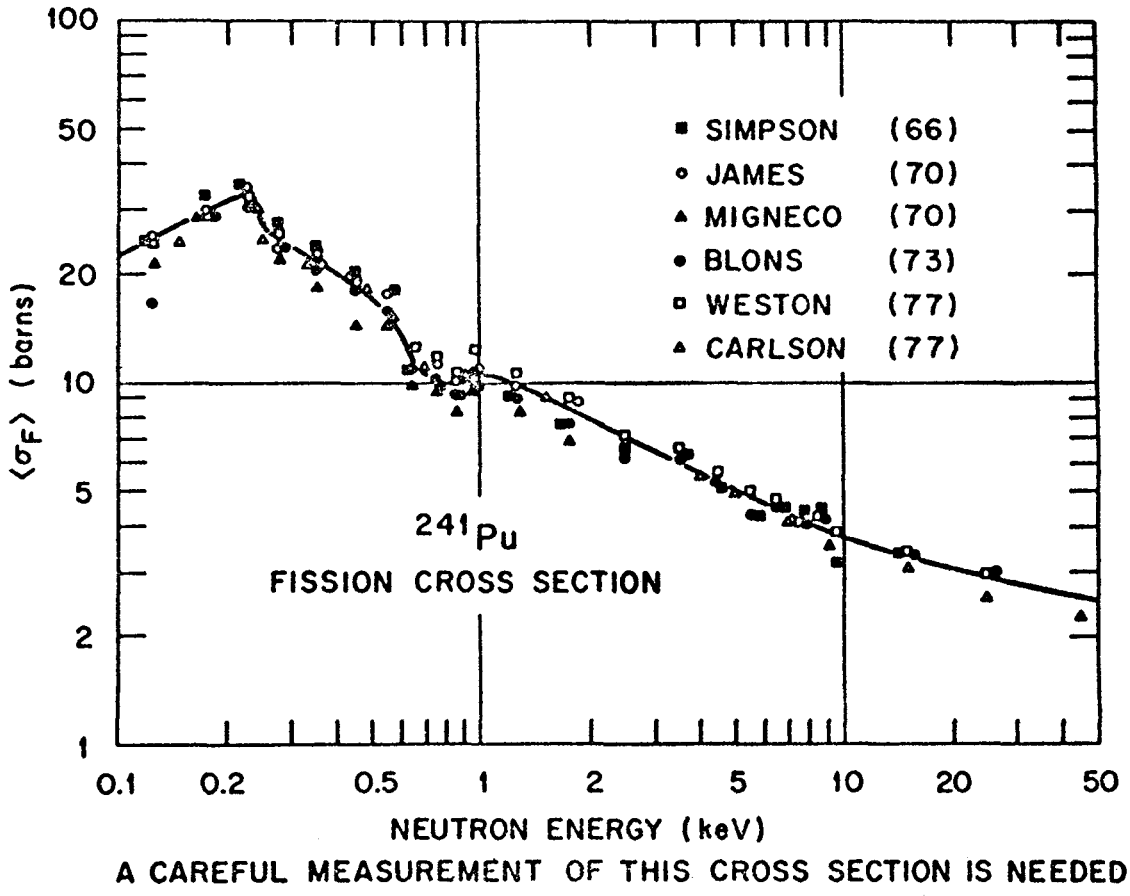
^{240}Pu average capture cross section, taken from L.Weston (1)

Fig. 3



^{240}Pu subthreshold fission cross section, taken from L.Weston (1)

Fig. 4



^{241}Pu average fission cross section, taken from L.Weston (1)

Fig. 5

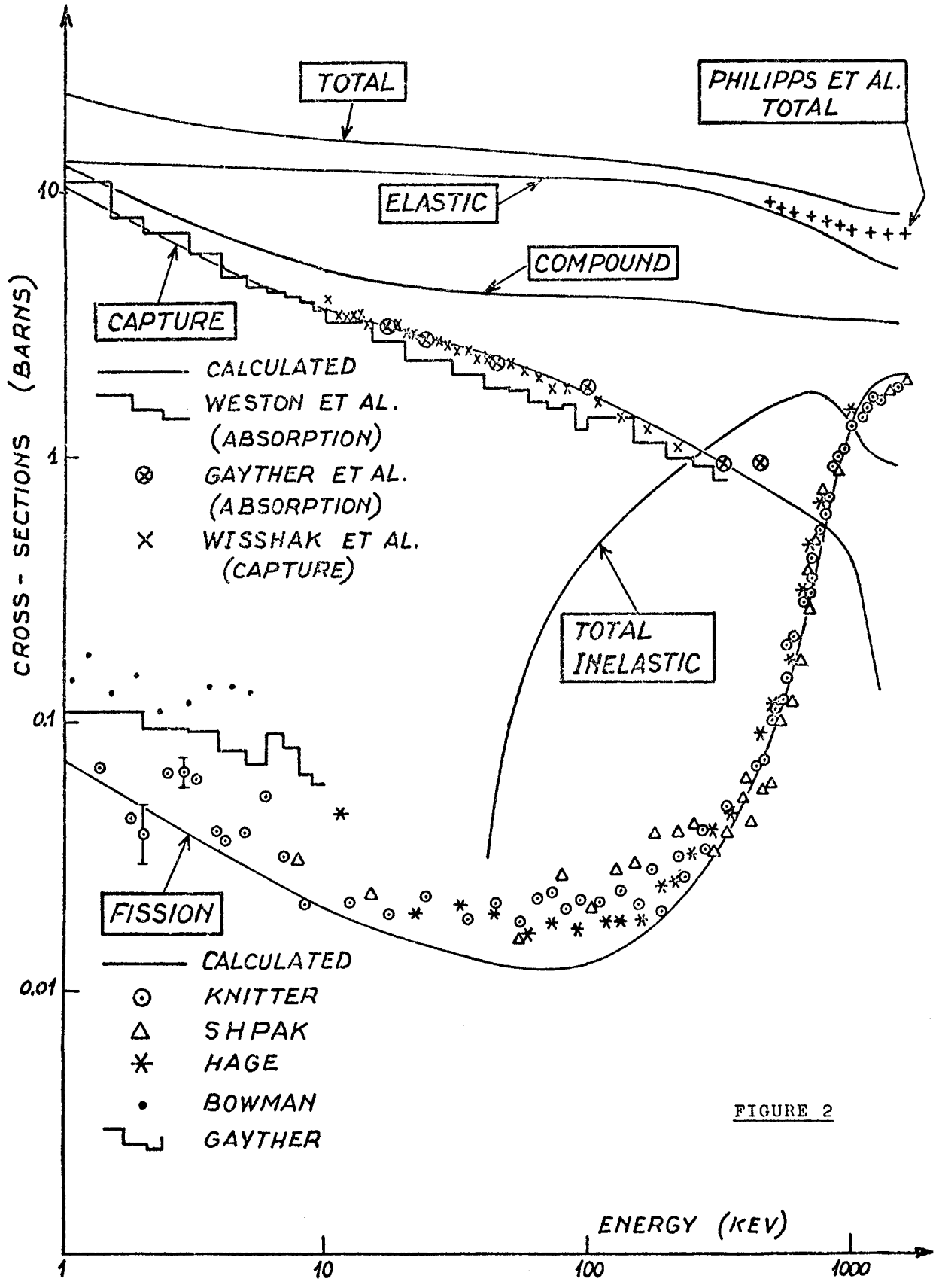
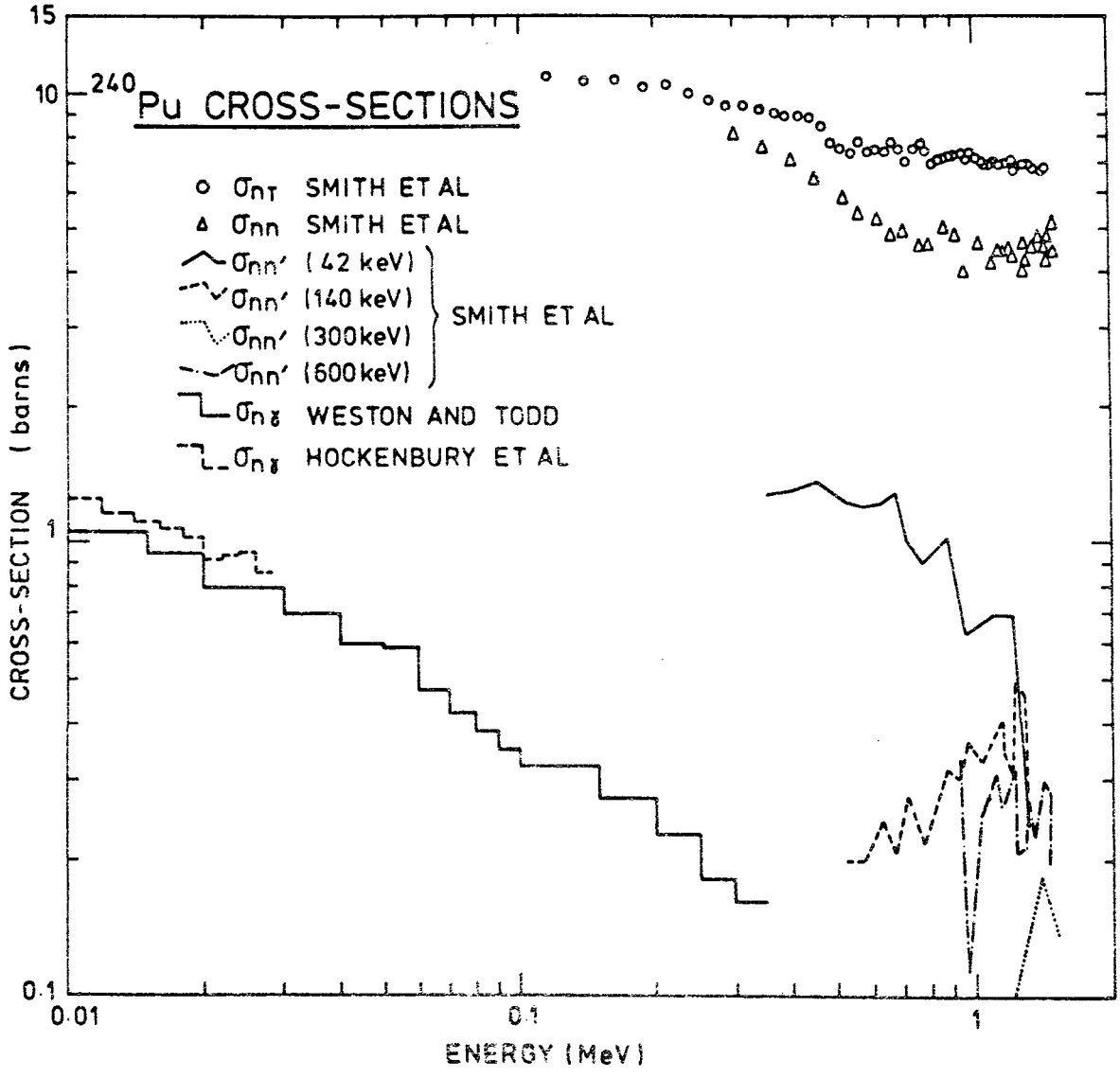


FIGURE 2

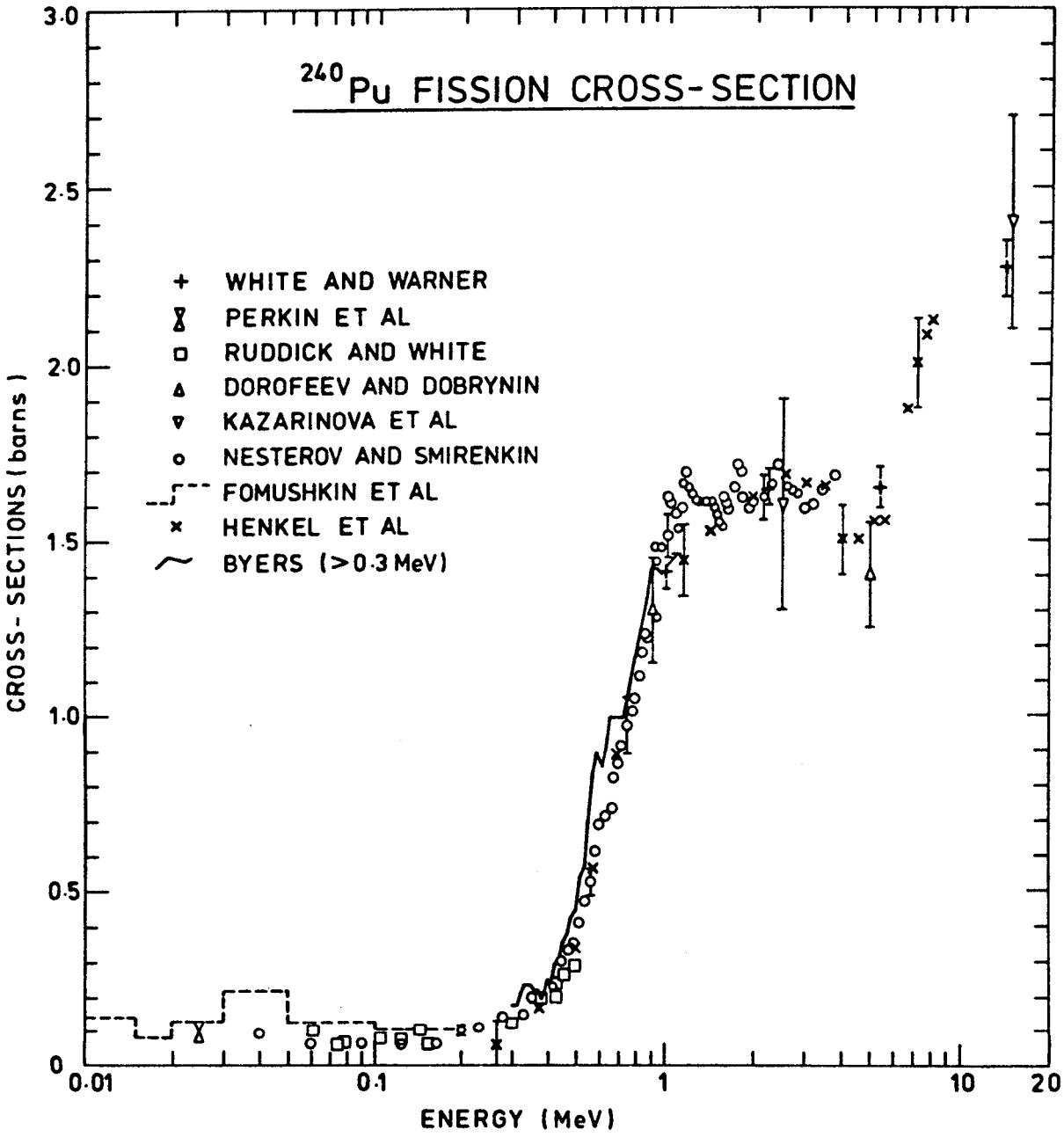
Overview over cross section set of ^{241}Am in the energy range from 1 keV to 2 MeV, taken from H.Derrien et al. (1)

Fig. 6



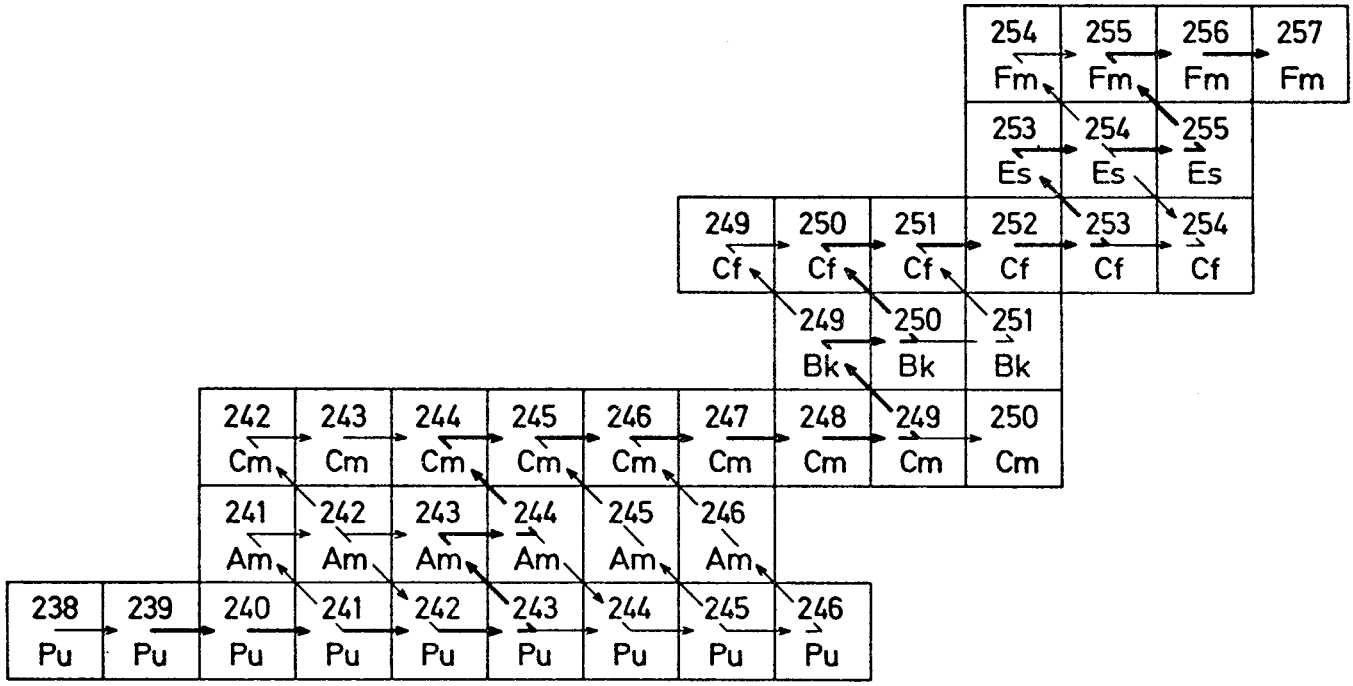
Overview of ^{240}Pu cross sections, except the fission cross section, taken from B.H.Patrick (1)

Fig.7



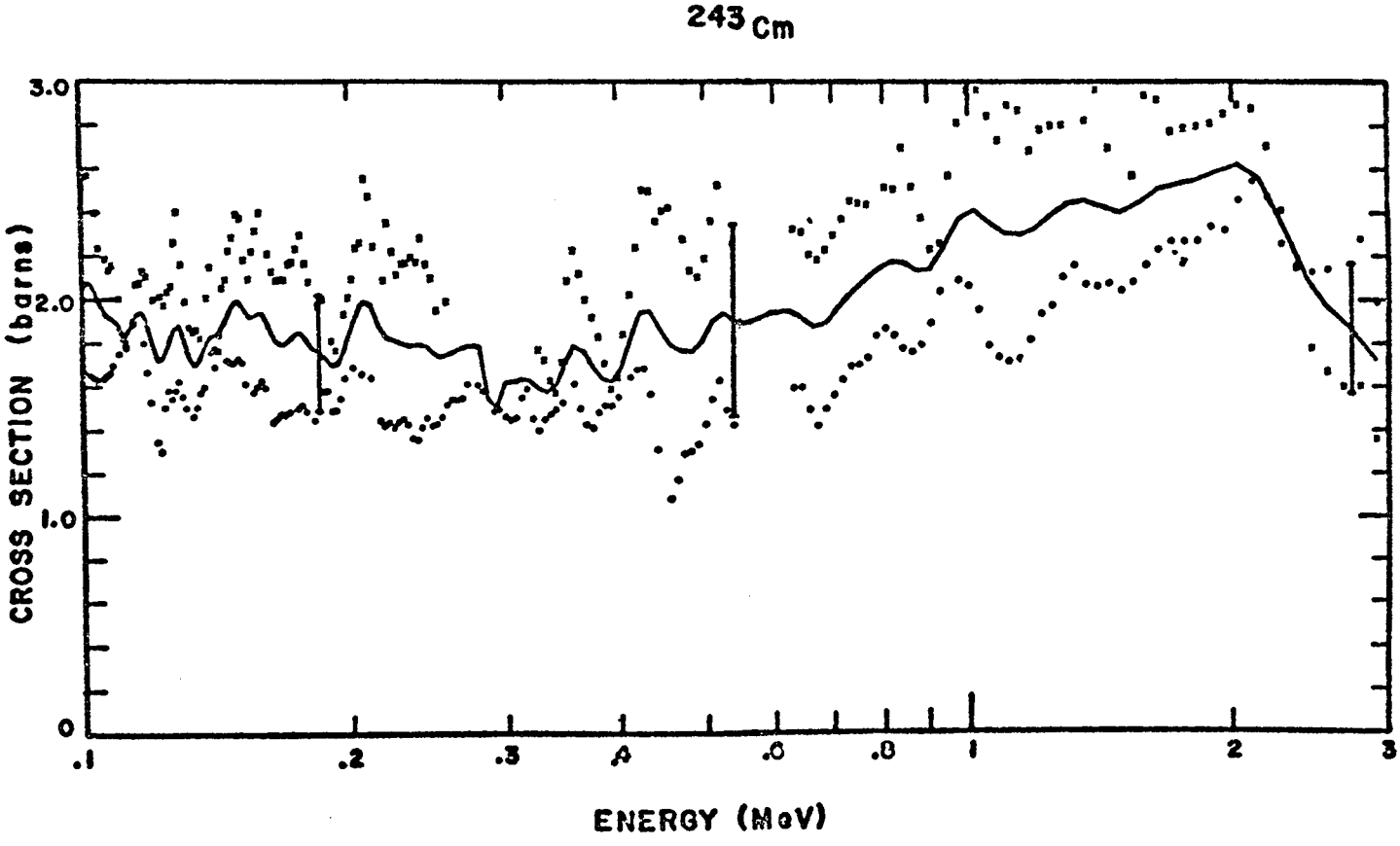
Fission cross section ratio of ^{240}Pu to ^{235}U, Patrick (1).

Fig. 8



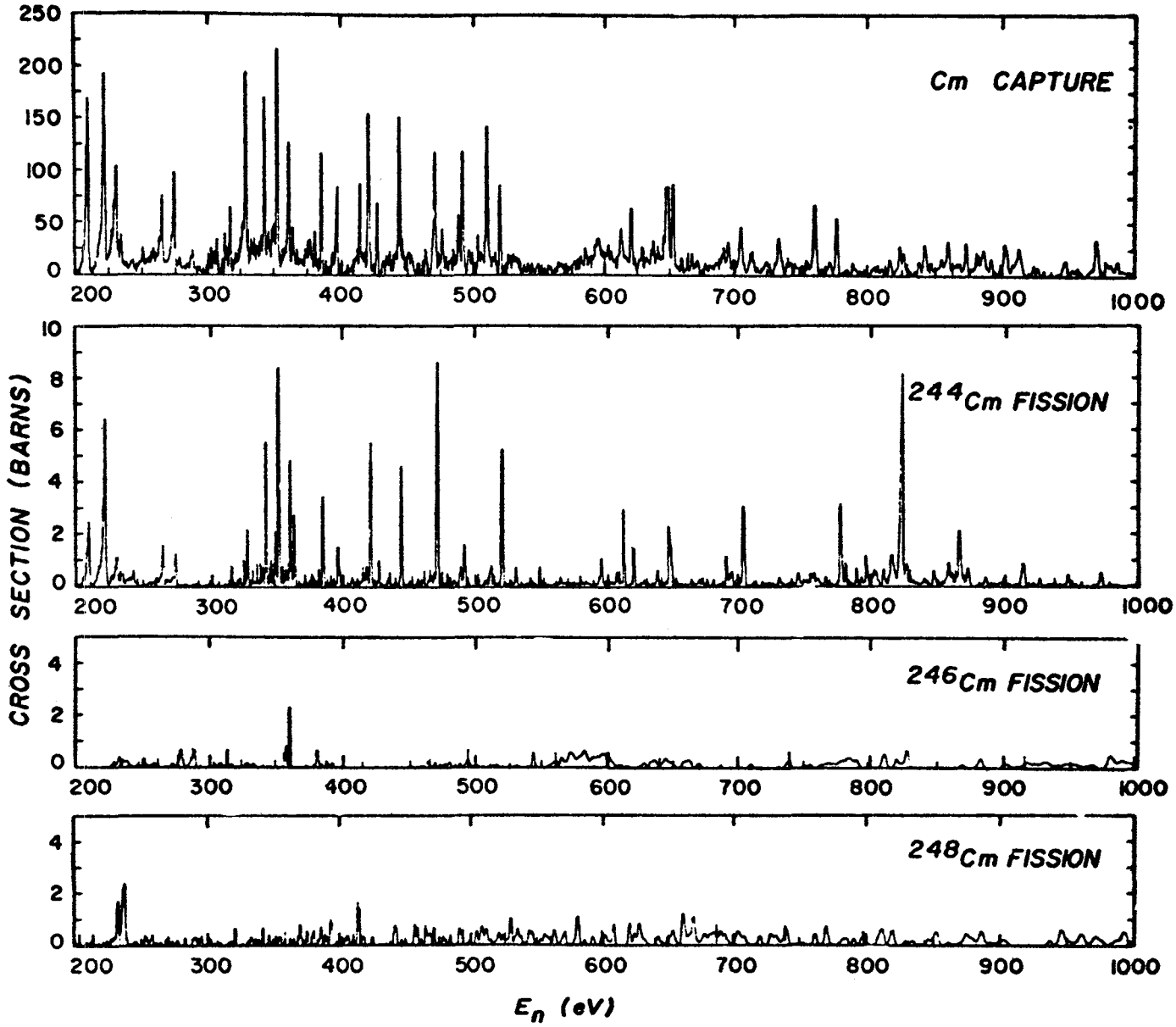
Part of nuclide chart with heavy element production line for slow neutrons.

Fig. 9



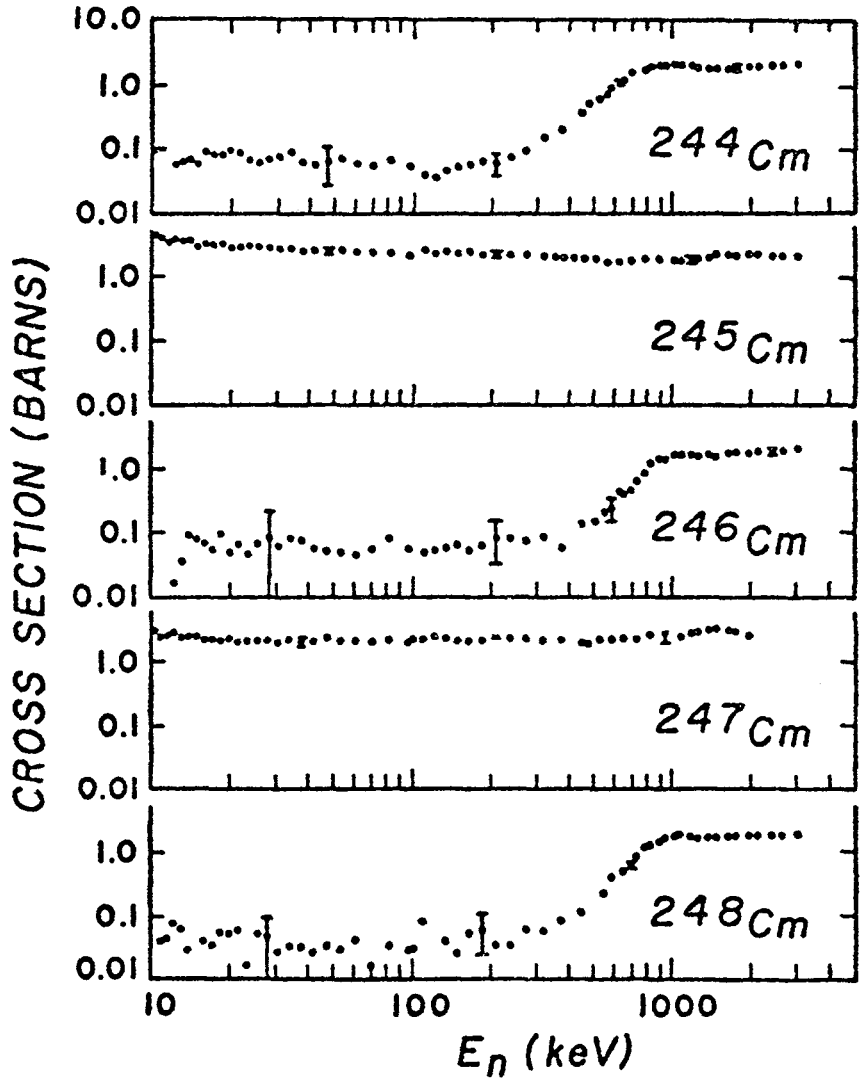
Fission cross section of ^{243}Cm from 0.1 to 3 MeV (15).

Fig. 10



Capture and fission cross section of curium isotopes between 0.2 eV and 1 keV (25).

Fig. 11



Fission cross section of curium isotopes between 10 keV and 3 MeV (25).

Fig. 12

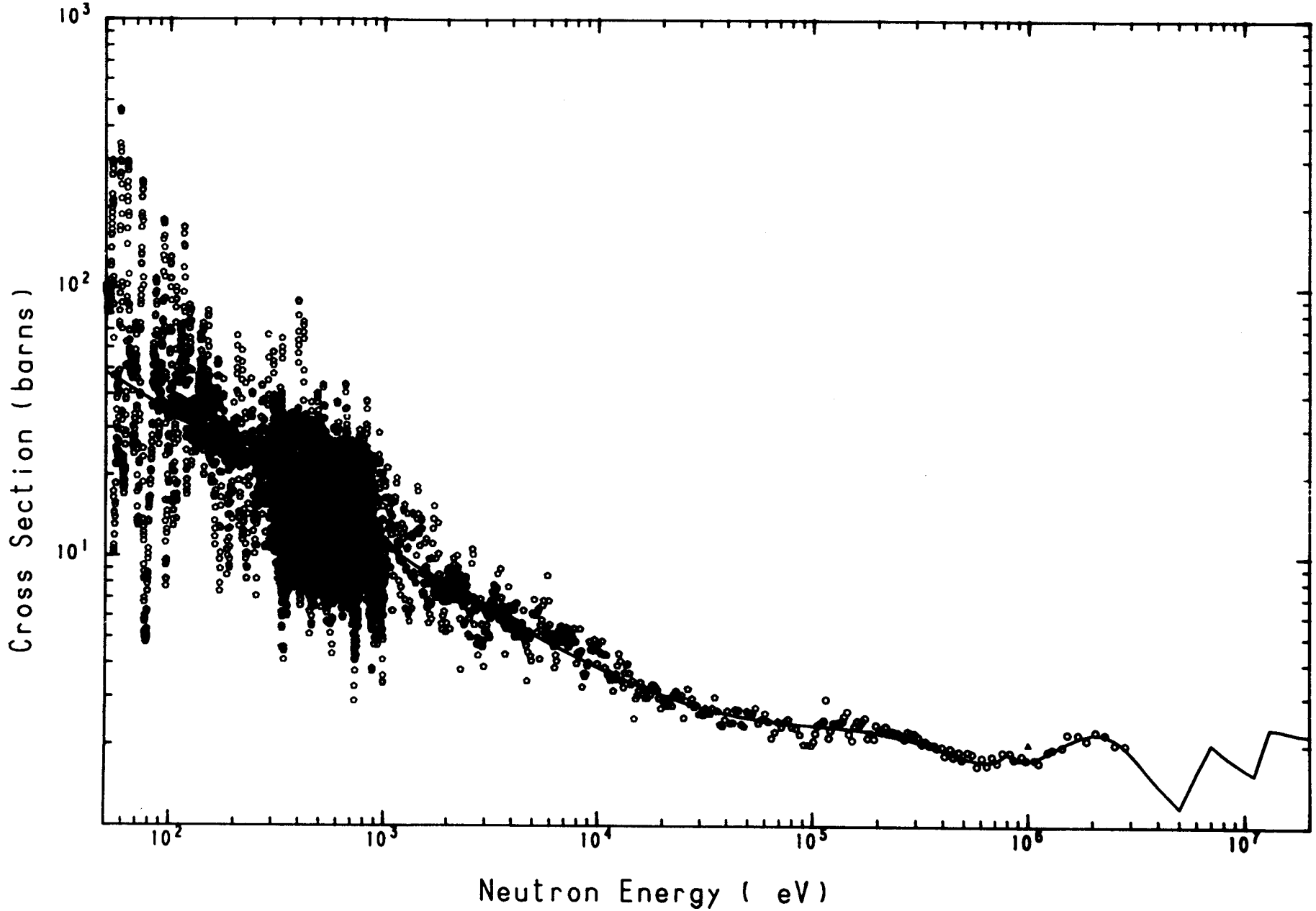


Fig. 13 ^{245}Cm fission cross section in the energy range from 50 eV to 15 MeV (31).

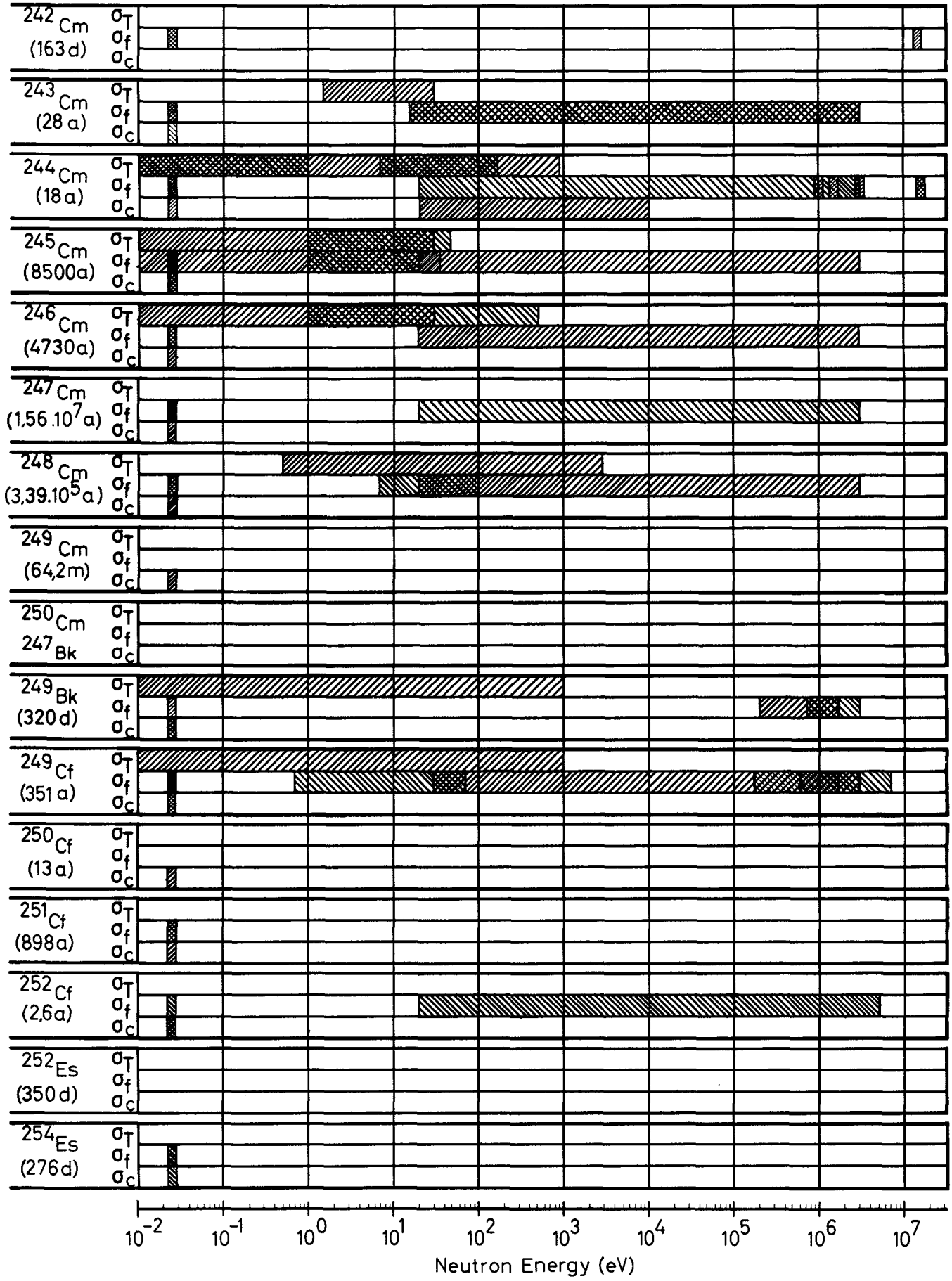


Fig. 14 Graphical display of cross section measurements on Cm, Bk, Cf and Es isotopes.

STATUS AND ACCURACY OF EXPERIMENTAL NEUTRON DATA FOR THE IMPORTANT ISOTOPES RELEVANT TO THE ^{232}Th - ^{233}U FUEL CYCLE IN THE THERMAL AND RESONANCE REGION

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ABSTRACT

The present review report contains the status and accuracy of experimental neutron data for the relevant isotopes to ^{232}Th - ^{233}U fuel cycle. The analyzed energy range is from thermal up to inelastic scattering threshold for each isotope.

The analysis is based on EXFOR data and WRENDA requirements. The main purpose of this survey is to offer to experimentalists and evaluators first brief picture for the future activity.

1. INTRODUCTION

The status and accuracy of experimental neutron data for thermal and resonance range is presented for Th-231, 232, 233, Pa-231, 232, 233 and U-232, 233, 234.

The experimental information surveyed is based on EXFOR* library and, in this respect, the completness of the report is the same with the corresponding completness of EXFOR data base.

The data are analysed per isotope in the increasing mass number, and the upper limit of energy range is defined by the specific threshold of the inelastic process.

Some general information regarding the analysed nuclei as spin and nuclear parity, the mode of decay, half-life, natural abundence, the energy of the first positive resonance, |Q| value for the inelastic process, and the corresponding threshold energy, are given in Table I.

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* All the EXFOR data used have been kindly supplied by the IAEA - Nuclear Data Section

Except the data for the first resonance which are selected from BNL-325 /1/, all the other information have been selected from "Table of isotopes" /2/ and the threshold energies are computed from the corresponding Q values.

The surveyed types of data,namely, total,fission, absorption cross sections, resonance parameters, α and η values, fission and absorption resonance integrals, total, prompt and delayed averaged numbers of neutrons per fission for the analysed isotopes from the point of view of availability in EXFOR library versus WRENDA requirements /3/ are presented in Table II.

The Table III summarizes the more restricted requested accuracies selected from WRENDA for the isotopes under consideration.

From Table II it is obvious that for Th-231, Th-233 and Pa-232 there are no experimental data available in thermal and resonance range.

The main experimental available results, for each isotope are discussed and for each reference short notes are given. They contain information about author, EXFOR access number energy range, energy resolution, number of points, errors, quantity

Table I

Main nuclear characteristics of analized isotopes

Isotope	I^{π}	$T_{\frac{1}{2}}$	Decay mode	Abn.%	First resonance (eV)	E^{in}_{thres} (keV)	$\|Q\|_{in}$ (keV)
Th-231	$5/2^+$	25.52h	β^-	-	-	42.13	41.95
Th-232	0^+	$1.41\cdot10^{10}$y	α	100%	8.35±0.01	49.58	49.37
Th-233	$1/2^+$	22.3m	β^-	-	-	5.93	5.9
Pa-231	$3/2^-$	$3.28\cdot10^{4}$y	α	-	0.396±0.003	9.26	9.22
Pa-232	(2^-)	1.31d	β^-	-	-	-	-
Pa-233	$3/2^-$	27d	β^-	-	0.795	6.71	6.68
U-232	0^+	72y	α	-	5.98±0.01	47.81	47.6
U-233	$5/2^+$	$1.592\cdot10^{5}$y	α	-	0.17±0.02	40.52	40.35
U-234	0^+	$2.446\cdot10^{5}$y	α	0.0054%	5.19±0.01	43.68	43.49

Table II

Status of EXFOR data versus WRENDA/76/77 requests

Data / Isotope	σ_{tot}	σ_f	σ_{abs}	α	η	Res. param.	I_{abs}	I_f	$\bar{\nu}$	$\bar{\nu}_{pr}$	$\bar{\nu}_{dl}$
Pa-231	x	x				x		x			
Pa-232											
Pa-233	(x)	( )	( )			x					
Th-231											
Th-232	(x)	x	x			(x)	x				
Th-233	( )					( )					
U-232	x	x	x	x		x		x		x	
U-233	(x)	(x)	x	(x)	(x)	(x)		x	(x)	x	(x)
U-234	(x)	x	x			x					

x - available EXFOR data

( )- WRENDA requests.

Table III

WRENDA 76/77 accuracy requests

Isotope / Data	Th 232	Th 233	Pa 233	U 232	U 233	U 234	Pa 231
Total	5%	5%	5%	-	5%	5%	-
Elastic	5%	5%	5%	-	5%	-	-
Capture	2-3%	2-5%	≥5%	2-10%	1-3%	3-10%	10%
Res.param.	10%	5%	-	-	10%<1keV 30%>1keV	-	-
Absorption	-	-	5%	-	-	-	---
Fission	-	-	≥5%	-	1%	-	-
Capt.res. int.	-	-	10%	-	-	-	-
α	-	-	-	-	-	≥2-3%	-
η	-	-	-	-	0.4-0.5%	-	-
$\bar{\nu}$	-	- -	-	-	0.25-3%	-	-
$\bar{\nu}_d$	-	-	-	-	5%	-	-

if it is associated with the main type of data (for example $\sigma_f \cdot \sqrt{E}$, ratios, averaged cross sections, etc.).

Always when was possible, the experimental facility used, source of neutrons, method, detectors, standards, corrections, errors and any other useful comments, have been mentioned.

For the single-point measurements, the data values, as well as the associated errors are given. The same manner has been adopted for the standards used, if they have been reported by authors.

For some isotopes and cross sections having a large number of measurements reported, figures, presenting the coverage of the energy range by experimental data, with number of points and errors reported, are given.

This makes easier to define the gaps of data and "gaps of accuracy" to be taken into account by the future activity.

Specific comments on these aspects are given at the end of each isotope analysis.

We have adopted this manner of analysis, hoping to offer an comprehensive and preliminare view on status of experimental neutron data for the important isotopes relevant to the ^{232}Th - ^{233}U fuel cycle.

In the same sense useful information for some of the analysed isotopes can be found in Benjamin's report /4/, presented at the first "Advisory Group Meeting on Transactinium Isotope Nuclear Data" held at Karlsruhe, 3-7 november 1975.

REFERENCES

/1/. S.F. Mughabghab et al. , BNL-325, vol.I, 3rd-edition, 1973

/2/. C.M. Lederer et al., Table of Isotopes, 7th-edition, 1978

/3/. R.M. Lessler, WRENDA 76/77, INDC(SEC) - 55

/4/. R.W. Benjamin, Rev. paper No.B1, proceeding of an Advisory group meeting on transactinium isotope nuclear data, 3-7 november, Karlsruhe 1975, IAEA-186, vol.2, p.1

2. SURVEY OF EXPERIMENTAL DATA

Status of the experimental data available in EXFOR library for the analysed transactinium isotopes, the selected literature for thermal and resonance energy range, is briefly surveyed in this section.

Short notes for each report regarding the experimental conditions as well as the data analysis are presented, always when such information there were available in EXFOR data base.

2.1. Thorium - 232

The energy range of interest for Th-232 is from thermal up to 50 keV.

For total cross section 18 references were surveyed, reporting experimental data from 1.9 meV, most of them being multi-point measurements.

Between the recent works, it can be mentioned the reference of Ribon /17/, reporting about 2300 experimental values, with an accuracy of 2%, between 212 eV and 2.246 keV. In addition, these measurements are reported at 77^{o}K, diminishing the Doppler effect on resonances.

There are too, two single-point measurements, by 65 Rayburn at 1.44 eV, of 13.28 ± 0.06 b , and by 76 Kobayashy at 24 keV, of 14.933 ± 0.041 b, with high accuracy, 0.45% and 0.27%respectively, which can be used for renormalizations.

The analysed energy range is quite well covered with experimental data (Fig. 1), but half of data sets existing in EXFOR are reported before 1960 , most of them having not specified the errors.

In this respect, there are two "gaps of accuracy", between 2.246 keV and 5.5 keV, for which should be useful new measurements.as well as for 1.44eV up to 212eV.

For the subthreshold fission, there are 3 reported measurements at 0.0253 eV, the newest one, by 76 Wagemans, of about 4 μb with and error ∿14%, using as standard ^{235}U(n,f) cross sections of 587.6 ± 2.6 b.

The absorption cross section is represented too, by 3 reported experimental values, at 0.0253 eV, measured by pile

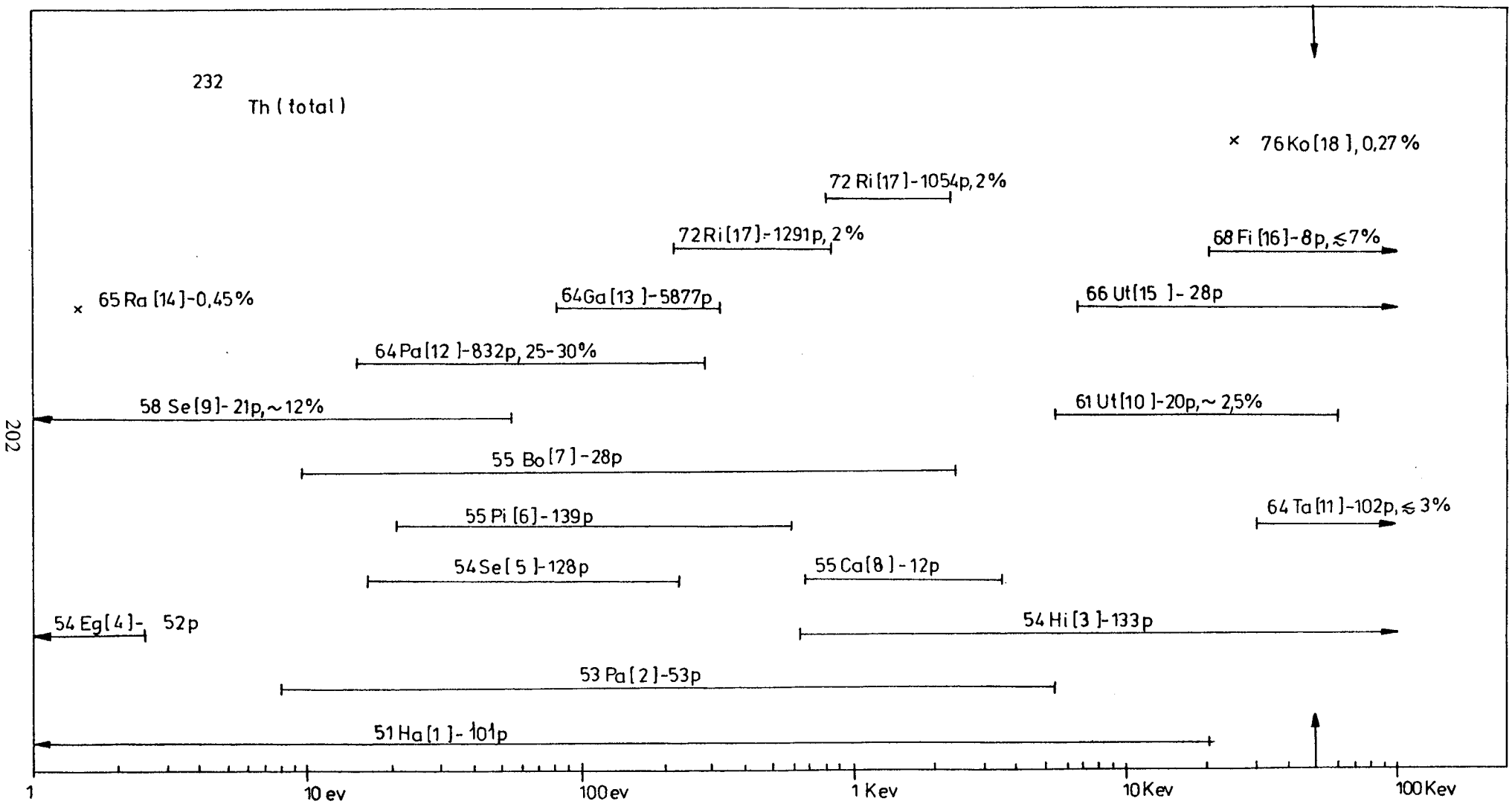
232
Th (total)
× 76 Ko [18], 0,27 %
72 Ri [17] - 1054p, 2 %
72 Ri [17] - 1291p, 2 %
68 Fi [16] - 8p, ≲ 7 %
× 65 Ra [14] - 0,45 %
64 Ga [13] - 5877p
66 Ut [15] - 28p
64 Pa [12] - 832p, 25-30 %
58 Se [9] - 21p, ~ 12 %
61 Ut [10] - 20p, ~ 2,5 %
55 Bo [7] - 28p
64 Ta [11] - 102p, ≲ 3 %
55 Pi [6] - 139p
54 Se [5] - 128p
55 Ca [8] - 12p
54 Eg [4] - 52p
54 Hi [3] - 133p
53 Pa [2] - 53p
51 Ha [1] - 101p
202
1
10 ev
100 ev
1 Kev
10 Kev
100 Kev

FIG.1

oscillator technique and using as standard the absorption cross sections of Boron.

It is to be noted, the large discrepance between the measurements of 60 Tatersall and 66 Carre on the one hand, and that of 64 Vidal on the other hand, the last one reporting a twice larger value than the first ones: 7.5 ± 0.1b, 7.5 ± 0.3b and 14.7 ± 0.35b respectively.

Regarding the experimental data for absorption resonance integral, the values given by 64 Vidal and 66 Carré and Vidal, with errors of about 4.5%, seems to be in good agreement to the value reported by 62 Brose, all of them using the pile-oscillating method, while the oldest value of 60 Tattersall seems to be overestimated (error of 9.43%) and the value of 57 Klimentov, using the coefficient reactivity method, seems to be subestimated (error of 19.4%).

In the resolved resonance range, there is a large number of experimental data sets (26), the newest one of Macklin et al. (1977).

The authors use the shape and area analysis methods to estimate the resonance parameters.

Some authors, 56 Radkevich, 61 Cooper, 62 Tiren, 68 Lundgreen, give the parameters for a negative resonance, to fit the total, elastic and capture cross sections, in the thermal energy range.

The reported resonances are generally s and p-waves, with ambiguities for "J" spin for p-wave resonances.

Generally, it seems that the number of s-wave resonances is overestimated.

Many of the authors assume the capture width, from systematic considerations.

Some authors performe also statistical analyses of resolved resonances, to estimate the strength functions: 64 Seth, 68 Coté, 72 Rahn, 72 Ribon, 77 Macklin.

The next table presents the status of gaps of data and gaps of accuracy versus WRENDA requirements, in the energy range of interest.

DATA	gap of data	gap of accuracy	Requested accuracy (WRENDA)
total	-	<212 eV 2.46 - 5.5 KeV	5%
fission	whole energy range*	-	-
absorption	whole energy range	-	-
resonance parameters	-	for p-wave resonances over whole energy range	10%

* except for 0.0253 eV

^{232}Th (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
51 Havens [1]				
E 12247 /2/	8.23 meV - 20.8 keV TOF method. Data from curves.	101		-
53 Panlicki [2]				
E 11773 /5/	7.97 eV - 5.46 keV Data from curves.	53		-
54 Hibdon [3]				
E 11002 /4/	670 eV - 0.155 MeV	133		-
54 Egelstaff [4]				
E 60303 /2/	1.9 meV - 2.5 eV TOF method. Absolute measurements.	52		-
54 Seidl [5]				
E 11671 /14/	16.9 - 225 eV	128		-
55 Pilker [6]				
E 12290 /2/	21 - 580 eV TOF method.	139		-
55 Bollinger [7]				
E 12304 /2/	9.7 eV - 2.331 keV (66 - 99 ns/m) Fast chopper. TOF method. Sample thickness ∿ 0.07 - 29.58 g/cm^2 for different energy ranges.	286		-

55 Caxter [8]

E 12310 /2/ 660 eV - 3.7 keV 12

Fast chopper. Data from curves (BNL-325/1958).

58 Seth [9]

E 11788 /22/ 0.526 - 53.7 eV 21 ∿12%

^{232}Th (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
61 Uttley [10]				
E 61032/2/	5.5 - 60 keV (1.6 ns/m)	20		∿2.5%
	TOF method. Absolute measurements.			
64 Tabony [11]				
E 11936 /9/	30 - 650 keV	102		≤3%
	TOF method.			
64 Pattenden [12]				
E 60823 /2/	15 - 289 eV (En.err.: 0.28-2.3eV)	832		25-30%
	TOF method.			
64 Garg [13]				
E 12278 /2/	82 - 329 eV	5877		-
	TOF method.			
65 Rayburn [14]				
E 11026 /34/	1.44 eV	1		0.45%
		13.28 ± 0.06 b		
66 Uttley [15]				
E 61028 /2/	6.5-950 keV (0.5 - 50 keV)	28		-
	TOF method. Absolute measurements.			

^{232}Th (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
68 Filipov [16]				
E 40082 /21/	20-350 keV (10 - 40 keV)	8		≤7%
	VDG. (P,T) and (D,D) sources. Transmission method. Proportional counter, long counter and fission chamber. Background, multiple scattering and detector efficiency corrections.			
72 Ribon [17]				
E 20149 /52/	212 - 853 eV	1291		∿2%
/53/	810 eV - 2.246 keV	1054		∿2%
	45 MeV LINAC (Saclay). Photoneutron source. TOF method (103.7 m flight path). Absolute transmission measurements (77°K). Systematic errors.			
76 Kobayashi [18]				
E 20701 /2/	24 keV	1	$(\langle\sigma_t\rangle)$	0.27%
		14.933 ± 0.041 b		
	Photoneutron source. TOF method. ^{6}Li glass scintilator, BF_3 proportional counter and NaI crystal. Absolute measurements. Background dead time, and air scattering corrections. Statistical error.			

^{232}Th (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
64 Bondarenko [19]				
E 80080 /2/	0.0253 eV	1	$(\sigma_f(^{232}Th)/\sigma_f(^{235}U))$	5.1%
		0.0313 ± 0.0016		
	BR1 reactor. Fission chamber detector.			

68 Neve de Mevergnies [20]

E 20263 /2/ 0.0253 eV 1 0.1%

$3.9 \cdot 10^{-3} \pm 4 \cdot 10^{-6}$ b

BR1 reactor. Thermal column. Maxwellian spectrum. Track detector. Standard: $\sigma_{n,\gamma}(^{197}Au)$ - not given.

77 Wagemans [21]

E 20587 /2/ 0.0253 eV 1 ∿14%

$7 \cdot 10^{-3} \pm 1 \cdot 10^{-3}$ b (without backgr.corr.)

$4 \cdot 10^{-3}$ b (with backgr.corr.)

High flux reactor (Grenoble). Thermal column. Gold-silicon surface barrier detector. Standard: $\sigma_{n,f}(^{235}U) = 587.6 \pm 2.6$ b. Pulse-height analysis.

^{232}Th (Resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
54 Seidl [5]				
E 11671 /13/	22.1 - 133 eV	7	(E_r)	<3%
		7	(Γ_t)	<50%
		7	(Γ_n)	<50%
	Fast chopper. TOF measurements of neutron resonances. Area analysis.			
55 Pilker [6]				
E 12290 /3/	22 - 310 eV (0.2 - 9 eV)	16	(Γ_n)	30%
	TOF measurements. Γ_γ assumed 30 meV.			
55 Bollinger [7]				
E 12304 /3/	21.8 - 263 eV	13	($\Gamma_t, \Gamma_n, \Gamma_\gamma$, $\sigma_{tot}(E_r)$)	<30%
	Fast chopper. TOF method. Γ_γ assumed.			
56 Levin [22]				
E 12274 /3/	22.1 - 23.8 eV	2	(Γ_n, Γ_γ)	25-30%
	Interference analysis.			

56 Radkevich [23]

E 80002 /2/	22 - 350 eV (En.err.: 0.15-9eV)	16	(Γ_n)	<40%
/9/	22 - 23.6 eV (En.err.: 0.15-0.16eV)	2	(Γ_γ)	<40%

TOF method.

^{232}Th (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
61 Cooper [24]				
E 12285 /2/	-3.5 eV	1	(Γ_n^o) 1.43 meV	-
			(Γ_n) 26 meV	
	SLBW analysis.			
62 Tiren [25]				
E 60936 /2/	-4.3 eV	1	(Γ_γ) 40 meV	-
	From thermal cross section and positive resonance parameters.			
62 Uttley [26]				
E 61112 /2/	1.091 - 1.203 keV (1.6 ns/m)	4	(E_r)	-
/3/	0.329 - 1.3 keV (1.6 ns/m)	46	(Γ_n)	15-80%
	TOF method. Area analysis. Γ_γ assumed 30 meV.			
63 Uttley [27]				
E 60013 /2/	128.78 eV	1	(Γ_n) 3.5 ± 1.1 meV	~31%
/3/	21.69 - 23.35 eV	2	(Γ_γ)	15%
/4/	21.69 - 23.35 eV	2	(Γ_n)	18%
/5/	192.22 - 341.16 eV	8	(Γ_n)	15-20%
/6/	145.39 - 195.96 eV	3	(E_r)	-
/7/	59 - 341 eV	7	(Γ_γ)	<25%
/8/	59.3 - 220.73 eV	4	(Γ_n)	<13%
	Area analysis. Γ_γ assumed 21 meV.			

^{232}Th (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
63 Pattenden [28]				
E 61114 /2/	-23.35 eV	1	(Γ_n) 3.7 meV	-
/3/	21.73 - 69.1 eV	4	(Γ_n)	7-20%
/4/	69.02 eV (En.err.: ±0.02eV)	1	(Γ_n) 46.1±2.5 meV	~5.5%
/5/	69.02 eV (En.err.: ±0.02eV)	1	(Γ_t) 65.9±4.1 meV	6.2%
	Area analysis/2/, /3/. Γ_γ assumed 25 meV /2/, and Γ_γ assumed 21.4 meV /3/. Shape analysis /4/, /5/.			
64 Seth [29]				
E 11665 /34/	3 - 650 keV	2	(S_n^o) $(1.2\pm0.5)10^{-4}$	~42%
			(S_n^1) $(0.5\pm0.25)10^{-4}$	50%
64 Palevsky [30]				
E 12270 /2/	365.3 - 866.2 eV	18	(E_r, Γ_n)	<30%
/3/	145.4 - 154.0 eV	2	(E_r, Γ_n)	<30%
/4/	8.24 eV	1	(Γ_n) 21±0.5 meV	<2.5%
			(Γ_γ) 29±25 meV	86.2%
/5/	21.69 - 842.4 eV	25	(E_r)	-
			(Γ_n)	<10%
			(Γ_γ)	<25%
	GA LINAC. Transmission method (180 m flight			

^{232}Th (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
	path)/2/. Capture measurements /3/. Transmission method (15 m flight path) /4/. Transmission capture and scattering /5/. Self-indication analysis of Breit-Wigner levels.			
64 Bollinger [31]				
E 12271 /2/	8.34 - 103.6 eV	11	(Γ_n)	∿25%
	Area analysis. P-wave resonances. Two resonances are doubtful (78.1eV, 96eV)			
64 Moxon [32]				
E 60025 /2/	21.69 - 489 eV	15	(Γ_γ)	15%
/3/	21.69 - 489 eV	16	(Γ_n)	<15%
	Capture measurements. Area analysis.			
64 Ribon [33]				
E 60761 /2/	2.286 - 2.947 keV	11	(E_r)	-
/3/	8.346 - 943 eV	21	(Γ_γ)	<40%
/4/	8.346 eV - 1.233 keV	134	(Γ_n)	<30%
/5/	8.346 - 943 eV	21	(Γ_t)	<25%
	Accelerator.			
64 Rae [34]				
E 60860 /2/	128.8 eV	1	(Γ_n) 3.5±0.5 meV	∿14.28%
/3/	21.69 - 463 eV	14	(Γ_γ)	15%
/4/	21.69 - 463 eV	14	(Γ_n)	<15%
	Γ_γ assumed 22 meV. Superseded by [31].			

^{232}Th (resonance parameters)

References	Energy Range (Resolution)	No.Points	(Quantity)	Error
65 Ribon [35]				
E 60096 /3/	21.78 - 305.5 eV (8 ns/m)	14	(Γ_γ)	7-24%
/4/	- " -	14	(Γ_t)	3-10%
	Shape analysis.			
65 Sanche [36]				
E 61122 /2/	8.346 eV - 2.6878 keV	68	(Γ_γ)	7-99%
/3/	- " -	68	(Γ_t)	7-99%
	Shape analysis.			
65 Haddad [37]				
E 12279 /2/	21.8 - 222 eV (En.err.: 0.04-0.4eV)	11	(E_r)	0.2%
			(Γ_n)	<30%
			(Γ_γ)	~30%
	LINAC. Area analysis. $\Delta\Gamma_n$= 0.2-15 meV, $\Delta\Gamma_\gamma$ = 2-7 meV.			
68 Lundgreen [38]				
E 20006 /4/	-5.1 eV (En.err.: ±0.5 eV)	1	(Γ_n^o) 1.8±0.4 meV	22.2%
	Reactor and fast chopper. TOF method (Flight path of 1.917 m). NaI crystal detector. Corrections for not 1/v part of cross section in Cooper and the not 1/v part of cross section due to positive resonances in ^{232}Th. Γ_γ assumed 24±2 meV.			

^{232}Th (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
68 Coté [39]				
E 12280 /4/	1.425 - 294 eV	1	(S_n^1) $1.3\cdot10^{-4}$	+23% -46%
	Fast chopper. $\Delta S_n^1 = (0.3\text{-}0.6)\cdot10^{-4}$			
71 Forman [40]				
E 10250 /2/	59.5 eV - 1.9712 keV (1 ns/m)	66	(Γ_γ)	≤50%
/3/	- " -		$(g\Gamma_n)$	
	Nuclear explosion. TOF method (Flight path of 250 m), and associated particle method. Moxon-Rae detector. Standard: ^{6}Li(n,T). Area analysis. Data for $g\Gamma_n$ not given /3/.			
72 Rahn [41]				
E 10274 /2/	21.78 - 3.9944 KeV (0.02 - 1.3 eV)	240	$(\Gamma_n^o,\Gamma_\gamma)$	<10%
/3/	58.84 - 2.932 keV (0.07 - 0.8 eV)	62	$(g\Gamma_n^o)$	<30%
/8/	0-1keV, 1-2 keV,	4	$(\langle\Gamma_n^o\rangle)$	<20%
	2-3keV, 3-4 keV		$(\langle\Gamma_\gamma\rangle)$	-
/9/	- " -	4	(S_n^o)	<22%
	Synchrocyclotron. TOF method. Moxon-Rae and scintilator detectors. Background and multiple scattering corrections. Area analysis. Errors include statistical and systematic errors.			

^{232}Th (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
72 Ribon [17]				
E 20149 /56/	8.316 eV - 2.7931 keV	87	(Γ_γ)	8-9%
/57/	22 - 306 eV	1	$(\langle\Gamma_\gamma\rangle)$ 21.8±1 meV	∿5%
/58/	8.3 eV - 3.0068 keV	312	$(g\Gamma_n)$	2.5-80%
/59/	8.31 eV - 2.7931 keV	87	(Γ_t)	7-80%
/60/	2.2 - 2.7 keV	10	(E_r)	-
/61/	8.316 eV - 2.9886 keV	166	(L)	-
/63/	8-3000 eV	1	(S_n^o) $(0.89\pm0.11)\cdot10^{-4}$	∿12.4%
/64/	8 eV - 0.5 keV	1	(S_n^1) $(1.4\pm0.5)\cdot10^{-4}$	36%
/65/	8 eV - 3 keV	1	$(\langle\Delta_n^o\rangle)$ 17±1 eV	∿6%

45 MeV LINAC (Saclay). Photoneutron source. TOF method (Flight path of 103.7 m). Absolute transmission measurements (77°K). Shape analysis /56/, /58/, /59/. Systematic errors.

76 Halperin [42]				
E 10677 /2/	23.439 eV	1	$(g\Gamma_n)$ 3.72±0.11 meV	∿3%

LINAC. TOF method. (Flight path of 40 m). Nonhydrogenous total gamma energy detector.

^{232}Th (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
77 Macklin [43]				
E 10554 /5/	2.6047 - 3.9972 eV	113	(E_r)	-
			$(g\Gamma_n\Gamma_\gamma/\Gamma_t)$	≤70%
			$(g\Gamma_n)$	<70%
			(Γ_γ)	<22%
/6/	4.012 - 10.392 keV	328	(E_r)	-
			$(g\Gamma_n\Gamma_\gamma/\Gamma_t)$	≤30%
/7/	2.6 - 105 keV	1	(S^o)	<5%
			$(14.95\pm0.67)\cdot10^{-4}$	
			$(<D_n^o>)$	<6%
			13.24±0.7 keV	
/8/	2.6 - 105 keV	3	(S_n^o)	< 7 %
			$(0.365\pm0.024)\cdot10^{-4}$	
			(S_n^1)	< 6 %
			$(1.078\pm0.057)\cdot10^{-4}$	
			(S_n^2)	<10%
			$(0.842\pm0.084)\cdot10^{-4}$	
/9/	2.6135 - 3.9781 keV	1	$(<\Gamma_\gamma>)$	<3%
			$19.8^{+0.2}_{-0.4}$ meV	

LINAC. TOF method (Flight path 40.123 m) and pulse height discrimination method. Liquid scintilator detectors. Standard: ^{6}Li(n,T). Single level analysis /5/, /6/.

^{232}Th (absorption)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
60 Tattersall [45]				
E 20638 /67/	0.0253 eV	1	(σ_{abs}^{Mxw}) 7.5±0.3 b	4%

Pile oscillator technique. Standard: σ_{abs}^{th}(B) = 764±4 b. Corrections for self screening, moderation of fast neutron by the sample, different sample lengths and nitrogen displacement by the sample. Analysis by Westcott formalism.

64 Vidal [46]				
E 60132 /5/	0.0253 eV	1	(σ_{abs}^{Mxw}) 14.7±0.35 b	2.4%

Pile oscillator technique. Standard: σ_{abs}^{th}(B) = 760.3 b.

66 Carré [47]				
E 20658 /26/	0.0253 eV	1	(σ_{abs}^{Mxw}) 7.5±0.1 b	1.3%

Oscillator method. Standard: $\sigma_{n,\gamma}^{th}$(^{197}Au) = 98.9 b and σ_{abs}^{th}(B) = 760±2 b. Corrections for self shielding, diffusion, epithermal component.

^{232}Th (absorption resonance integral)

Reference	Min.Energy	No.Points	(Quantity)	Error
57 Klimentov [48]				
E 80015 /2/	0.5 eV	1	$(I_{abs}(+1/v))$ 61.8±12 b	19.4%
	Reactivity coefficient measurements. Standard: Abs.res.int.(Li) = 32.2 b.			
60 Tattersall [45]				
E 20638 /68/	0.67 eV	1	$(I_{abs}(-1/v))$ 106±10 b	9.43%
	Pile oscillator method. Standard: Capt.Res.Int.(-1/v) (^{197}Au) = 1513±60 b; g factor = 1.006. Corrections for self-screening moderation of fast neutron by the sample, different sample length and nitrogen displacement by the sample.			
62 Brose [49]				
E 61117 /2/	0.5 eV	1	(I_{abs}) 84.4 b	-
64 Vidal [46]				
E 60132 /3/	0.5 eV	1	$(I_{abs}(+1/v))$ 91±4 b	4.39%
	Pile oscillator. Standard: Capt.Res.Int.(^{197}Au)= 1540 b and $\sigma^{th}_{n,\gamma}$(^{232}Th) = 7.5 b.			
66 Carré [47]				
E 20658 /27/	0.55 eV	1	$(I_{abs}(-1/v))$ 87±4 b	∿4.6%
	Oscillator method. Standards: Capt.Res.Int.(-1/v) (^{197}Au)=1540 b, $\sigma^{th}_{n,\gamma}$(^{197}Au)=98.9 b and σ^{th}_{abs}(B)= 760±2 b. Corrections for self-shielding,diffusion and epithermal component.			

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2.2. Protactinium - 231

The **total** cross section for Pa-231 was measured by 62 Simpson, reporting 1232 values, from 15.23 meV up to 2.141 KeV, with an energy resolution of 2 μsec/m, and 110 values from 4.905 eV to 10.59 eV with an energy resolution of 0.05 nsec/m.

At 0.0253 eV, the reported value is 211 ± 2.2 b (error 1%).

The fission cross section of Pa-231 was measured using the activation method by 76 Gryntakis at 0.0253 eV, giving a value of 0.006 ± 0.001 b (error ∿16%).

Leonard in 1961 had measured $\sigma_f \cdot \sqrt{E}$ (20 values) between 0.37 eV and 0.5225 eV, with an energy resolution of 2 μsec/m and errors of 20% up to 60%.

The resonance parameters are reported by 3 authors : 61 Leonard, between 0.396 eV and 1.235 eV (4 values, for Γ_f, $\sigma_f(E_r)$) without errors; 62 Simpson, between - 0.318 eV and 10.73 eV (25 energies) for $2g\Gamma_n^o$ (errors <6%), Γ_γ (errors 15-60%); 62 Patterson, from 0.4 eV up to 99 eV for $g\Gamma_n^o$ (118 values), and Γ_γ (8 values) with errors 5-15 %.

62 Simpson reported also $\bar{D}$ = 0.45 eV and S_n^o = 0.63 x 10^{-4}, for energy range 1 eV up to 11 eV.

The fission resonance integral for Pa-231 is measured only by 76 Gryntakis using the activation method, and gives the value of 0.049 ± 0.013 b (error ∿27%) including 1/v contribution, from 0.55 eV.

Consequently,the status of gaps of data and gaps of accuracy versus WRENDA accuracy requests, could be summarized as follows:

DATA	Gap of data	Gap of accuracy	Requested accuracy (WRENDA)
total	>2 KeV	-	-
fission	<0.37 eV* >0.52	-	-
resonance parameters	>10.7 eV	-	-

* Except for 0.0253 eV

^{231}Pa (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
62 Simpson [1]				
E 12265 /2/	15.23 meV - 2.141 keV (2 μsec/m)	1232		-
/3/	4.905 - 10.59 eV (0.05 ns/m)	110		-
/9/	0.0253 eV	1		∿1%
			211±2.2 b	

Fast chopper. TOF method.

^{231}Pa (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
76 Grytakis [2]				
E 20625 /35/	0.0253 eV	1	(σ_f^{Mxw})	∿16%
			0.006±0.001 b	

Reactor. Activation method. GeLi and scintillator detectors. Standards: Capt.Res.Int.(+1/v)(^{197}Au)= 1551±12 b, $\sigma^{th}_{n,\gamma}$(^{197}Au) = 98.8±0.3 b, Capt.Res.Int.(+1/v)(^{59}Co)= 71.1±4 b, $\sigma^{th}_{n,\gamma}$(^{59}Co)=37.2±0.6 b, Fis.Res.Int.(+1/v) (^{235}U)=274±10 b, $\sigma^{th}_{n,f}$(^{235}U)=577.1±0.9 b, $\langle\sigma_{n,p}\rangle$(^{58}Ni)=113±7 mb, $\langle\sigma_{n,p}\rangle$(^{24}Mg)=1.53±0.09 mb, $\langle\sigma_{n,\alpha}$(^{27}Al)$\rangle$= 0.725±0.045 mb. ^{95}Zr, ^{140}La fission yields for ^{231}Pa and ^{232}U. Averaged cross section in the fission spectrum of ^{235}U.

^{231}Pa (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
61 Leonard [3]				
E 12286 /4/	0.37 - 0.5225 eV (2 μsec/m)	20	$(\sigma_f\sqrt{E})$	20-60%
	Crystal spectrometer. Multiple-plate gas ionization counter.			

^{231}Pa (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
61 Leonard [3]				
E 12286 /2/	0.396 - 1.235 eV	4	(Γ_f)	-
/3/	- " -	4	$(\sigma_f(E_r))$	-
	Crystal spectrometer.			
62 Simpson [1]				
E 12265 /4/	1 - 11 eV	2	$(\bar{D})$	-
/5/	0.743 - 10.73 eV	21	$(2g\Gamma_n^o)$	<6%
			(Γ_γ)	15-60%
/6/	-0.318 - 10.73 eV	25	$(E_r, 2g\Gamma_n^o, \Gamma_\gamma)$	-
/7/	1 - 11eV	1	$(\bar{D})$ 0.45 eV	-
/8/	1 - 11 eV	1	(S_n^o) $0.63 \cdot 10^{-4}$	-
	Fast chopper. TOF method. Area analysis. /5/, BWSL analysis /6/, $\bar{D}$ assumed proportional to 2J+1. J = 2, J = 3 for /4/.			

^{231}Pa (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
62 Patterson [4]				
E 12269 /2/	0.4 - 3.48 eV	8	(E_r)	-
			($g\Gamma_n^o$)	<15%
			(Γ_γ)	≤13%
/3/	4.12 - 99 eV	110	(E_r)	-
			($g\Gamma_n^o$)	≤5%

Fast chopper. Shape analysis /2/, area analysis /3/. ℓ = 0. Γ_γ assumed 45 meV /3/.

^{231}Pa (fission resonance integral)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
76 Gryntakis [2]				
E 20625 /36/	0.55 eV	1	(I_f(+1/v)) 0.049±0.013 b	26%

Reactor. Activation method. GeLi detector. Standards: $\sigma_{n,\gamma}^{th}$(^{197}Au)=98.9±0.3 b, Capt.Res.Int. (^{197}Au)(+1/v) =1551±12 b, $\sigma_{n,\gamma}^{th}$(^{59}Co)=37.2±0.6 b, Capt.Res.Int.(^{59}Co)(+1/v)=71.1±4 b, $\sigma_{n,f}^{th}$(^{235}U)= 577.1±0.9 b, Fis.Res.Int.(^{235}U)(+1/v)=274±10 b, $\langle\sigma_{n,p}\rangle$(^{58}Ni) =113±7 mb, $\langle\sigma_{n,p}\rangle$(^{24}Mg)=1.53±0.09 mb, $\langle\sigma_{n,\alpha}\rangle$ (^{27}Al)=0.725±0.045 mb, The threshold cross sections are averaged in ^{235}U thermal fission spectrum.

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2.3. Protactinium - 233

There is a very poor experimental information in the energy range of concern, for this isotope.

The total cross section between 11 meV and 10 keV (847 values) and at 0.0253 eV of 55 ± 3 b (error 5.45 %) is reported by 67 Simpson.

The same author reports some resonance parameters E_r, Γ_n^o and Γ_γ at 28 energies up to 17 eV, including one negative level (-1 eV) without errors.

The status of gaps of data and gaps of accuracy, taking into account the accuracy requests from WRENDA, is presented in the next table.

DATA	Gap of data	Gap of accuracy	Requested accuracy (WRENDA)
total	>10 keV	whole energy range	5%
fission	-	-	5%
absorption	-	-	5%
resonance parameters	>17 eV	-	-

^{233}Pa (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
67 Simpson [1]				
E 12263 /2/	11 meV - 10 keV	847		-
/3/	0.0253 eV	1	55±3 b	5.45%
	Fast chopper. TOF method. Sample of different thicknesses.			

^{233}Pa (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
67 Simpson [1]				
E 12263 /5/	-1 - 17 eV	28	(E_r)	-
		28	(Γ_n^o)	-
		6	(Γ_γ)	-
	Fast chopper. TOF method. Sample of different thicknesses. "s" resonances; 6 of them are assumed.			

References

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2.4. Uranium - 232

The total cross section is experimental reported only by 67 Simpson, from 10 meV up to 9.292 keV (931 points) without errors.

Data for fission cross section are reported by seven authors, four of them giving single-point measurements at 0.0253 eV: 46 Seaborg (70 ± 10 b, error 14 %), 53 Elson (83 ± 15 b, error 18 %), 71 Cabell (75.2 ± 4.7 b, error 6.25%) and 76 Gryntakis (74 ± 8 b, error 11%).

The Cabell's and Gryntakis's data seems to be in good agreement in the limits of experimental errors.

In Figure 2 are presented the multi-point data reported by 64 James, 68 Auchampangh and 70 Farrell.

James reported, from 3.8 eV up to 401.2 eV, about 2900 values, but with very large errors, suggesting their careful use.

Between 3.6 eV and 27.9 eV he gives 114 values having errors less than 25%.

Very accurate measurements seems to be those of 68 Auchampangh between 5.05 eV and 1.927 KeV (707 points) with 5% error, using spark chamber technique.

Useful results seems to be also those of Farell, between 40 eV and 21 KeV, giving 2199 values with errors of about 6% (but without corrections for energy resolution and target impurities).

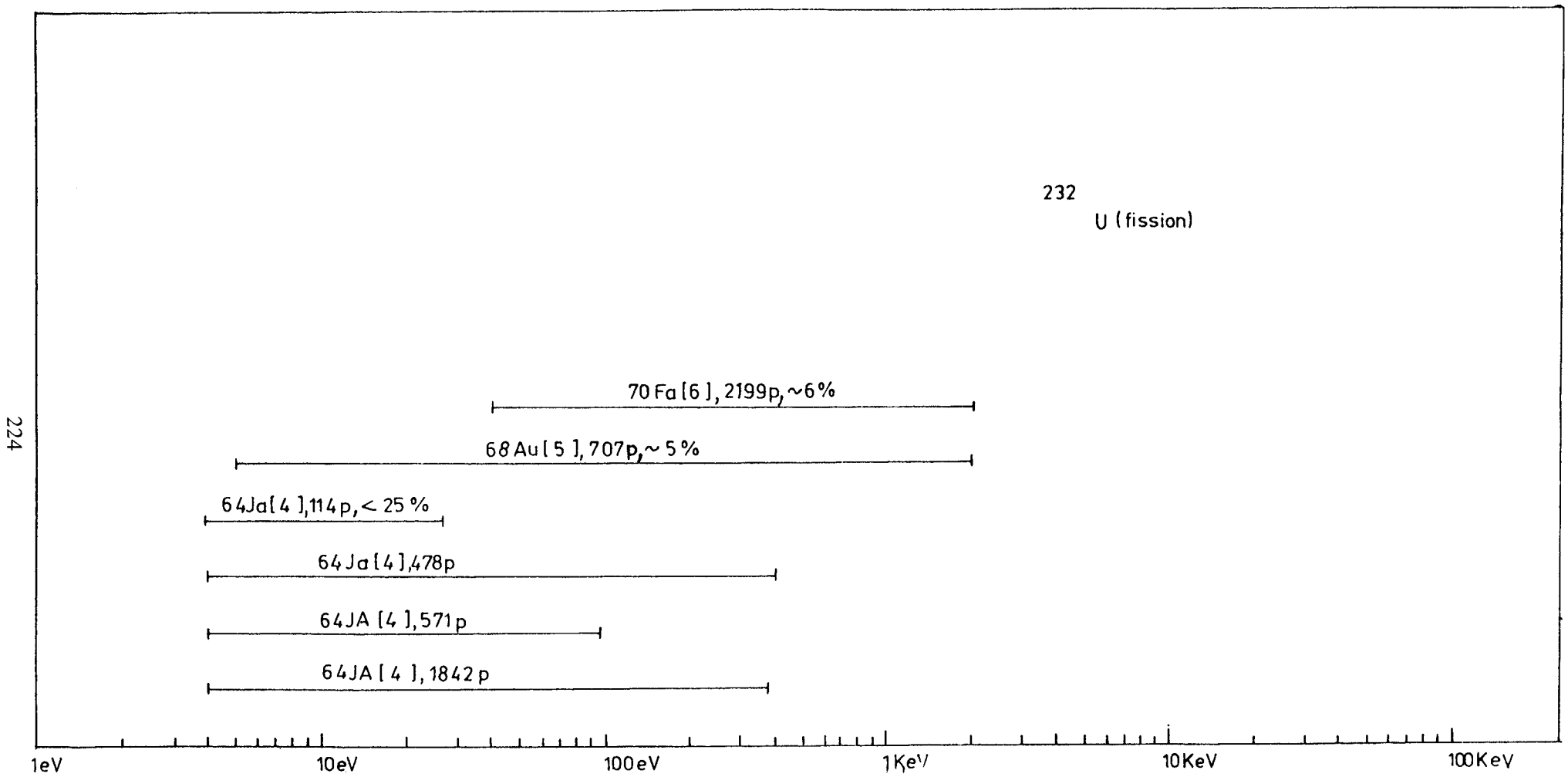

232
U (fission)
224
70 Fa [6], 2199p, ~6%
68 Au [5], 707p, ~ 5%
64Ja[4], 114p, < 25 %
64 Ja [4], 478p
64JA [4], 571p
64JA [4], 1842 p
1eV
10eV
100eV
1KeV
10KeV
100KeV

FIG.2.

The absorption cross section at 0.0253 eV has been reported by 71 Cabell, giving a value of 148.3 ± 4.4 b (error 3%), measured by activation method, using ^{59}Co (n,γ) cross sections as standard.

We have available for fission resonance integral only the value of 76 Gryntakis, 378 ± 116 b (error 30%) from cutoff energy of 0.55 eV.

$\bar{\nu}$ prompt data are represented by two values of Jaffey from 1962 and 1970 at 0.0253 eV.

The reported values are 3.07 ± 0.06 and 3.13 ± 0.6 (errors of 2%) respectively, and have been measured by coincidence method.

The last one is more accurate because of newer standards used and of better corrections applied.

Only one value for α of 0.972 ± 0.061 (error 6.3%) at 0.0253eV isreported by 71 Cabell using activation method and ^{59}Co (n,γ) cross section as standard.

The resonance parameters for U-232 are reported by 64 James and 68 Auchampangh. James gives Γ_f(error 150 %) and assuming 25 meV for Γ_γ , at 43.5 eV resonance energy, as well as seven values of Γ_f(error <75%) and Γ_n(error <80%) between 5.99 eV and 75.1 eV, and nine resonance energies between 109 eV and 258 eV, using an interference analysis method and assuming Γ_f of 50 meV.

Also he reports $S_n^o = (1 \pm 0.5) \times 10^{-4}$ (error 50%) and $\bar{D} = 7.6 \pm 1.5$ (error 20%) for 0 - 75 eV energy range.

Auchampangh reports 14 values of Reich-Moore parameters between 0.6 eV and 74.24 eV using the shape analysis method.

In the next table are summarized the gaps of data for this isotope, in the absence of any WRENDA request.

DATA	Gap of data
total	>9.2 KeV
fission	<3.6 eV
	>21 KeV
absorption	whole energy range*
resonance parameters	>75 eV Breit-Wigner parameters
	>74 eV Reich-Moore parameters
α	whole energy range*
$\bar{\nu}_{pr}$	whole energy range*

* except for 0.0253 eV

^{232}U (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
67 Simpson [1]				
E 12375 /2/	10 meV - 9.292 keV	931		
	TOF method. Sample: 287.2-2217 b/atom.			

^{232}U (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
46 Seaborg [2]				
E 12287 /3/	0.0253 eV	1	70±10 b	14%
	Fission chamber.			
53 Elson [3]				
E 12387 /2/	0.0253 eV	1	(σ_f^{Mxw}) 83±15 b	18%
	Thermal column. Fission counting method. Fission chamber. Standard: $\sigma_{n,f}^{th}(^{239}Pu)$.			
64 James [4]				
E 60638 /6/	4.101 - 395.5 eV (17.3 ns/m)	1842		350%
/7/	3.921 - 99.34 eV (50 ns/m)	571		900%
/8/	3.889 - 401.2 eV (69 ns/m)	478		900%

^{232}U (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
/9/	3.691 - 27.93 eV (200ns/m) TOF method.	114		<25%
68 Auchampangh [5]				
E 12383 /3/	5.05 eV - 1.927 keV Spark chamber. Data normalized to 20.85 eV resonance of material testing reactor measurements (NSE, 29,415,1967). Normalization error = 5%.	707		5%
70 Farrell [6]				
E 10055 /2/	40.1498 eV - 21.3314 keV Nuclear explosion. TOF method. Solid-state detector. Standards: $\sigma_{n,T}(^6Li)$ from 35 eV to 1 keV, $\sigma^{th}_{n,\alpha}(^6Li)$ = 940.3±1.6 b, Fiss.Res.Int. (^{235}U) below 35 eV. No corrections for resolution and for target impurities. Systematic errors about 6%.	2199		6%
71 Cabell [7]				
E 20477 /3/	0.0253 eV DIDO reactor. Thermal spectrum. Activation method. Mass spectrometer. Sample: 98.9% ^{232}U. Standard: $\sigma_{n,\gamma}(^{59}Co)$. Westcott's epithermal index parameter $(R\sqrt{T/T_o}) = (8.6\pm1.2)\cdot10^{-4}$; T = (116±9)°C. Statistical, systematic and random errors. σ_f obtained as $\sigma_{abs} - \sigma_{n,\gamma}$.	1	75.2±4.7 b	6.25%

^{232}U (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
76 Gryntakis [8]				
E 20625 /39/	0.0253 eV	1	(σ_f^{Mxw}) 74±8 b	11%

Reactor. Activation method. GeLi and scintillator detectors. Standards: Capt.Int.Res.(+1/v)(^{197}Au) = 1551±12 b, $\sigma_{n,\gamma}^{th}$(^{197}Au) = 98.8±0.3 b, Capt.Int.Res.(^{59}Co)(+1/v)= 71.1±4 b, $\sigma_{n,\gamma}^{th}$(^{59}Co) = 37.2±0.6 b, $\sigma_{n,f}^{th}$(^{235}U) = 577.1±0.9 b, Fis.Int.Res.(^{235}U) = 274±10 b, $\langle\sigma_{n,p}\rangle$(^{58}Ni) = 113±7 mb, $\langle\sigma_{n,p}\rangle$(^{24}Mg) = 1.53±0.09mb, $\langle\sigma_{n,\alpha}\rangle$(^{27}Al) = 0.725±0.045mb, ^{95}Zr, ^{140}La fission yields for ^{231}Pa and ^{232}U. Averaged cross sections in the fission spectrum of ^{235}U.

^{232}U (fission resonance integral)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
76 Gryntakis [8]				
E 20625 /40/	0.55 eV	1	378±116 b	30%

Reactor. Activation method. GeLi and scintillator detectors. Standards as above.

^{232}U ($\bar{\nu}_{pr}$)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
62 Jaffey [9]				
E 12251 /3/	0.0253 eV	1	3.07±0.06	2%

Thermal column. Coincidence method.
Scintillator detector. Standards:
$\bar{\nu}_{pr}^{th}(^{233}U) = 2.503\pm0.03$, $\bar{\nu}_{pr}^{th}(^{235}U) = 2.454\pm0.03$.

70 Jaffey [10]				
E 10125 /9/	0.0253 eV	1	$(\bar{\nu}_{pr}^{Mxw})$ 3.13±0.06	∿2%

Reactor. Coincidence method. Four Hornyak buttons, ionization chamber. Standards:
$\bar{\nu}_{pr}^{Mxw}(^{239}Pu)=2.884\pm0.007$, $\bar{\nu}_{pr}^{Mxw}(^{235}U)=2.407\pm0.005$,
$\bar{\nu}_{pr}^{Mxw}(^{233}U)=2.478\pm0.007$, $\bar{\nu}_{pr}^{Mxw}(^{252}Cf)=3.764\pm0.015$.
Corrections for neutron detector drift, other fissioning isotopes, spontaneously fissioning isotopes, correlation between fission fragment and fission neutrons. Statistical error.

^{232}U (resonance paramaters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
64 James [4]				
E 60638 /2/	43.5 eV	1	(Γ_f) 40^{+60}_{-20} meV	150%
/3/	43.5 eV	1	(Γ_n) 3.6 meV	-
/4/	5.99 - 75.1 eV	7	(Γ_f)	75%
/5/	- " -	7	(Γ_n)	<80%
/10/	109 - 258 eV	9	(E_r)	-
/11/	<60 eV	1	$(\bar{D})$ 7.6±1.5	~20%
/12/	0 - 75 eV	1	(S_n^o) $(1\pm0.5)\cdot10^{-4}$	50%
	Interference analysis. Γ_γ assumed 25 meV for /2/,/3/, Γ_γ assumed 50 meV for /4/.			
68 Auchampangh [5]				
E 12383 /2/	0.6 - 74.24 eV	14	Reich-Moore parameters	-
	Shape analysis.			

^{232}U (α)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
71 Cabell [7]				
E 20477 /4/	0.0253 eV	1	0.972±0.061	6.3%

DIDO reactor. Thermal spectrum. Activation method. Mass spectrometer. Sample: 98.9% ^{232}U. Standard: $\sigma_{n,\gamma}(^{59}Co)$.

^{232}U (absorption)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
71 Cabell [7]				
E 20477 /5/	0.0253 eV	1	148.3±4.4 b	∿3%

Comments as above.

References

[1]. O.D.Simpson et al., NSE,29,415, 1967.
[2]. G.T.Seaborg et al., CS-3471,2, 1946.
[3]. R.Elson et al., PR,89,320, 1953.
[4]. G.D.James, NP,55,517, 1964.
[5]. G.F.Auchampangh et al., NP/A,112,329, 1968.
[6]. J.A.Farrell, LA-4420,3, 1970.
[7]. M.J.Cabell et al., 71Canterbury,161, 1971.
[8]. E.M.Gryntakis, Priv.comm., 1976.
[9]. A.H.Jaffey et al., ANL-66,124, 1961.
[10]. A.H.Jaffey et al., NP/A,145,1, 1970.

2.5. Uranium - 233

The total cross section is covered by 21 references reporting data from 0.8 meV.

Three authors, 55 Nikitin, 56 Pattenden, and 60 Safford give single-point measurements at 0.0253 eV.

The relative measurements of Safford (standard ^{238}U (n,γ) are reported with high accuracy (less than 1%), and are in good agreement with the older measurements of Nikitin and Pattenden in the limits of experimental errors.

All the other authors give multi-point absolute measurements, with different precisions (fig. 3 and fig. 4).

There are many works, between the older ones, which have not specified the errors. The references of 63 Pattenden, 66 Brooks and especially 70 Kolar and 74 Deruyther for the resolved resonance energy range are to be taken into account.

In this respect, Pattenden gives 1512 values with errors up to 5.5 %, on the energy range 0.0723 eV - 8.814 keV; Brooks reports 189 values between 0.148 eV and 2.828 eV with errors, less than 5%; Kolar gives 3189 values for total cross section between 0.677 eV and 37.99 eV with errors of about 3%, and 3596 points over energy range 77.07 eV - 314.08 eV, with errors less than 5%; Deruyther reports 1359 values with errors of about 1.5 % between 0.01822 eV and 30 eV (using ^{233}U (n,f) cross section as standard).

It is obvious that, according to the precisions quoted by authors, the requested accuracy in NRENDA (< 5%) is generally reached, for the total cross section.

Measurements for absorption cross section are reported by 7 authors, before 1960, except 60 Block' and 70 Vidal's data.

56 Macklin is the only author which reported some data (4 points) at 4.4 keV, 10.8 keV and 11.8 keV, with errors between 10.7 % and 12.5%.

All the other experimental data for absorption cross section of U-233, are single-point measurements, at 0.0253 eV, which are rather discrepant.

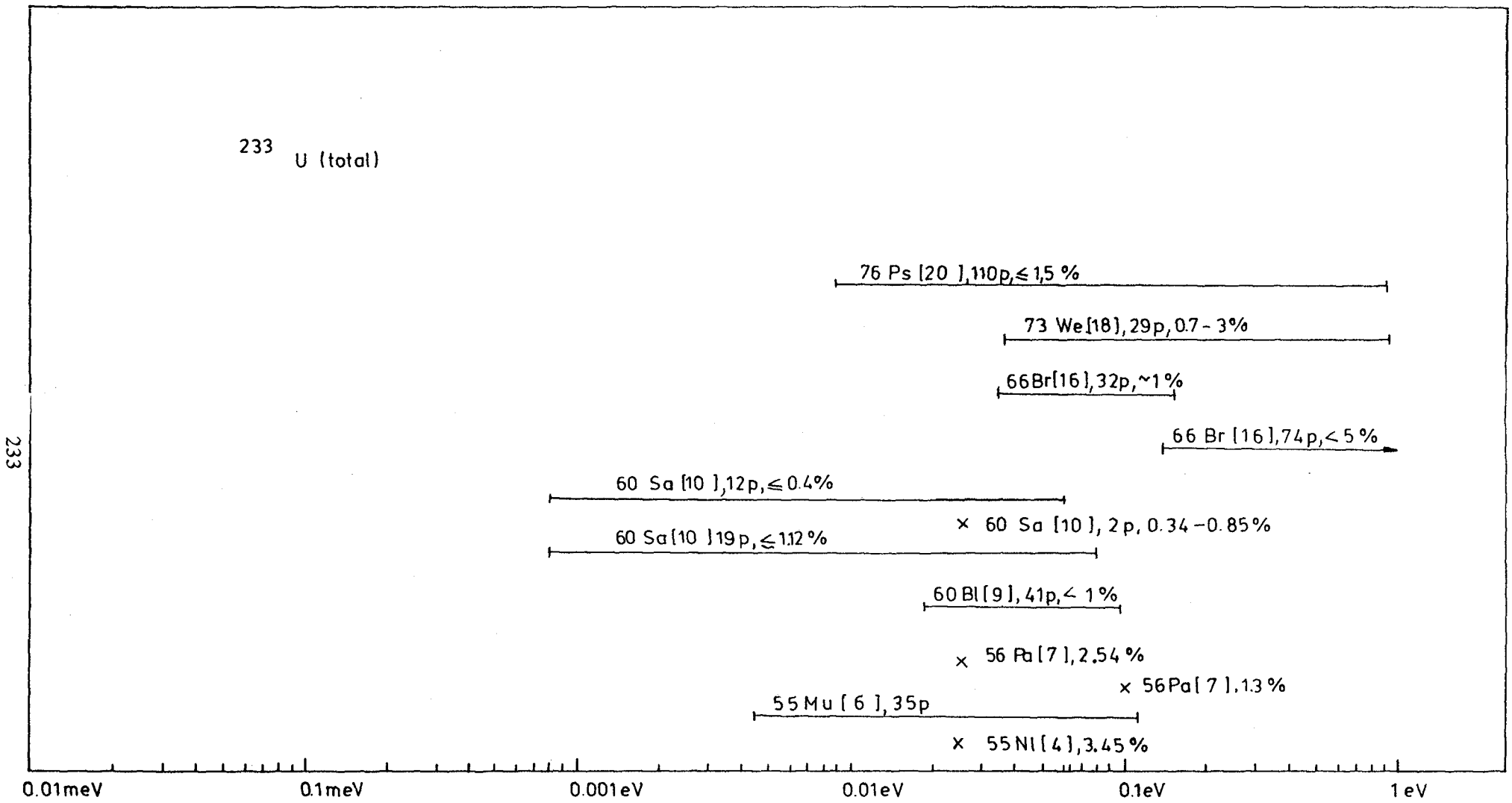

233 U (total)
233
76 Ps [20], 110p, ≤ 1,5 %
73 We [18], 29p, 0.7 - 3%
66 Br [16], 32p, ~1%
66 Br [16], 74p, < 5 %
60 Sa [10], 12p, ≤ 0.4%
60 Sa [10], 2p, 0.34 - 0.85 %
60 Sa [10] 19p, ≤ 1.12 %
60 Bl [9], 41p, < 1 %
56 Pa [7], 2.54 %
56 Pa [7], 1.3 %
55 Mu [6], 35p
55 Ni [4], 3.45 %
0.01meV
0.1meV
0.001eV
0.01eV
0.1eV
1 eV

FIG. 3

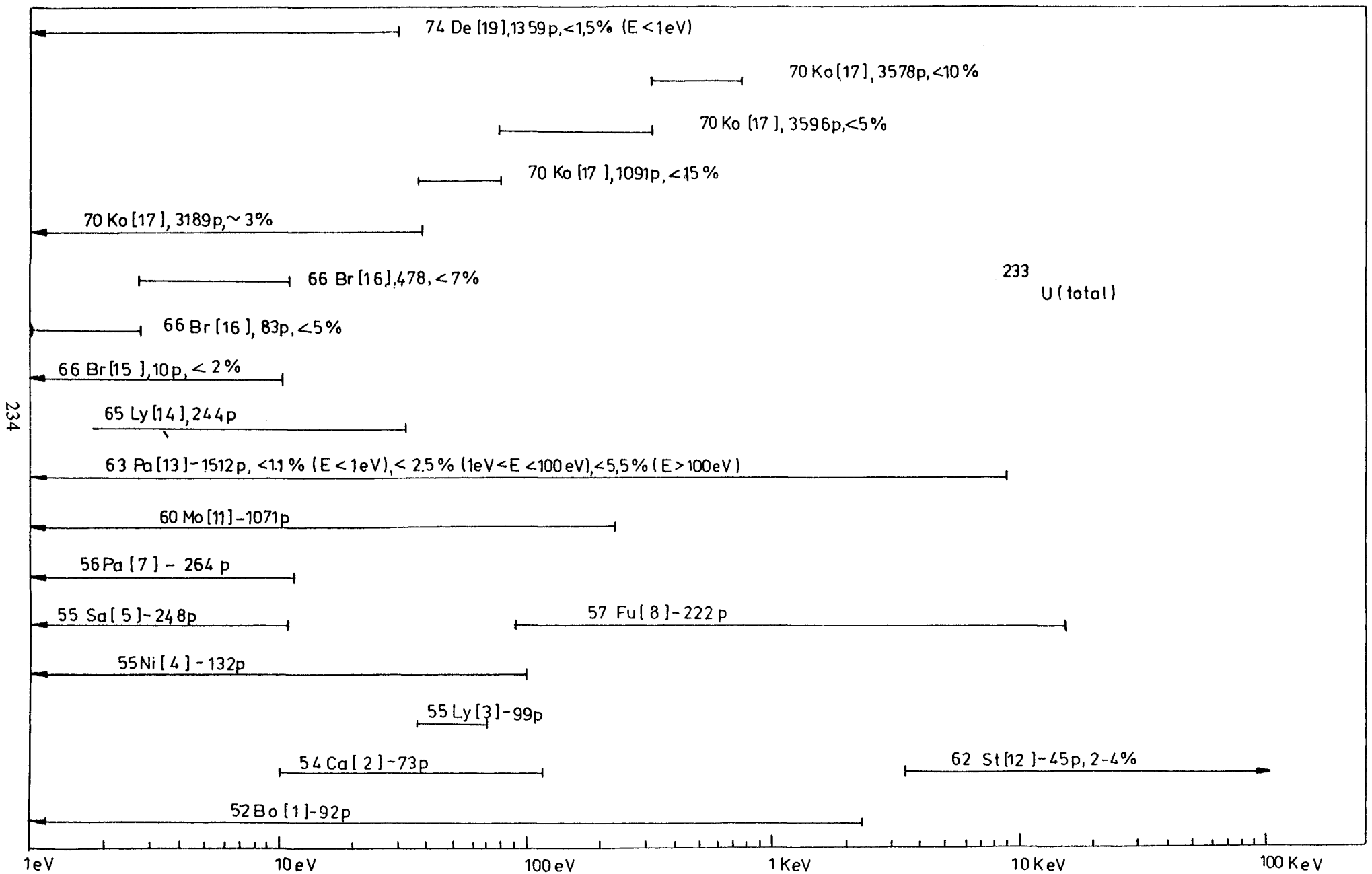

74 De [19], 1359p, <1,5% (E < 1eV)
70 Ko [17], 3578p, <10%
70 Ko [17], 3596p, <5%
70 Ko [17], 1091p, <15%
70 Ko [17], 3189p, ~ 3%
66 Br [16], 478, <7%
233
U (total)
66 Br [16], 83p, <5%
66 Br [15], 10p, < 2%
65 Ly [14], 244p
63 Pa [13] - 1512p, <1.1% (E < 1eV), < 2.5% (1eV < E < 100eV), <5,5% (E > 100eV)
60 Mo [11] - 1071p
56 Pa [7] - 264 p
55 Sa [5] - 248p
57 Fu [8] - 222 p
55 Ni [4] - 132p
55 Ly [3] - 99p
54 Ca [2] - 73p
62 St [12] - 45p, 2-4%
52 Bo [1] - 92p
234
1eV
10eV
100eV
1KeV
10KeV
100KeV

FIG. 4

The single-point experimental data are relative to the following standards: $^{235}U(n,f)$, $^{233}U(n,f)$, $^{197}Au(n,\gamma)$, ^{235}U - absorption cross sections, with errors varying between 0.69% (60 Block) and 3% (57 Green).

55 Kukavadse reported for 0.0253 eV the ratio of capture to absorption cross sections, 0.087 $\pm$ 0.003 (error 3.45%) as well as two averaged values in reactor spectrum, 615 $\pm$ 30 b(error about 4.9%) and 624 $\pm$ 30 b (error about 4.8%), using the absorption cross section of Li-6 as standard.

The fission cross section of U-233 is the best one represented in EXFOR library with experimental data, from 38 references, 22 of them being after 1960 (fig. 5 and fig. 6).

15 authors report single-point measurements, 13 of them at 0.0253 eV (fig. 5).

Six from the last ones /21/, /29/, /31/, /38/, /41/,/47/ give the ratios of fission cross section of U-233 to thermal fission cross section of U-235.

55 Popovic measured the ratio of $^{233}U(n,f)$ to $^{23}Na(n,\gamma)$ cross sections.

The most accurate measurements at 0.0253 eV seems to be those of 70 Lounsbury giving for σ_f(U-233)/σ_f(U-235) ratio the value of 0.9203 $\pm$ 0.0057 (error 0.62%), and 70 Vidal which reports the fission cross section of 530 $\pm$ 4 b with an error of 0.75%.

The multi-point measurements are relative to fission cross sections of U-233, U-235, Pu-239, capture cross section of Au-197, absorption cross section of U-233, scattering cross sections of Pu-239, U-233, total cross section of U-233, and $\bar{\nu}$ of Pu-239, and most of them are to be updated.

According to the accuracy request from WRENDA, of 1%, it seems that the most of data are affected by larger errors, except the measurements reported by 76 Pshenichnyj, up to 0.768 eV, with errors between 0.4% and 0.7%.

However, the results of 68 Weston, giving 3416 values between 0.405 eV and 2.048 keV with an accuracy of 1.5%, as well as those of 74 Nizamuddin, giving 7534 values over energy range between 6 eV and 30 keV with an error less than 5% could be mentioned.

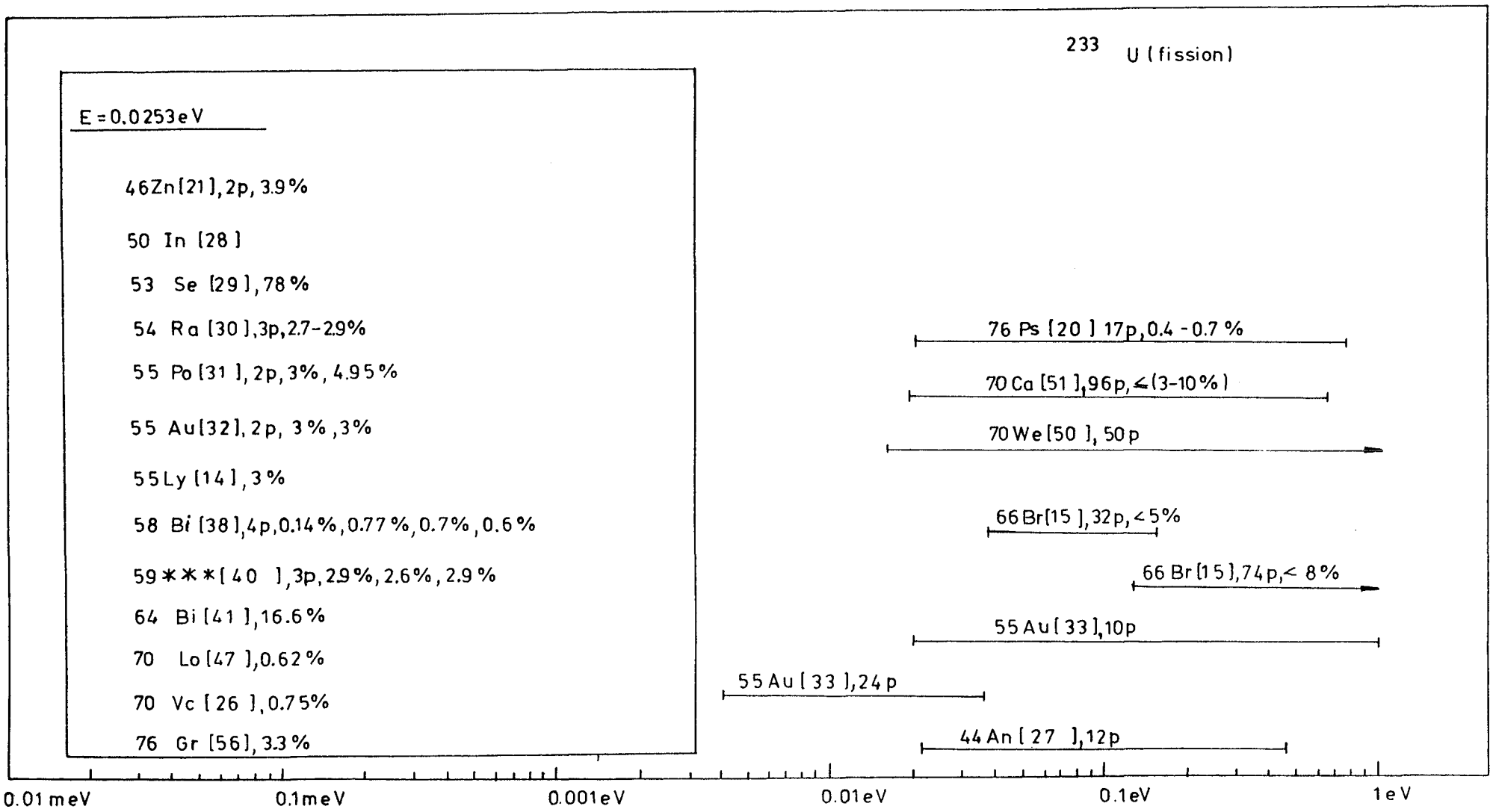
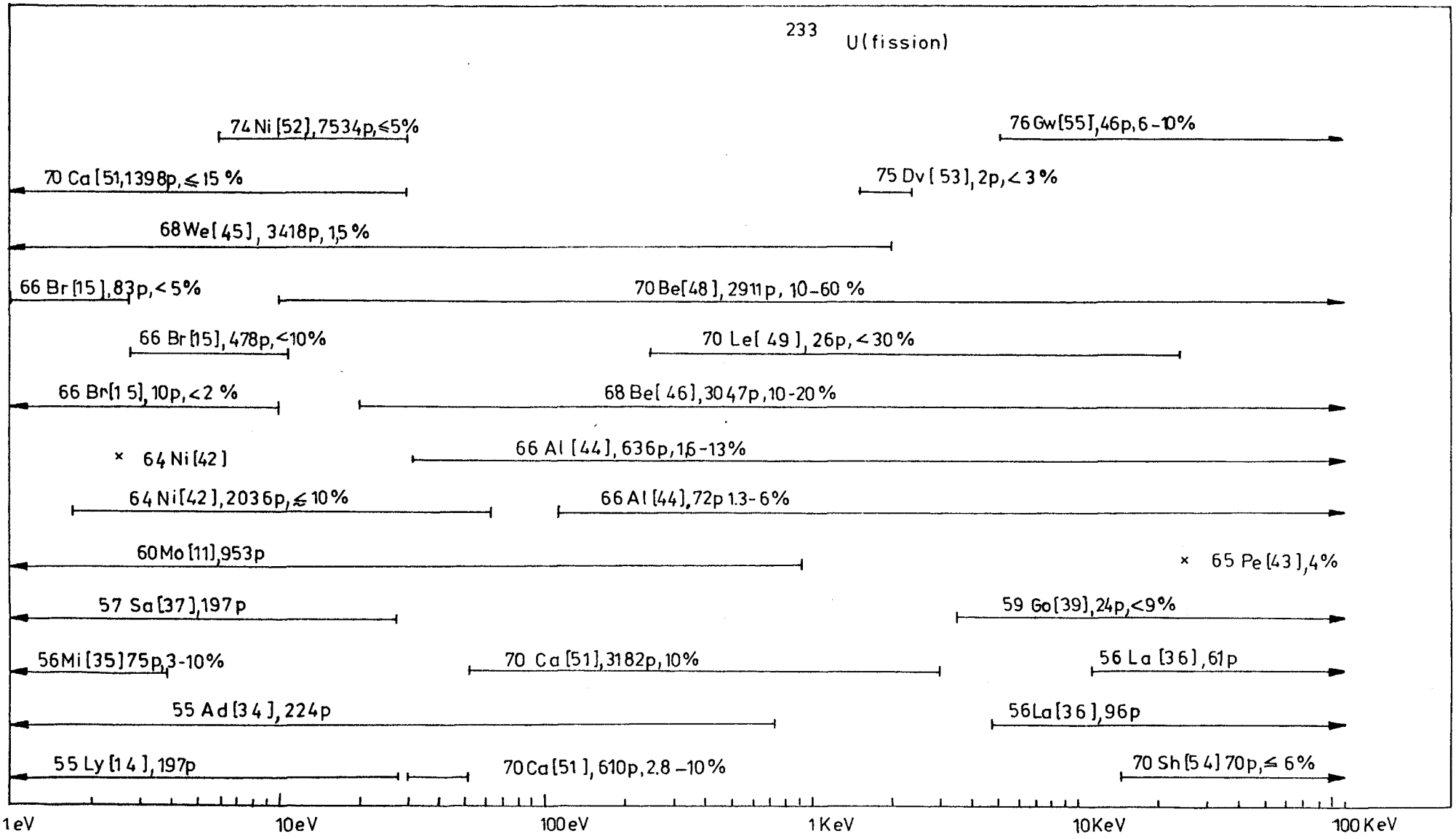

233 U (fission)
E = 0.0253eV
46Zn[21], 2p, 3.9%
50 In [28]
53 Se [29], 78%
54 Ra [30], 3p, 2.7-2.9%
55 Po [31], 2p, 3%, 4.95%
55 Au[32], 2p, 3%, 3%
55Ly [14], 3%
58 Bi [38], 4p, 0.14%, 0.77%, 0.7%, 0.6%
59***[40], 3p, 2.9%, 2.6%, 2.9%
64 Bi [41], 16.6%
70 Lo [47], 0.62%
70 Vc [26], 0.75%
76 Gr [56], 3.3%
76 Ps [20] 17p, 0.4 - 0.7 %
70 Ca [51], 96p, ≤ (3-10%)
70 We [50], 50p
66 Br[15], 32p, < 5%
66 Br [15], 74p, < 8%
55 Au [33], 10p
55 Au [33], 24p
44 An [27], 12p
0.01 meV
0.1meV
0.001eV
0.01eV
0.1eV
1eV

FIG. 5


233 U(fission)
74 Ni [52], 7534p, ≤5%
76 Gw[55], 46p, 6-10%
70 Ca [51, 1398p, ≤ 15 %
75 Dv [53], 2p, < 3 %
68 We[45], 3418p, 1,5 %
66 Br [15], 83p, < 5%
70 Be[48], 2911p, 10-60 %
66 Br [15], 478p, <10%
70 Le[49], 26p, < 30 %
66 Br[15], 10p, < 2 %
68 Be[46], 3047p, 10-20 %
64 Ni [42]
66 Al [44], 636p, 16-13%
64 Ni[42], 2036p, ≤ 10%
66 Al [44], 72p 1.3-6%
60 Mo [11], 953p
65 Pe [43], 4%
57 Sa [37], 197p
59 Go[39], 24p, <9%
56 Mi [35] 75p, 3-10%
70 Ca [51], 3182p, 10%
56 La [36], 61p
55 Ad [34], 224p
56 La [36], 96p
55 Ly [14], 197p
70 Ca [51], 610p, 2.8 -10%
70 Sh [54] 70p, ≤ 6%
1 eV
10 eV
100 eV
1 KeV
10 KeV
100 KeV

237

FİG. 6

The last data are relative to value of 168.31 b for fission resonance integral of U-233, from 8.32 eV up to 101.2 eV.

The importance of U-233 fission cross section for Th-U fuel cycle, being well known, the above analysis suggests that new measurements will be useful.

Data for fission resonance integral are reported by 9 authors, the cutoff energy varying between 0.35 eV and 3 eV. Three authors 66 Brooks, 70 Cao and 76 Gwin reported measurements for the fission resonance integral on a number of energy regions.

Most of the authors use the activation method. From the point of view of quoted errors, could be mentioned 64 Bigham, with errors between 3.23% and 4.78%, 65 Hardy Jr., with error of 3.25%, 65 Yasuno, with error of 4.77%,

66 Brooks, with errors between 0.5% and 2.5%, 67 Conway, with error of 6.35%, 71 Eiland, with errors between 4.05% and 7.23%, while 76 Gryntakis quoted and error of 11%.

The measurements are relative to $^{115}In(n,\gamma)$, $^{197}Au(n,\gamma)$ $^{233}U(n,f)$, $^{233}U(n,\gamma)$ $^{59}Co(n,\gamma)$ $^{235}U(n,f)$ cross sections and other standards and most of them must be updated.

A detailed study for concluding about the consistency of these data is to be done.

A number of 13 references supply experimental data for α ratio. From these, only 4 references report multi-point measurements, all the others being single-point data at 0.0253 eV, or averaged values on different neutron spectra.

The single-point measurements are more accurate and obey the WRENDA request of precision (2-3%).

In this respect, can be mentioned 50 Inghram ($\langle\alpha\rangle$ = 0.0976 + 0.0018, error about 2%), 64 Okazaki (α^{MXW} = 0.0917 $\pm$ 0.0022, error about 2.3%) and ($\langle\alpha\rangle$ = 0.094 + 0.0004, error about 0.4%), 70 Lounsbury (α = 0.0899 $\pm$ 0.0004, error of 5%). These data can be very useful for thermal cross sections evaluations.

The multi-point values are affected by errors up to 50%; 62 Hopkins (20%), 56 Spivak (4-50%), 66 Brooks (<50%) and must be used carefully.

The last two references report computed data from η measurements, and this fact suppose a renormalization against ν values used as standards.

A number of 24 references report experimental data for η value and only 10 of them give multi-point measurements over 8.8 meV.

There are also measurements at thermal energy of 0.0253 eV, and only one measurement is reported at 0.057 eV by 66 Smith.

These single-point data are η, η^{MXW}, $\eta^{MXW}(U\text{-}233)/\eta^{MXW}(U\text{-}235)$, reported by 46 Zinn, $\eta(Pu\text{-}239)/\eta(U\text{-}233)$, reported by 66 Smith, $\eta(U\text{-}233)/\eta(U\text{-}235)$, reported by 70 Vidal and 71 Gwin, and $\langle \eta(U\text{-}233) \times \sigma_{abs}(U\text{-}233) \rangle^{MXW} / \langle \eta(U\text{-}235) \times \sigma_{abs}(U\text{-}235) \rangle^{MXW}$ reported by 71 Gwin.

According to the requested accuracy for η from WRENDA (0.4 - 0.5%), are the references: 56 Palevsky, giving 14 points between 0.0104 eV and 0.099 eV, with errors between 0.2% and 0.8%; 60 Macklin, measured η_{th} of 2.296 ± 0.02 (error 0.87%); 66 Smith reported 3 values on energy range 0.025 eV up to 0.057 eV and with errors between 0.4% and 0.56%; 70 Vidal gives $\eta = 2.24 \pm 0.012$ and $\eta(U\text{-}233)/\eta(U\text{-}235) = 1.081 \pm 0.005$, with errors of 0.46% and 0.54%, respectively; 71 Gwin gives $\eta^{MXW} = 2.283 \pm 0.015$ (error about 0.65%).

The standards used were $^{235}U(n,f)$, $^{233}U(n,f)$ cross sections, the absorption cross section for B, U-233, U-235, η for U-233 and U-235, the scattering cross sections for Pu-239 and U-233, $\bar{\nu}$ for Pu-239 and U-233, and are to be updated.

The resonance parameters of U-233 are supplied by 20 papers, and some attempts to fit the cross sections by single and multilevel analyses, are presented.

The last resonance energy quoted in the multilevel analyses, is arround 85 eV (70 Kolar), and in the single level Breit-Wigner analyses, is at 124 eV (74 Nizamuddin).

The Reich-Moore parameters are given by 46 Williams, for the energy region from - 5eV up to 4.7 eV (7 resonances) the Vogt parameters are reported by 60 Pattenden, between - 1 eV and 25.48 eV (27 data values), and Adler-Adler parameters are given by 70 Cao, between 0.018 eV and 65 eV, by 70 Kolar, for 0.9 eV - 93 eV, and by 70 Saussure, for 0.02 eV - 64.3 eV, without the errors.

The parameters reported by the other ones are Breit-Wigner type.

According to the WRENDA requested accuracy (< 10% under 1 keV and <30% above 1 keV) are the measurements of: 55 Sailor, supplying the resonance energies from 4.5 up to 9.25 eV, with errors

less than 2 %; 55 Nikitin reports the resonance energies between 1.7 eV and 21 eV with errors less than 10%; 55 Pilker, gives values for $2g\,\Gamma_n$ and $2g\,\Gamma_n^o$, between 3.21 eV and 19 eV with errors of about 15 %; 57 Sanders supplies Γ_f values from 1.76 eV up to 3.6 eV with errors less than 3%; 57 Sokolovsky reports Γ_t values (errors <5 %) and between 6.8 eV and 37 eV $\Gamma_f\ \sigma_t(E_r)$ values, with errors ≤ 8 % between 1.47 eV and 19 eV; 74 Nizamuddin gives values for Γ_t, Γ_f, $\sigma_o\Gamma_f$, with errors $\leq$ 10%, from 5.89 eV up to 124.12 eV.

55 Sailor, 65 Lynn, 70 Kolar and 74 Nizamudin performed shape analyses while area analysis were performed by:

55 Pilker, 57 Sokolowsky, 58 Vladimirskii, 64 Nifenecker, 65 Lynn and 70 Rjabov.

The most of data are obtained by absolute measurements. Relative measurements have been reported however by 60 Moore, for $S_n^o = (1 \pm 0.2) \cdot 10^{-4}$ (error 20 %) on the energy range up to 20 eV, using as standard ^{235}U (n,f)thermal cross section of 524 b., by 70 Cao which used the same standard, and by 74 Nizamuddin , for $\langle\Gamma_f\rangle$ of 372 meV, $\bar{D}$, Γ_t, Γ_f, $\sigma_o\,\Gamma_f$, between 5.9 eV and 124 eV.

In the thermal range there are only 2 old references, concerning the <u>averaged number of neutrons emitted per fission</u>, namely: 46 Zinn, reported for $\bar{\nu}$ in the thermal spectrum a value of 2.61, relative to ^{235}U (n,f) cross section of 560 b and also to ^{233}U (n,f) cross section of 518 $\pm$ 20 b; 55 McNillan supplied for $\bar{\nu}$ a value of 2.502 $\pm$ 0.063 (error 2.5 %), by reactivity coefficient method, relative to $\bar{\nu}_{th}$(U-235) = 2.46 + 0.3, as well as $\langle\bar{\nu}$(U-233)$\rangle$ / $\langle\bar{\nu}$(U-235)$\rangle$ = 1.017 (error 2.2 %).

These data must be renormalized using the newest standards. They obey the accuracy requested by WRENDA (0.25% - 3%).

There are available 9 experimental works for $\bar{\nu}$ <u>prompt</u> data.

Only one author, 73 Reed, reported multi-point measurements, from 0.01 eV up to 111.5 eV, with errors less than 1.6 %.

All the other authors have been performed experimental measurements at 0.0253 eV, most of them relative to $\bar{\nu}_{pr}^{MXW}$ of U-235 and Pu-239, or to $\bar{\nu}$ SF for ^{252}Cf, many of them to be updated.

From the point of view of accuracy must be mentioned the result of 75 Boldeman, which have an error less than 0.5 %, $\bar{\nu}_{pr}^{MXW} = 2.455 \pm 0.01$.

Measurements for $\bar{\nu}$ delayed are reported by 69 Notea, 71 Connant and 76 Eccleston.

The first two references have data at 0.0253 eV. It can be pointed out the value of 0.0027 ± 0.0001 for the ratio $\bar{\nu}_{dl}^{MXW} / \bar{\nu}^{MXW}$ with an error of 3.8 %, reported by Connant, value which can lead to a value for $\bar{\nu}_{dl}$ in the accuracy limits requested by WRENDA. (5 %).

Eccleston reports 129 values between 32.84 keV and 1.444 MeV for energy distributions of averaged number of delayed fission neutrons, with errors less or equal to 30 %.

In the next table are showed the gaps of data and of accuracy for U-233, as well as the requested accuracy from WRENDA.

Data	Gap of data	Gap of accuracy	Requested accuracy (WRENDA)
total	-	-	5 %
fission	-	<20 meV > 0.7 eV	1 %
absorption	whole energy range*	-	-
α	11 eV - 30 keV	whole energy range*	2 % - 3 %
η	820 eV - 30 keV	<0.01 eV >0.1 eV	0.4 % - 0.5 %
$\bar{\nu}$	whole energy range*	whole energy range*	0.25% - 3 %
$\bar{\nu}_{pr}$	>111 eV	-	-
	<32 keV*	whole energy range	5 %
resonance parameters	>93 eV Adler-Adler parameters	-	10 % <1 keV
	>124 eV Breit-Wigner parameters		30 % >1 keV

* Except 0.0253 eV

^{233}U (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
52 Bollinger [1]				
E 12346 /2/	0.034 eV - 2.325 keV	92		-
	Fast chopper. TOF method, transmission. Data from curves (BNL-325).			
54 Carter [2]				
E 12366 /2/	10.075 - 115 eV	73		-
	Fast chopper.			
55 Lynn [3]				
E 60048 /2/	37 - 68.9 eV	99		-
	TOF method. Absolute measurements.			
55 Nikitin [4]				
E 80332 /3/	0.0253 eV	1	580±20 b	3.45%
/4/	0.01 - 100 eV	132		-
	TOF method. Absolute measurements /4/.			
55 Sailor [5]				
E 12363 /4/	0.3 eV - 11.26 eV	248		-
	Crystal spectrometer.			
55 Muether [6]				
E 12324 /2/	5.69 - 110 meV	35		-
	Slow chopper. TOF method.			

^{233}U (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
56 Pattenden [7]				
E 60401 /2/	0.1 eV	1		1.3%
			305±4 b	
/3/	1.568 meV - 11.4 eV	264		-
/4/	0.0253 eV	1		2.5%
			590±15 b	
	Slow chopper /3/, /4/. TOF method. Crystal spectrometer. Absolute measurements /3/.			
57 Fulwood [8]				
E 11681 /3/	89.74 eV - 0.0155 MeV	222		-
	TOF method.(19.55 m flight path). Samples: 3.94 and 11.7 g/cm^2.			
60 Block [9]				
E 12024 /5/	0.0184 - 0.0958 eV	41		<1%
	Fast chopper. Statistical errors.			
60 Safford [10]				
E 12362 /2/	$8.18 \cdot 10^{-4}$ - 0.0818 eV	19		≤1.12%
/3/	0.0253 eV	1		0.85%
			587±5 b	
/4/	0.0253 eV	1		0.34%
			586±2 b	
/5/	$8.18 \cdot 10^{-4}$ - 0.06 eV	12		≤0.4%
	Crystal spectrometer. Liquid /2/, /3/ and metalic /4/,/5/ samples. Standard: $\sigma^{th}_{n,\gamma}(^{238}U)$= 2.74±0.02 b. Least squares fit to total data /3/, /4/, /5/.			

^{233}U (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
60 Moore [11]				
E 12341 /2/	0.0203 - 216.9 eV	1071		-
	Fast chopper. TOF method. Standard: $\sigma_{n,f}^{th}(^{233}U)$= 524 b.			
62 Stupegia [12]				
E 12323 /2/	3.4 keV - 1.6112 MeV (1.2 - 8 keV)	45		2-4%
63 Pattenden [13]				
E 12333 /2/	0.0723 eV - 8.814 keV	1512		<5.5%
	Fast chopper. TOF method.			
65 Lynn [14]				
E 60317 /16/	1.86 - 31.7 eV	244		-
	TOF method. Crystal spectrometer. Absolute measurements.			
66 Brooks [15]				
E 20623 /7/	0.35 - 10 eV	10	($<\sigma_t>$)	<2%
	LINAC. TOF method. Standard: $\sigma_{sct}(^{239}Pu)$ = 10.5±0.6 b and $\sigma_{sct}(^{233}U)$ = 12.0±2.0 b. Corrections for scattering in the canning material for the probability that the neutron scattered in the sample will undergo further interaction in the sample.			

^{233}U (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
66 Brooks [16]				
E 61133 /5/	2.799 - 11.04 eV	478		<7%
/8/	1.005 - 2.828 eV	83		<5%
/11/	0.15 - 1.027 eV	74		<5%
/14/	35 meV - 0.148 eV	32		∿1%
	TOF method (Flight path of 22.5 m for /5/, /8/, and 5.05 m for /11/, /14/. Timing channels: 1 μsec /5/, 8 μsec /8/, /11/, and 32 μsec for /14/.			
70 Kolar [17]				
E 20114 /2/	0.677 - 37.99 eV	3189		∿3%
/3/	38 - 77.052 eV	1091		<15%
/4/	77.07 - 314.08 eV	3596		<5%
/5/	314.14 - 753.54 eV	3578		<10%
	LINAC. Photoneutron source. TOF method (Flight path 100 m), transmission method. Liquid scintilator (BF_3) and BORSL detectors. Absolute measurements. Corrections for background and for the influence of the Al can (total thickness = 0.6 mm).			
73 Wertebnyj [18]				
E 40191 /2/	0.939 - 0.0325 eV (1.7 - 7 μsec/m)	29		0.7-3%
	VVRM reactor. Slow chopper. TOF method (Flight path of 10.3 - 18.7 m). Sample: 2.2 - 9.98 nuclei/kb.			

^{233}U (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
74 Deruyther [19]				
E 20411 /2/	0.01822 - 30 eV	1359		<1.5% for E<1eV
	LINAC. TOF method (Flight path of 8.1 m) for E < 10 eV and of 8.3 m for E < 30 eV). Gold-silicon surface barrier detector. Standard: $\sigma_{n,f}(^{233}U)$. Detected particles: fission fragments.			
76 Pshenichnyj [20]				
E 40426 /4/	0.8968 - 0.0086 eV	110		≤1.5%
	Reactor. TOF method. Helium counters and NaI crystal.			

^{233}U (absorption)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
46 Zinn [21]				
E 12319 /3/	0.0253 eV	1	(σ_{abs}^{Mxw}) 566±15 b	2.65%
	Fission chamber. Thermal specrum. Standard: $\sigma_{n,f}^{th}(^{235}U)$ = 560 b.			
55 Spivak [22]				
E 80329 /5/	0.0253 eV	1	(σ_{abs}^{Mxw}) 590±2.95 b	0.5%
	Thermal spectrum. Ionization chamber. Standard: σ_{abs}^{th}(B) = 759 b.			

^{233}U (absorption)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
55 Kukavadse [23]				
E 80333 /2/	0.0253 eV	1	$(\sigma_{n\gamma}/\sigma_{abs})$ 0.087±0.003	3.45%
/3/	0.0253 eV	1	$(<\sigma_{abs}>)$ 615±30 b	∿4.9%
/7/	0.0253 eV	1	$(<\sigma_{abs}>)$ 624±30 b	∿4.8%

Burn-up method /3/, /7/. Mass sepctrometer. Standard: $\sigma^{th}_{abs}(^6Li)$ = 930 b,/3/. α counting and isotopic dilution /3/, Reactor spectrum /3/,/7/.

56 Macklin [24]				
E 12334 /2/	4.4; 11.8 keV	2		<12.5%
/3/	4.4; 10.8 keV	2		<10.7%

Spherical shell transmission method.
$\sigma_{n,f}$ assumed 6.7 b at 4.4 keV and 4.9 b at 11.8keV.

57 Green [25]				
E 60405 /2/, /3/, /4/	0.0253 eV	3		<3%

Pile oscillator. Thermal spectrum. Standard: $\sigma^{th}_{n,\gamma}(^{197}Au)$ = 98.9 b.

60 Block [9]				
E 12024 /4/	0.0253 eV	1	576±4 b	0.69%

From total cross section.

70 Vidal [26]				
E 20552 /4/	0.0253 eV	1	589±7 b	<2%

Reactors ULYSSE and MINERVA. Thermal column. Fission chamber. Sample: 0.1 - 0.15% ^{233}U. Standards: $\sigma_{abs}(^{235}U)$ = 678.5±1.96 b, $\bar{\nu}(^{233}U)/\bar{\nu}(^{235}U)$ = 1.0262, and $\sigma_{abs}(^{233}U)/\sigma_{abs}(^{235}U)$ = 0.868±0.008.

^{233}U (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
44 Anderson [27]				
E 12359 /2/	0.0218 - 0.46 eV	12		-
	TOF method. Standard: σ_{abs}(B). Data from curves (BNL-325).			
46 Zinn [21]				
E 12319 /2/	0.0253 eV	1	518±20 b	3.9%
/9/	0.0253 eV	1	$(\sigma_f(^{233}U)/\sigma_f(^{235}U))$ 0.928	-
	Fission chamber. Standard: $\sigma_f(^{235}U)$= 560 b. Thermal spectrum.			
50 Inghram [28]				
E 12351 /4/	0.0253 eV	1	$(\langle\sigma_f\rangle)$ 455 b	-
	Reactor spectrum. Mass spectrometer. Calculated from α, using $\sigma_{abs}(^{233}U)$ = 499 b.			
53 Sellers [29]				
E 12352 /2/	0.0253 eV	1	$(\sigma_f(^{233}U)/\sigma_f(^{235}U))$ 0.948±0.74	78%
	U - D_2O reactor. Fission chamber. Thermal spectrum.			
54 Raffle [30]				
E 61131 /2/	0.0253 eV	1	(σ_f^{Mxw}) 517±15 b	2.9%
/3/	0.0253 eV	2	$(\langle\sigma_f\rangle)$	2.7-2.9%
	Fission chamber. Standard: $\sigma^{th}_{n,\gamma}(^{197}Au)$ = 98.5 b. Thermal spectrum /2/, reactor spectrum /3/.			

^{233}U (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
55 Popovic [31]				
E 20047 /2/	0.0253 eV	1	$(\sigma_f(^{233}U)/\sigma_\gamma(^{23}Na))$ 985 b	3%
/4/	0.0253 eV	1	526±26 b	4.95%
	Thermal column. Direct detection of fission fragment, track detector. Standard: $\sigma^{th}_{n,\gamma}(^{23}Na)$= 0.534 b.			
55 Auclair [32]				
E 60152 /2/	0.0253 eV	2		3%
/3/	0.0253 eV	2		3%
	Fission chamber. Thermal spectrum. Standards: $\sigma^{th}_{n,f}(^{239}Pu)$ = 750 b /2/ and 742 b /3/ and $\sigma_{n,f}(^{233}U)/\sigma_{n,f}(^{239}Pu)$ = 0.626 for Maxwellian spectrum.			
55 Lynn [14]				
E 60317 /5/	9.06 meV - 28.2 eV	197		-
/6/	0.0253 eV	1	515±15 b	∿3%
	LINAC source. Slow chopper. TOF method. Crystal spectrometer. Standards: $\sigma^{th}_{n,f}(^{233}U)$= 533 b for /5/ and $\sigma_{n,f}(^{197}Au)$ for /6/.			
55 Auclair [33]				
E 60318 /2/	4.1 - 35 meV	24		-
/3/	20 meV - 1 eV	10		-
	TOF method. Crystal spectrometer /3/. Standard: $\sigma^{th}_{n,f}(^{233}U)$ = 518 b /2/, /3/.			
55 Adamchuk [34]				
E 80331 /3/	11.7 meV - 743 eV	224		-
	TOF method. Standard: $\sigma^{th}_{n,f}(^{233}U)$.			

^{233}U (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
56 Miller [35]				
E 12315 /2/	0.1238 - 3.797 eV (0.9 - 0.08 μs/m)	75		3-10%
	Crystal spectrometer.			
56 Lamphere [36]				
E 12338 /2/	4.85 keV - 3 MeV	96	$(\sigma_f(^{233}U)/\sigma_f(^{235}U))$	-
/3/	13 keV - 3.05 MeV	61		-
	Ionization chamber. Standard: $\sigma_{n,f}(^{235}U)$ from BNL-325 (1965) for /3/. Data from curves /2/.			
57 Sanders [37]				
E 60410 /3/	9.06 meV - 28.2 eV	197		-
	TOF method. Standard: $\sigma^{th}_{n,f}(^{233}U)$ = 525 b.			
58 Bigham [38]				
E 12356 /2/	0.0253 eV	1	$(\sigma_f(^{233}U)/\sigma_f(^{235}U))$ 0.9319±0.0013	0.14%
/3/	0.0253 eV	1	(σ_f^{Mxw}) 518.2±4 b	0.77%
/4/	0.0253 eV	1	518±4 b	0.7%
/10/	0.0253 eV	1	$(\sigma_f^{Mxw}(^{239}Pu)/\sigma_f^{Mxw}(^{233}U))$ 1.5048±0.009	0.6%
	Thermal column of NRX. Isotopic dilution method. Back-to-back fission counter. Thermal spectrum /2/,/3/,/4/. 20°C,Maxwell spectrum /10/. Standard: $\sigma^{th}_{n,\gamma}(^{197}Au)$ = 98.8 b /3/.			

^{233}U (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
59 Gorlov [39]				
E 40055 /3/	3.4 - 722 keV (0.7 keV at 3.4 keV 17 keV at 200 keV 9.5 keV at 340 kev 10-40 keV for other energies)	24		<9%
	VDG. (P,T) source. Direct detector. Fission chamber and long counter (for flux monitoring).			
59 XXX [40]				
E 61128 /2/	0.0253 eV	1	(σ_f^{Mxw}) 520±15 b	2.9%
/3/	0.0253 eV	1	$(<\sigma_f>)$ 567±15 b	2.6%
/4/	0.0253 eV	1	$(<\sigma_f>)$ 515±15 b	2.9%
	Fission chamber. Standard: $\sigma_{n,\gamma}^{th}(^{197}Au)$=98.7 b. Thermal spectrum /2/, pile spectrum with R = 0.05 /3/,/4/.			
60 Moore [11]				
E 12341 /2/	0.0194 - 959.7 eV	953		-
	Fast chopper. TOF method. Standard: $\sigma_{n,f}^{th}(^{235}U)$ = 524 b.			
64 Bigham [41]				
E 12230 /9/	0.0253 eV	1	$(<\sigma_f(^{233}U)>/<\sigma_f(^{235}U)>)$ 0.9642±0.16	16.6%
	Reactor. Activation method. Fission chamber.			
64 Nifenecker [42]				
E 60511 /2/	1.738 - 62.82 eV	2036		≤10%
64 Nifenecker [42]				
E 61132 /2/	2.542 eV	1	50.85 b	-

^{233}U (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
65 Perkin [43]				
E 20584 /2/	24 keV	1		4%
E 60442 /2/			2.73±0.11 b	

Photoneutron source. Direct calibration of neutron source by Mn-bath and oil-bath, indirect calibration with boron pile methods. Fission chamber. Corrections: self-absorption of fission fragments in sample, effect of finite size of neutron source in sample, spontaneus fission background. σ_f at 24 keV obtained from cross section average over source spectrum.

66 Brooks [15]				
E 20623 /4/	0.35 - 10 eV	10	($<\sigma_f>$)	<2%

LINAC. TOF method. Standards: $\sigma_{sct}(^{239}Pu)$= 10.5±0.6 b, $\sigma_{sct}(^{233}U)$ = 12.0±2 b, $\bar{\nu}(^{239}Pu)$= 2.87, $\bar{\nu}(^{233}U)$ = 2.5. Corrections for scattering in the canning material, and for interaction of the scattered neutrons in the sample.

66 Brooks [15]				
E 61133 /4/	2.799 - 11.04 eV	478		<10%
/7/	1.005 - 2.828 eV	83		<5%
/10/	0.15 - 1.027 eV	74		<8%
/13/	35 meV - 0.148 eV	32		<5%

TOF method. (Flight path of 22.5 m /4/,/7/ and 5.05 m /10/,/13/). Timing channel: 1 μsec /4/, 8 μsec /7/,/10/ and 32 μsec /13/. Standard: $\sigma^{th}_{n,f}(^{233}U)$.

66 Albert [44]				
E 12343 /2/	32.5 eV - 7.75 MeV (En.err.: 2.5eV-0.25MeV)	636	($\sigma_f(^{233}U)$/ $\sigma_f(^{235}U)$)	1.6-13%
/3/	112 eV - 6.5 MeV	72		1.3-6%

Space nuclear explosion. TOF method.

^{233}U (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
68 Weston [45]				
E 12336 /4/	0.405 eV - 2.048keV	3416		1.5%
	TOF method. Sample 99.99% ^{233}U. Standards: $\sigma_{n,t}$ and σ_{sct} = 12.5 b. Total nonstatistical errors ∿1.5%.			
68 Bergen [46]				
E 12360 /2/	20.05 eV - 0.9779 MeV	3047		10-20%
	Underground nuclear explosion. TOF method.			
70 Lounsbury [47]				
E 10013 /7/	0.0253 eV	1	$(\sigma_f(^{233}U)/\sigma_f(^{235}U))$ 0.9203±0.0057	0.62%
	Reactor NRU. Activation and burn-up methods. Error analysis.			
70 Bergen [48]				
E 10056 /2/	10.0249 eV - 2.845 MeV	2911		10-60%
	Nuclear explosion. TOF method. Standard: $\sigma_{n,f}(^{235}U)$.			

^{233}U (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
70 Lehto [49]				
E 10084 /3/	0.24 - 24 keV	26	$(\sigma_f(^{233}U)/\sigma_f(^{235}U))$	<30%
	Cockroft-Walton accelerator. (D,T) reaction as neutron source. Lead slowing-down time spectrometer. Back-to-back fission chamber. Statistical errors.			
70 Weston [50]				
E 10100 /2/	0.01679 - 1.06276 eV	50	$\sigma_f\sqrt{E}$	-
	TOF method. Fission chamber and liquid scintilator. Standard: $\sigma^{th}_{n,f}(^{233}U)$ = 527.7 b.			
70 Cao [51]				
E 20003 /2/	18.411 meV - 0.67305 eV	96		<10%
/3/	0.68499 - 29.99 eV	1398		≤15%
/4/	30.004 - 52.159 eV	610		2.8-10%
/5/	52.302 eV - 3.008 keV	3182		10%
	Photoneutron source. TOF method. Spark chamber and liquid scintillator. Standard: $\sigma^{th}_{n,f}(^{233}U)$ = 524.5±1.9 b. Corrections for background, neutron spectrum and self-screening. Statistical errors.			
70 Vidal [26]				
E 20552 /2/	0.0253 eV	1	530±4 b	0.75%
	Thermal column. Fission chamber. Sample: 0.1-0.15% ^{233}U.			
74 Nizamuddin [52]				
E 20446 /2/	6 eV - 30 keV	7534		≤5%
	LINAC. Photoneutron source. TOF method. Gas scintillator detector. Sample: 99.57% ^{233}U, <0.01% ^{235}U, 0.4% ^{234}U, 0.02% ^{238}U. Standard: Fis.Res.Int.(^{233}U) = 168.31 b for energy range 8.32 eV - 101.2 eV. Statistical errors.			

^{233}U (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
75 Dvukhsherstnev [53]				
E 40321 /3/	1.5 - 2.3 keV	2	$(\sigma_f(^{233}U)/\sigma_f(^{235}U))$	<3%
	Reactor. Scandium filter. Direct measurements. Double fission chamber. Corrections for non-monoenergetic spectrum of Sc filtered neutron beam. Statistical errors.			
75 Shpak [54]				
E 40361 /3/	15 keV - 1.94 MeV (En.err.: 8-30 keV)	70	$(\sigma_f(^{233}U)/\sigma_f(^{235}U))$	≤6%
	VDG. (P,T) and (P,^{7}Li) sources. Glass detector. Standard: $\sigma_{n,f}(^{233}U)/\sigma_{n,f}(^{235}U)$ = 1.51 (at 1 MeV). Statistical errors.			
76 Gwin [55]				
E 10267 /13/	5 - 200 keV	11	$(\langle\sigma_f\rangle)$	<6%
/14/		11	$(\langle\sigma_f(^{233}U)\rangle/\langle\sigma_f(^{235}U)\rangle)$	<7%
/41/		12	$(\langle\sigma_f\rangle)$	∿10.3%
/42/		12	$(\langle\sigma_f(^{233}U)\rangle/\sigma_f(^{235}U)\rangle)$	<9%

^{233}U (fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
	Photoneutron source. Direct detection method. Scintillator detector and fission chamber. Errors are standard deviation not including systematic erors (0.5%) and relative errors (1%). All experimental errors are included for /41/, /42/.			

^{233}U (fission)

Reference	Energy Range (resolution)	No.Points	(Quantity)	Error
76 Gryntakis [56]				
E 20625 /42/	0.0253 eV	1	(σ_f^{Mxw}) 511±17 b	3.3%

Reactor. Activation method. GeLi detector. Standards: $\sigma_{n,\gamma}^{th}(^{197}Au)$=98.8±0.3 b, Capt.Res.Int.= 1551±12 b, $\sigma_{n,\gamma}^{th}(^{59}Co)$=37.2±0.6 b, Capt.Res.Int.= 71.1±4 b, $\sigma_{n,f}^{th}(^{235}U)$=577.1±0.9 b, Fiss.Res.Int.= 274±10 b, $<\sigma_{n,p}(^{58}Ni)>$=113±7 mb, $<\sigma_{n,p}(^{24}Mg)>$= 1.53±0.09 mb, $<\sigma_{n,\alpha}(^{27}Al)>$=0.725±0.045mb. (All res.int. are including 1/v contribution). The threshold cross sections are averaged in ^{235}U thermal fission spectrum. Error analysis. Corrections given.

76 Pshenichniyj [20]				
E 40426 /2/	0.768 - 0.0212 eV	17		0.7-0.4%

Reactor. TOF method. Helium and NaI crystal counters. Standard: $\sigma_{n,f}^{th}(^{233}U)$ = 525.1 b.

^{233}U (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
46 Williams [57]				
E 12312 /6/	-5 - 4.7 eV	7	Reich-Moore parameters	-

D(D,N) source. Multilevel analysis.

55 Sailor [5]				
E 12363 /2/	4.5-9.25 eV	5	(E_r)	≲2%
/3/	1.785 - 10.4 meV	5	(E_r)	≲1%
			(Γ_t)	5-20%
			$(2g\Gamma_n)$	∿14%
			$(2g\Gamma_n^0)$	10-20%
			(Γ_f)	≲20%

Shape analysis.

^{233}U (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
55 Adamchuk [34]				
E 80331 /2/	1.82 - 16 eV	8	(E_r)	-
	TOF method.			
55 Nikitin [4]				
E 80332 /2/	1.7 - 21 eV	9	(E_r)	10%
	TOF method.			
55 Nikitin [58]				
E 80334 /3/	1.45 - 2.23 eV	3	$\sigma_t(E_r)$	-
/4/	- " -	3	(Γ_f)	-
/5/	- " -	3	(Γ_γ)	-
/6/	- " -	3	(Γ_t)	-
	TOF method.			
55 Pilker [59]				
E 12290 /5/	3.21 - 19 eV	16	($2g\Gamma_n$)	∿25%
/6/	- " -	16	($2g\Gamma_n^o$)	∿25%
	TOF method. Area analysis.			
57 Sanders [37]				
E 60410 /2/	1.76- 3.6 eV	3	(Γ_f)	<3%
	Accelerator.			

^{233}U (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
57 Sokolovsky [60]				
E 80009 /2/	20.85 eV (En.err.: 0.15 eV)	1	$(\sigma_t(E_r))$	29%
/3/	- " -	1	(Γ_t)	33%
/4/	- " -	1	(Γ_n)	7.4%
/6/	6.8 - 29.2 eV (En.err.: 30-200meV)	6	$(\sigma_t(E_r))$	<50%
/7/	62.5 - 110 eV	7	(E_r)	-
/8/	6.8 - 37 eV (En.err.: 30-300meV)	8	(Γ_t)	<5%
/9/	6.8 - 37 eV (En.err.: 30-700meV)	25	$(2g\Gamma_n)$	<25%
/10/	- " -	25	$(2g\Gamma_n^o)$	<30%
	Area analysis.			
58 McCallum [61]				
E 61129 /2/	-2 eV (En.err. 0.5eV)	1	(Γ_n^o) 3.2±1.2 meV	37.5%
	TOF method. Γ_γ = 30 meV assumed.			
58 Vladimirskii [62]				
E 80022 /2/	6.8 - 19 eV	5	(Γ_f)	≤60%
/3/	1.47 - 19 eV	11	$(\Gamma_f \cdot \sigma_t(E_r))$	<8%
	Area analysis.			
60 Moore [11]				
E 12341 /4/	0 - 20 eV	1	(S_n^o) $(1\pm0.2)\cdot10^{-4}$	20%
	Fast chopper. TOF method. Standard: $\sigma_{n,f}^{th}(^{235}U)$=524b.			
60 Moore [63]				
E 12342 /2/	0.195 - 10.47 eV	10	(E_r)	-
/3/	1.55 - 4.75 eV	2	$(E_r,J,\Gamma_n^o,\Gamma_\gamma,\Gamma_f)$	-
/4/	0.15 - 10.47 eV	8	$(E_r,R\Gamma_n^o,R\Gamma_\gamma, R\Gamma_f^1,R\Gamma_f^2)$	-
	Multi-level analysis. One fission channel.			

^{233}U (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
60 Pattenden [64]				
E 12358 /2/	-1 - 25.48 eV	27	Vogt param.	-
/3/	0.188 eV	1		
	Multi-level analysis. Vogt parameters. $r\Gamma_\gamma$ assumed of 45 meV for /2/ and 40 meV /3/. $\ell = 0$.			
64 Nifencker [42]				
E 60511 /5/	1.799 - 38.05 eV	40	$(2g\Gamma_n^o)$	-
/6/	1.799 - 4.83 eV	4	$(\Gamma_t/\sigma_t(E_r))$	-
	Area analysis. Γ_γ assumed 45 meV.			
65 Nifenecker [65]				
E 60872 /2/	1.823 - 32.56 eV	39	(Γ_f)	-
/3/	- " -	39	(Γ_n)	-
/4/	- " -	39	(Γ_t)	-
/5/	- " -	39	$(2g\Gamma_n^o)$	-
	Gas scintillator counter.			

^{233}U (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
65 Lynn [14]				
E 60317 /2/	1.775 eV	1	$(\sigma_t(E_r))$ 1650±350 b	21.2%
/3/	1.775 eV	1	(Γ_t) 210±40 meV	19%
/4/	5 meV	1	(Γ_t) 110 meV	-
/7/	1.775 eV	1	$(\sigma_t(E_r))$ 890±75 b	8.5%
/10/	2.3 eV	1	(E_r)	-
/11/	1.775 eV	1	$(\sigma_t(E_r))$ 1050±25 b	2.4%
/12/	4.76 - 98.1 eV	32	(E_r)	-
/13/	79.5 eV	1	(E_r)	-
/14/	3.62 eV	1	$(\sigma_t(E_r))$ 184 b	-
/15/	3.62 eV	1	(Γ_t) 340 meV	--

Accelerator /7/,/12/.Crystal spectrometer . Shape analysis /4/,/14/, area analysis /15/.

70 Cao [51]				
E 20003 /9/ /10/ /11/	0.018 - 65 eV	72	Adler-Adler parameters	-

LINAC. TOF method. Spark chamber and liquid scintillator detectors. Standard: $\sigma_{n,f}^{th}(^{233}U)$= 524.5±1.9 b. Adler-Adler multi-level analysis. Corrections for background. Neutron spectrum corrected for self-screening in the natural boron counter.

^{233}U (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
70 Kolar [17]				
E 20114 /6/	2.8 - 52.15 eV	72	$(2g\Gamma_n^o)$	-
/7/	2.5 - 30 eV	1	$(<2g\Gamma_n^o>)$ 0.136 ± 0.03 meV	22%
/8/	2.8 - 52.15 eV	72	(Γ_t)	-
/9/	0.9 - 93 eV	85	Adler-Adler parameters	-
/10/	0.9 - 93 eV	85	- " -	-
/11/	0.9 - 93 ev	85	- " -	-
/12/	2.5 - 30 eV	1	(S_n^o) $(2.25\pm0.55)\cdot10^{-4}$	24%
/13/	2.5 - 30 eV	1	$(\bar{D}_n)$ 0.61 ± 0.07 eV	11.5%

Photoneutron source. TOF method (Flight path of 100 m). Liquid scintillator (BF_3) and BORSL detectors. Corrections for background and for the influence of the Al can (total thickness of 0.6 mm). Single level shape analysis /6/,/8/. Adler-Adler multi-level analysis /9/,/10/,/11/.

70 Rjabov [66]				
E 40070 /23/	1.79 - 20.6 eV (40 - 50 ns/m)	13	$(2g\Gamma_n)$	<30%
/25/	1 - 21 eV	1	(S_n^o) $(1.39^{+0.9}_{-0.39})\cdot10^{-4}$	65%

Pulsed fast reactor. TOF method (Flight path of 1010 m), transmission and self indication method. Liquid scintillator with boron and with cadmium. Area analysis.Correction for background.

70 de Saussure [67]				
E 10079 /2/	0.02 - 64.3 eV	70	Adler-Adler parameters	-
/5/	- " -			
/6/	- " -			

Simultaneous least squares fit to capture and fission cross sections reported in 1966.

^{233}U (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
74 Nizamuddin [52]				
E 20446 /3/	5.9 - 124 eV	1	$(\langle\Gamma_f\rangle)$ 372 meV	-
/4/	5.89 - 124.12 eV	169	$(\Gamma_t,\Gamma_f,\sigma_o\Gamma_f)$	≤10%
/5/	5.9 - 124 eV	2	$(\bar{D})$	-

60 MeV LINAC (Saclay). Photoneutron source. TOF method. Gas scintillator detector (BF_3 and ^{10}B counters). Sample: 99.57% ^{233}U. Standard: Fis.Res.Int.(^{233}U) = 168.31 b (8.32 - 101.2 eV). Shape analysis, Breit-Wigner single level analysis. Statistical errors. Γ_γ calculted 39 meV.

^{233}U (fission resonance integral)

Reference	Min.Energy	No.Points	(Quantity)	Error
64 Bigham [41]				
E 12230 /2/	0.45 eV	1	753±36 b	4.78%
/3/	0.45 eV	1	743±24 b	3.23%

Reactor. Activation method. Fission chamber detector /3/. Standards: Capt.Res.Int.(^{115}I)= 2790 b, $\sigma^{Mxw}_{n,\gamma}(^{115}I)$ = 189 b /2/, Capt.Res.Int. (^{197}Au) = 1535 b, $\sigma^{Mxw}_{n,\gamma}(^{197}Au)$ = 98.8 b /3/ and $\sigma^{Mxw}_{n,f}(^{233}U)$ = 521 b for both.

65 Hardy Jr. [68]				
E 12283 /3/	0.5 eV	1	798±26 b	3.25%

Standards: Capt.Res.Int.(^{197}Au) = 1555 b, $\sigma^{th}_{n,\gamma}(^{197}Au)$ = 98.8 b and $\sigma^{th}_{n,\gamma}(^{233}U)$ = 526 b.

^{233}U (fission resonance integral)

Reference	Min.Energy	No.Points	(Quantity)	Error
65 Yasuno [69]				
E 20309 /2/	0.5 eV	1	838±40 b	4.77%

Reactor, 1/E spectrum. Activation method. NaI scintillator. Sample: 99.92% ^{233}U. Corrections: edge effect, self-shielding, effective cadmium cut-off energy. Statistical errors.

66 Brooks [15]

E 20623 /5/ 0.35 - 10 eV 10 0.5-2.5%

LINAC. TOF method. Standards: $\sigma_{sct}(^{239}Pu)$= 10.5±0.6 b, and $\sigma_{sct}(^{233}U)$ = 12.0±2.0 b; $\bar{\nu}(^{239}Pu)$ = 2.87 and $\bar{\nu}(^{233}U)$ = 2.5. Corrections for scattering in the canning material.

67 Conway [70]

E 12313 /3/ 0.5 eV 1 771±49 b 6.35%

Reactor. Standard: $\sigma_{n,\gamma}(^{59}Co)$ = 37.5 b and Capt.Res.Int.(^{59}Co) = 72.0 b.

70 Cao [51]

E 20003 /6/	0.414 eV - 1.222 keV	30		-
/7/	- " -	5		-
/8/	20.01 eV - 3 keV	13	($\int\sigma_f(E)dE$)	-

Photoneutron source. TOF method. Spark chamber and liquid scintillator counter. Standards: $\sigma^{th}_{n,f}(^{233}U)$ = 524.5±1.9 b. Corrections for background, neutron spectrum and self-screening. Statistical errors.

^{233}U (fission resonance integral)

Reference	Min.Energy	No.Points	(Quantity)	Error
71 Eiland [71]				
E 10143 /9/	0.5 eV	1	830±60 b	7.23%
/10/	0.5 eV	1	(I_γ/I_f) 0.176±0.008	4.55%
/12/	3 eV	1	405±24 b	∿6%
/13/	3 eV	1	(I_γ/I_f) 0.148±0.006	4.05%

Reactor. Epicadmium neutron flux. Reaction rates integrated over epithermal distributions. NaI detector. Standard: Capt.Int.Res.(^{197}Au) = 1550±40 b.

76 Gwin [55]

E 10267 /39/ 8.322 - 1223 keV 22 -

Photoneutron source. Direct detection method. Fission chamber and scintillator detector.

76 Gryntakis [56]

E 20625 /43/ 0.55 eV 1 812±90 b 11%

Reactor. Activation method. GeLi detector. Standards : $\sigma^{th}_{n,\gamma}(^{197}Au)$=98.8±0.3 b, Capt.Res.Int. (+1/v)=1551±12 b, $\sigma^{th}_{n,\gamma}(^{59}Co)$= 37.2±0.6 b, Capt.Res.Int.(+1/v)=71.1±4 b, $\sigma^{th}_{n,f}(^{235}U)$=577.1±0.9b, Fis.Res.Int.(+1/V)=274±10 b, $<\sigma_{n,p}>(^{58}Ni)$=113±7mb, $<\sigma_{n,p}>(^{24}Mg)$=1.53±0.09 mb, $<\sigma_{n,\alpha}>(^{27}Al)$=0.725±0.045mb. The threshold cross sections are averaged in ^{235}U thermal fission spectrum.

^{233}U ($\bar{\nu}$)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
46 Zinn [21]				
E 12319 /4/	0.0253 eV	1	$(\bar{\nu}^{Mxw})$ 2.61	-
	Thermal spectrum. Fission chamber. Standards: $\sigma_{n,f}(^{235}U)$=560 b, $\sigma^{th}_{n,f}(^{233}U)$=518±20 b.			
55 McMillan [72]				
E 12357 /2/	0.0253 eV	1	$(<\bar{\nu}>)$ 2.502±0.063	2.5%
/3/	0.0253 eV	1	$(<\bar{\nu}(^{233}U)>/ <\bar{\nu}(^{235}U)>)$ 1.017	2.2%
	Reactivity coefficient method. Reactor spectrum averages. Standard: $\bar{\nu}_{th}(^{235}U)$=2.46± 0.03.			

^{233}U ($\bar{\nu}_{pr}$)

References	Energy Range (Resolution)	No.Points	(Quantity)	Error
56 Sanders [73]				
E 60400 /4/	0.0253 eV	1	$(\bar{\nu}^{Mxw}_{pr})$ 2.45±0.04	<2%
/5/	0.0253 eV	1	$(\bar{\nu}^{Mxw}_{pr}(^{233}U)/ \bar{\nu}^{Mxw}_{pr}(^{235}U))$ 1.005±0.016	≈1.6%
	Concidence method. Thermal spectrum. Standard: $\bar{\nu}^{th}_{pr}(^{235}U)$= 2.426±0.01 /4/.			

^{233}U ($\bar{\nu}_{pr}$)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
58 Jacob [74]				
E 60128 /2/	0.0253 eV	1	$(\bar{\nu}^{Mxw}_{pr}(^{239}Pu)/\bar{\nu}^{Mxw}_{pr}(^{233}U))$ 1.165±0.02	∿2%
	Coincidence method. Thermal spectrum.			
58 Colvin [75]				
E 60324 /2/	0.0253 eV	1	$(\bar{\nu}^{Mxw}_{pr}(^{239}Pu)/\bar{\nu}^{Mxw}_{pr}(^{233}U))$ 1.158±0.013	∿1%
/3/	0.0253 eV	1	$(\bar{\nu}^{Mxw}_{pr}(^{233}U)/\bar{\nu}^{Mxw}_{pr}(^{235}U))$ 1.034±0.008	∿0.8%
	Coincidence method. Thermal spectrum.			
59 de Saussure [76]				
E 12328 /2/	0.0253 eV	1	$(\bar{\nu}^{Mxw}_{pr}(^{233}U)/\bar{\nu}^{Mxw}_{pr}(^{235}U))$ 1.024±0.01	1%
	Thermal spectrum. Fast coincidence technique. Hornyak button detector.			
63 Hopkins [77]				
E 12326 /2/	0.0253 eV	1	$(\bar{\nu}^{Mxw}_{pr})$ 2.473±0.034	<1.4%
	Thermal spectrum. Moderating tank detector. Standard: $\bar{\nu}^{sf}(^{252}Cf)$.			

^{233}U ($\bar{\nu}_{pr}$)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
65 Mather [78]				
E 60657 /3/	0.0253 eV	1	$(\bar{\nu}_{pr}^{Mxw})$ 2.533±0.035	1.4%
	Thermal spectrum. Liquid scintillator. Standard: $\bar{\nu}^{sf}(^{252}Cf)=3.782$.			
72 Segarchev [79]				
E 40106 /3/	0.0253 eV	1	2.48	-
	VDG. Neutron source: $(P,^{7}Li)$, (P,T), (D,D). Coincidence method. Silicon detector. Statistical errors.			
73 Reed [80]				
E 10427 /2/	0.01 - 11.5 eV	54		≤1.6%
	TOF and coincidence methods. Scintillator tank and fission chamber detector. Standard: $\bar{\nu}^{sf}(^{252}Cf)$. Corrections for background, detector efficiency and accidental cioncidences. Statistical errors. The values are given at resonance energies.			
75 Boldeman [81]				
E 30046 /2/	0.0253 eV	1	$(\bar{\nu}_{pr}^{Mxw})$ 2.455±0.01	<0.5%
	Reactor thermal column. Gadolinium bath coincidence method. Liquid scintillator tank. Absolute measurement . Corrections for counter drifts, fast neutron fission, impurities, geometry, dead time, etc.			

^{233}U ($\bar{\nu}_{dl}$)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
69 Notea [82]				
E 30238 /2/	0.0253 eV	1	$(\bar{\nu}_{dl}(^{233}U)/\bar{\nu}_{dl}(^{235}U))$ 0.345±0.086	24%
	GeLi detector. Standard: $\bar{\nu}_{dl}(^{235}U)=0.0151$. Gamma ray analysis of fission products.			
71 Conant [83]				
E 10144 /4/	0.0253 eV	1	$(\bar{\nu}_{dl}^{Mxw}/\bar{\nu}^{Mxw})$ 0.0027±0.0001	3.8%
	Reactor. Long counter and two spiral fission chambers. Corrections for room scattered neutrons and detector response.			
76 Eccleston [84]				
E 10640 /2/	32.84 - 1444.01 keV	129		≤30%
	(P,^{9}Be) neutron source. Proportional counters. Data are energy distributions of averaged number of delayed fission neutrons.			

^{233}U (α)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
46 Zinn [21]				
E 12319 /5/	0.0253 eV	1	(α^{Mxw}) 0.114	-
	Thermal spectrum. Fission chamber. Standards: $\sigma_{n,f}(^{235}U)$=560 b, $\sigma_{n,f}(^{233}U)$(2200m/s)= 518±20 b.			
50 Inghram [28]				
E 12351 /3/	0.0253 eV	1	$(<\alpha>)$ 0.0976±0.0018	<2%
	Reactor spectrum. Mass spectrometer.			
55 Kukavadse [23]				
E 80333 /5/	0.0253 eV	1	(α^{Mxw}) 0.095±0.003	∿3%
	Thermal spectrum. Burn-up method. Calculated from ^{233}U capture to absorption cross section ratio.			
56 Spivak [85]				
E 80001 /4/	30 - 900 keV	5		4-50%
	Spherical shell transmission method. Calculated from η using $\bar{\nu}_{pr}$ from BNL-325(1965), and $\bar{\nu}_{dl}$.			
57 Sanders [86]				
E 60407 /2/	1.07 - 2.16 eV	12		-
	Crystal spectrometer. Calculated from η, using $\bar{\nu}$ = 2,504.			
58 Cocking [87]				
E 60412 /2/	1.1 meV	1	0.113±0.018	∿18%
	Fission chamber. Absolute measurement.			

^{233}U (α)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Errors
62 Hopkins [88]				
E 12331 /2/	30 keV - 1 MeV (10 - 90 keV)	9		20%
	Scintillating tank detector.			
64 Okazaki [89]				
E 12365 /2/	0.0253 eV	1		∿2.3%
			0.0917±0.0022	
64 Esch [90]				
E 12314 /2/	>0.5 eV	1	($<\alpha>$)	7.5%
			0.165±0.012	
	Epicadmiun spectrum.			
64 Okazaki [89]				
E 12350 /2/	0.0253 eV	1	($<\alpha>$)	∿0.4%
			0.094±0.0004	
	Reactor spectrum. Burn-up method. Mass spectrometer. $\sigma_{abs}(^{233}U)$ assumed 591 b.			
66 Cabell [91]				
E 60740 /2/	0.0253 eV	1		5.4%
			0.0942±0.0016	
	Mass sepctrometer.			
66 Brooks [15]				
E 61133 /2/	35 meV - 11.04 eV	660		<50%
	LINAC. TOF method. Standard: ^{233}U. Calculated from η, assuming $\bar{\nu}$ = 2.5.			
70 Lounsbury [47]				
E 10013 /2/	0.0253 eV	1		0.5%
			0.0899±0.0004	
	Reactor. Activation and burn-up methods. Isotopic composition analysis by mass spectrometer.			

^{233}U (n)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
46 Zinn[21]				
E 12319 /7/	0.0253 eV	1	$(\eta^{Mxw}(^{233}U)/\eta^{Mxw}(^{235}U))$ 1.114	-
/8/	0.0253 eV	1	(η^{Mxw}) 2.33±0.06	2.6%
	Thermal spectrum. Long counter /7/. Standard: $\sigma_{n,f}(^{235}U)$ = 560 b.			
48 Crnikshank [92]				
E 12347 /2/	0.0253 eV	1	(η^{Mxw}) 2.38±0.08	3.4%
	Pile oscillator. Thermal spectrum. Standard: $\sigma_{abs}(B)$.			
55 Alichanov [93]				
E 80260 /2/	0.0253 eV	1	(η^{Mxw}) 2.36±0.03	1.27%
	Thermal spectrum. Reactivity coefficient method.			
55 Spivak [22]				
E 80329 /6/	0.0253 eV	1	(η^{Mxw}) 2.28±0.028	1.23%
	Thermal spectrum. Ionization chamber detector.			
55 Nikitin [58]				
E 80334 /2/	8.8 meV - 3 eV (0.5 - 400 meV)	21	$(\eta(E)/\eta_{th})$	<4%
	TOF method.			
56 Harvey [94]				
E 60980 /2/	0.0253 eV	1	(η^{Mxw}) 2.26±0.06	2.65%
	Pile oscillator. Thermal spectrum.			
56 Spivak [85]				
E 80001 /2/	30 - 250 keV	3		<5%
	Spherical shell transmission method. BF_3 counters.			

^{233}U (n)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
56 Magleby [95]				
E 12317 /2/	0.0221 - 11.18 eV	154		1.5-4%
	Crystal spectrometer. Standard: $\eta(^{233}U)=2.298$ at 0.025 eV, and = 2.288 at 0.57 eV.			
56 Palevsky [96]				
E 12322 /2/	0.0104 - 0.099 eV	14		0.2-0.8%
	Hornyak button detector. Standard: $\eta^{th}(^{233}U)=2.28$.			
56 Thomas [97]				
E 12348 /2/	0.0253 eV	1	$(<\eta>)$ 2.31 ± 0.03	1.3%
/3/	0.0253 eV	1	2.29 ± 0.03	1.3%
	Standard: $\eta^{th}(^{235}U) = 2.08$.			
57 Sanders [86]				
E 60407 /3/	48 meV - 0.79 eV	15		-
/4/	1.07 - 2.16 eV	12		-
	Crystal spectrometer.			
57 Egelstaff [98]				
E 60942 /2/	0.0253 eV	1	2.25 ± 0.05	2.22%
58 Gaerttner [99]				
E 12327 /2/	0.0253 eV	1	$(\eta^{Mxw}(^{233}U)/\eta^{Mxw}(^{235}U))$ $1.078\pm1.2\%$	1.2%
		1	(η^{Mxw}) 2.231 ± 0.034	1.5%

^{233}U (η)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
	Subcadmium graphite reactor spectrum. Reactivity coefficient method.			
59 Muehlhause [100]				
E 12361 /2/	0.0253 eV	1	(η^{Mxw}) 2.25±0.03	1.33%
	Reactor. Standard: σ_{abs}(B).			
60 Macklin [101]				
E 12349 /2/	0.0253 eV	1	2.296±0.02	0.87%
	Subcadmium reactor spectrum. Manganese bath method.			
61 Yeater [102]				
E 12330 /2/	0.9976 - 820.7 eV	155		-
	TOF method. Hornyak button detector.			
66 Smith [103]				
E 12318 /2/	0.025 - 0.057 eV	2	($\eta(^{233}U)$/ $\eta(^{235}U)$)	<0.5%
/5/	0.057 eV	1	($\eta(^{239}Pu)$/ $\eta(^{233}U)$) 0.889±0.005	0.56%
	Crystal spectrometer.			
66 Brooks [15]				
E 20623 /6/	0.35 - 10 eV	10	($\langle\eta\rangle$)	<1.5%
	LINAC. TOF method. Standards: $\sigma_{sct}(^{239}Pu)$ = 10.5±0.6 b, $\sigma_{sct}(^{233}U)$= 12±2 b, $\bar{\nu}(^{239}Pu)$=2.87, $\bar{\nu}(^{233}U)$=2.5.			

^{233}U (η)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
66 Brooks [15]				
E 61133 /3/	2.779 - 11.04 eV	479		<10%
/6/	1.005 - 2.828 eV	83		<5%
/9/	0.15 - 1.027 eV	74		<5%
/12/	35 meV - 0.148 eV	32		<6%
	TOF method. (Flight path of 22.5 m) for /3/,/6/, and 5.05 m for /9/,/12/). Timing channel: 1 μsec for /3/, 8 μsec for /6/,/9/, and 32 μsec for /12/.			
70 Weston [50]				
E 10100 /4/	0.01679 - 1.06276 eV	50		
	TOF method. Fission chamber and liquid scintillator. Standard: $\sigma^{th}_{n,f}(^{233}U)$ = 527.7 b.			
70 Vidal [26]				
E 20552 /3/	0.0253 eV	1	2.24±0.012	0.54%
	Thermal column. Fission chamber. Sample: 0.1 - 0.15% ^{233}U. Standard: $\eta(^{235}U)$ = 2.072±0.006. $\eta(^{233}U)/\eta(^{235}U)$ = 1.081±0.005 (0.46% error).			
71 Gwin [104]				
E 10207 /9/	0.0253 eV	1	$(\eta\sigma_{abs}(^{233}U)/\eta\sigma_{abs}(^{235}U))^{MXW}$ 0.953±0.014	<1.5%
/11/	0.0253 eV	1	$(\eta^{Mxw}(^{233}U)/\eta^{Mxw}(^{235}U))$ 1.04	-
/13/	0.0253 eV	1	2.292	-
	Thermal column. Reactivity coefficient method. Standards: $\sigma_{abs}(^{233}U)$=575.6 b, $\sigma_{abs}(^{235}U)$=679.5 b for /11/, $\eta(^{235}U)$=2.076 /13/. Corrections for epithermal neutron effects, assuming incident spectrum to be Maxwellian + 1/E.			

^{233}U (n)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
71 Gwin [104]				
E 10208 /5/	0.0253 eV	1	(η^{Mxw}) 2.283±0.015	<0.65%
	Reactor. Corrections for epithermal neutrons and for neutron leakage.			
76 Pshenichnyj [20]				
E 40426 /3/	0.0212 - 2.76 eV	22		1.2-2.5%
	Reactor. TOF method. Helium and NaI crystal counters. Standard: $\sigma^{th}_{n,f}(^{233}U)$ = 525.1 b.			

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2.6. Uranium - 234

The experimental data for total cross section of U-234, are reported by 3 authors, 58 Mc Callum, 58 Harvey, 60 Block.

The accuracy request for this cross section in WRENDA is of 5%, and the data which obey to this restraint are those of McCallum in the energy range 102 meV - 20.3 eV (76 points) with an error of 5%, and those of Block between 19.9 meV and 44.4 meV (26 points, with an error less than 4%).

Other data reported by McCallum between 5.143 eV and 5.264 eV (4 data points) have errors of about 15%, between 4.803 and 5.611 eV (17 data points) have errors less than 50% and at 0.0253 eV has error of 6.6% and the cross section of 121 ± 8 b.

Harvey's data between 2.65 eV and 695 eV (253 points) have no quoted errors.

As it can be seen between 695 eV and 43.5keV there are no experimental data.

The U-234 fission cross section is reported by 3 authors, two of them supplying single-point measurements, 61 Leonard and 65 Perkin, at 5.2 eV (5 ± 0.9 b) and 24 keV (0.015 ± 0.04 b) with errors of 18% and 26.6%, respectively.

Odegaarden (1960) gives 20 values between 4.18 eV and 5.68 eV with an energy resolution of 1.06 μsec/m, and with errors greater than 15 %, relative to $^{235}U(n,f)$ cross section at 2200 m/sec, of 590,8 b.

There are very few data for absorption cross section.

In this respect at 0.0253 eV there are only 3 values reported by: 59 McCallum gives a value of 103 ± 8 b (error of 7.8%); 58 Craig reports a value of 143 ± 9 b (error of 6.3 %); 60 Block reports a value for absorption cross section of 92 ± 5 b (error of 5.4%).

Craig used as standard the averaged absorption cross section for U-235, of 665 b.

The experimental data for resolved and unresolved resonance paramters of ^{234}U are represented by 7 references.

Single-point measurements are reported in four references and 3 references give parameters on larger energy ranges: 58 Harvey, between 5.2 eV and 369 eV, gives 20 values for Γ_n and Γ_n^o (with errors larger than 20 %) and James reported data (for 40 energies) for E_r and Γ_n in the energy range 5.19 eV - - 817 eV (with errors ≤ 10 % for Γ_n), for Γ_f, 38 values in

the energy range 5.19 - 686.7 eV (with errors <10 %) and for $\sigma(E_r)\ \Gamma_f$ between 5.19 and 722 eV assuming Γ_γ = 25 meV.

In its last paper, 1977, James reported 118 values for E_r, Γ_n (with errors <25 %) and Γ_f (with errors < 50 %) in the energy range 5.16 eV - 1.4992 keV, assuming Γ_γ = 40 meV.

The single-point measurements are dealing with a resonance arround 5.2 eV, namely: 57 Sokolovsky gives Γ_n with an error of 8.8 %, 58 McCallum with errors of 25-27 %, 58 Harvey with errors of 20-60%, 60 Odergaarden, with errors of 7-11 % and 70 Rjabov (with errors between 9-20 %). Area analysis have been performed by Sokolovsky, Harvey, Adegaarden, Rjabov and James.

Strength functions values and averaged level spacing are reported by Harvey for energy range 0 - 155 eV (S_n^o = (1.2 $\pm$ $\pm$ 0.5).10^{-4}, 42%error, and D = 12 $\pm$ 3 eV, 25 % error), James (1969) for 1 eV - 210 eV (S_n^o = (1.09 $\pm$ 0.36) 10^{-4}, 33 % error, and $\bar{D}$ = 12.3 $\pm$ 1.5 eV, 12.2 % error) and in 1977 for 5.16 eV - - 1.499 keV (S_n^o = (0.86 $\pm$ 0.11) 10^{-4}, 13 % error, and $\bar{D}$ = 10.6 $\pm$ 0.5, 5 % error).

The data and accuracy needs are summarized below:

Data	Gap of data	Gap of accuracy	Requested accuracy (WRENDA)
total	44-102 meV	44-102 meV	5 %
	>695 eV	> 20 eV	-
absorption	whole energy range*	-	-
subthreshold fission	>5.6 eV	-	-
resonance parameters	>1.49 keV Breit-Wigner parameters	-	-

* Except 0.0253 eV

^{234}U (total)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
58 McCallum [1]				
E 61129 /3/	5.143 - 5.185 eV	2		<15%
/4/	5.224 - 5.264 eV	2		<15%
/5/	102 meV - 20.3 eV	76		<5%
/6/	4.803 - 5.611 eV	17		<50%
/14/	0.0253 eV	1		6.6%
			121±8 b	
	TOF method. Samples: $3.9 \cdot 10^4$ b/atom for /3/,/4/, $1.46 \cdot 10^2$ b/atom for /5/, $6.29 \cdot 10^3$ b/atom for /6/, /14/. Absolute measurements.			
58 Harvey [2]				
E 12339 /6/	2.65 - 695 eV	253		-
	Fast chopper. Sample: 95.55% ^{234}U. Data are from curves.			
60 Block [3]				
E 12024 /7/	19.9 -44.4 meV	26		<4%
	Fast chopper. Statistical errors.			

^{234}U (subthreshold fission)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
60 Odegaarden [4]				
E 12320 /2/	4.18 - 5.68 eV (1.06 μsec/m)	20	15-3	15-130%
	Crystal spectrometer. Standard: $\sigma_{n,f}^{th}(^{235}U)$=590.8 b. Data from curves.			
61 Leonard [5]				
E 12286 /5/	5.2 eV	1		18%
	Crystal spectrometer.			
65 Perkin [6]				
E 20584 /3/	24 keV	1		26.6%
E 60442 /3/			0.015±0.04 b	
	Photoneutron source ($\sigma_{\gamma,n}(^{9}Be)$ from a spherical Sb-Be source). Method: direct calibration of neutron source by Mn-bath and oil-bath, indirect calibration with boron pile. Fission chamber. Statistical errors.			

^{234}U (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
57 Sokolovsky [7]				
E 80009 /11/	5.18 eV	1	(Γ_n) 3.4±0.3 meV	8.8%
/12/	5.18 eV	1	$(\Gamma_t\sigma_t(E_r))$ 1730±170 beV	10%
	Area analysis.			
58 McCallum [1]				
E 61129 /9/	5.19 eV	1	$(\sigma_t(E_r))$ $(5.9\pm1.4)\cdot10^4$ b	25%
/10/	5.19 eV	1	(Γ_γ) 31±9 meV	30%
/11/	5.19 eV	1	(Γ_n) 4.2±1.2 meV	30%
/12/	5.19 eV	1	(Γ_t) 35±9 meV	26%
/13/	5.19 eV	1	(Γ_n^o) 1.83±0.5 meV	27%
	TOF method. Thick and thin targets ($1.46\cdot10^2$ - $3.9\cdot10^4$ b/atom). Absolute measurements.			
58 Harvey [2]				
E 12339 /2/	5.2 - 369 eV	20	(Γ_n,Γ_n^o)	20-60%
/3/	5.2 eV	1	(Γ_γ) 22±9 meV	41%
/4/	0 - 155 eV	1	$(\overline{D^o})$ 12±3 eV	25%

^{234}U (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
/5/	0-155 eV	1	(S_n^o) $(1.2\pm0.5)\cdot10^{-4}$	42%

Fast chopper. Sample: 95.55% ^{234}U. Area analysis. Γ_γ = 25 meV for E > 10 meV and ℓ = 0.

60 Odegaarden [4]

E 12320 /3/	5.2 eV	1	(Γ_f) 450±50 meV	11%
			$(\sigma_f(E_r))$ 4.86±0.34 b	7%

Crystal spectrometer. Standard: $\sigma_{n,f}^{th}(^{235}U)$ = 590.8 b. Area analysis.

69 James [8]

E 20467 /2/	5.19 - 817 eV	40	(Γ_n)	≤10%
/3/	5.19 - 686.7 eV	38	(Γ_f)	<10%
/4/	5.19 - 722 eV	39	$(\sigma(E_r)\Gamma_f)$	>100%
/5/	5.19 - 817 eV	41	(E_r)	-
/6/	1 eV - 35 keV	1	(S_n^o) $(1.09\pm0.72)\cdot10^{-4}$	66%
/7/	1 eV - 35 keV	1	$(\bar{D}^o)$ 12.3±1.5 eV	12.2%

LINAC. Photoneutron source (Booster target). TOF method (Flight path of 14.646 m). Li gas scintillator detector. Sample: 99.37% ^{234}U. Corrections for background. Area analysis. Γ_γ assumed 25 meV for /3/,/4/. Maximum likelihood method for /6/. Level spacing from 17 resonances with E_r < 210 eV (ℓ = 0) /7/.

^{234}U (resonance parameters)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
70 Rjabov [9]				
E 40070 /15/	5.19 eV (40 - 50 ns/m)	1	(Γ_t) 29.4±4.7 meV	16%
/16/	- " -	1	(Γ_n) 3.88±0.35 meV	9%
/17/	- " -	1	(Γ_γ) 23.5±4.7 meV	20%
	Pulsed fast reactor. TOF method.(Flight path of 1010 m). Liquid scintillator with boron. Corrections for background. Area analysis.			
77 James [10]				
E 10620 /2/	5.16 eV - 1.49922 keV	118	(E_r,Γ_n)	<25%
			(Γ_f)	<50%
/3/	- " -	1	(D) 10.6±0.5	5%
			(S^o) $(0.86\pm0.11)\cdot10^{-4}$	13%
	TOF method. Ionization chamber. Glass detector. Area analysis. Γ_γ assumed 40 meV /2/. Statistical errors.			

^{234}U (absorption)

Reference	Energy Range (Resolution)	No.Points	(Quantity)	Error
58 McCallum [1]				
E 61129 /8/	0.0253 eV	1	103±8 b	7.8%
	TOF method. Absolute measurement. Data from measured total and calculated bound atom scattering.			
58 Craig [11]				
E 12355 /3/	0.0253 eV	1	$(\langle\sigma_{abs}\rangle)$ 143±9 b	6.3%
	NRX reactor spectrum. Burn-up method. Standard: $\langle\sigma_{abs}\rangle(^{235}U)$ = 665 b.			
60 Block [3]				
E 12024 /6/	0.0253 eV	1	92±5 b	5.4%
	Fast chopper. Estimated from total cross section.			

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STATUS AND ACCURACY OF NEUTRON DATA FOR THE IMPORTANT ISOTOPES RELEVANT TO THE THORIUM-URANIUM FUEL CYCLE IN THE FAST ENERGY REGION

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Abstract

The current status and accuracy of neutron cross section data for each important isotope relevant to the Th-232 - U-233 fuel cycle in the fast neutron energy region is reviewed. The aim of this review is to present the status of these data in terms of the required accuracies specified in WRENDA, to specify the extent to which these accuracies have been met, and to indicate the discrepancies which still need to be resolved.

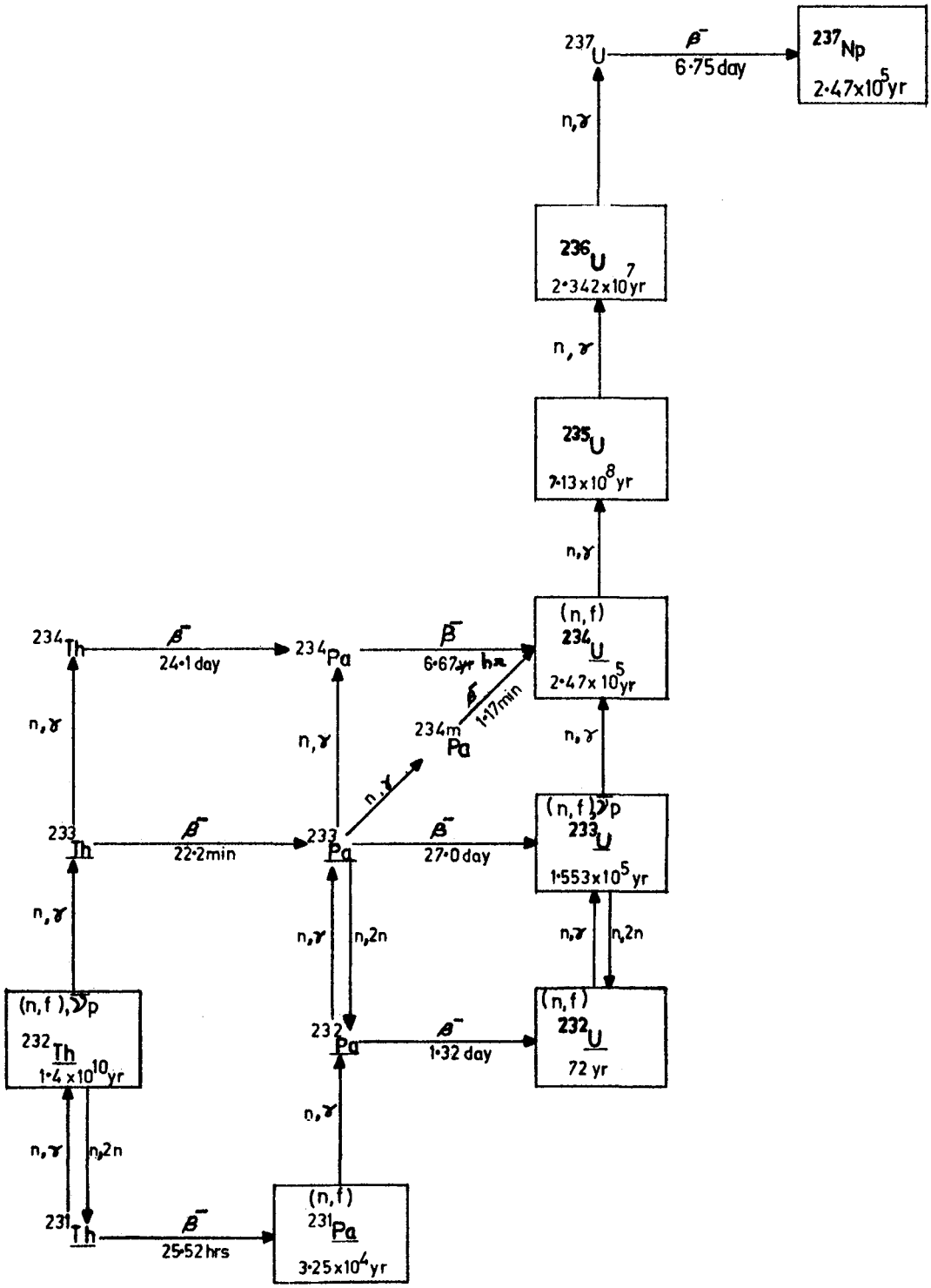
1. INTRODUCTION

The thorium-uranium fuel cycle, inspite of some drawbacks, has sufficiently attractive features to command serious attention [Rev. Mod. Physics (1978)]. Although at the first advisory group meeting [IAEA-186 (1976)] this alternate fuel cycle was not treated explicitly under a separate title, some of the isotopes of importance to this cycle, were included in general reviews covering groups of neighbouring isotopes. During the last four years the case for this cycle has become strong enough to justify a data status review for the isotopes relevant to this cycle. This paper reviews the present status of the measured or predicted neutron cross sections for these nuclides in the fast energy range i.e. between 50 keV and 20 MeV, the upper and lower limits are chosen rather arbitrarily and are not rigorously imposed. The thermal and resonance region has been covered by Dr. Vasiliu in the preceding paper. Generally WRENDA 76/77 is used to establish the relative importance to

each cross section, however, some subjective elements might have influenced the details of the coverage. CINDA 76/77 and its Supplement 4 (1978) are used as the main information source for the concerned literature. The IAEA-NDS EXFOR TAPE 3000 has been extensively used and we are grateful to the NDS for the support they have given. Effort has been made to include works published subsequently as well as those under progress. For the latter we thank the colleagues on the INDC who made the relevant information available to us. Reference to all such material is given as "Private Communication". Some of these may be preliminary data and should not be quoted elsewhere without the permission of the respective authors. It is likely that some information is missed (especially due to the long time interval required for communications between Bombay and other active laboratories in the world). Nevertheless it is felt that the available data are substantially covered and any missed information is not likely to alter the general conclusions of this review. To confine the review to reasonable time and page co-ordinates, emphasis is placed mainly on energy dependent cross sections because of their general utility. Angular distributions as well as some of the less important cross sections are not included. This review paper is not an evaluation, but the aim is to present the status in terms of the target accuracies and the extent to which they are met as well as to indicate existing discrepancies which still need to be resolved.

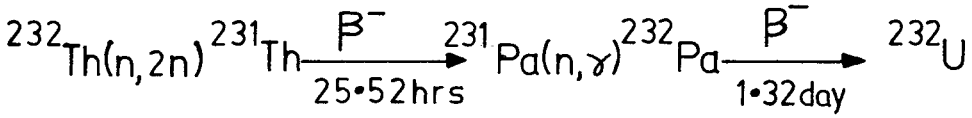
The important nuclides and the corresponding reactions resulting in production and the build up of transactinides involved in Th-U fuel cycle are summarised in Fig.1-1.

Fig.1-1 The important isotopes and relevant reaction cross sections for the ^{232}Th- ^{233}U fuel cycle

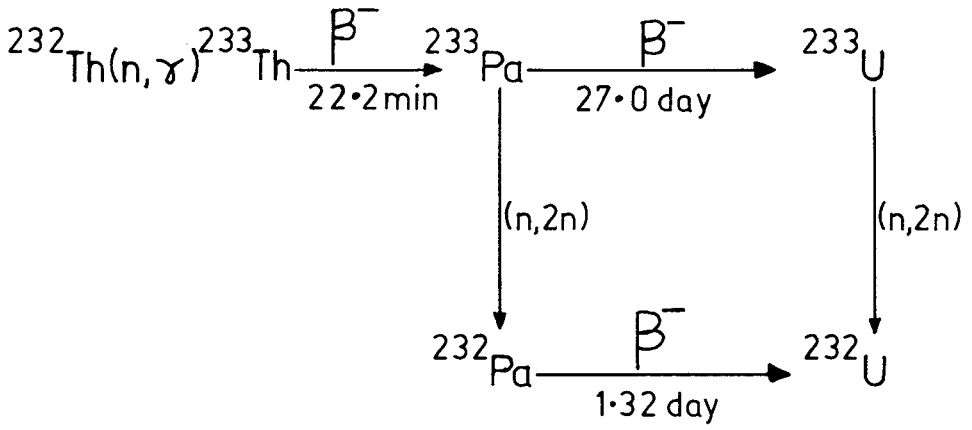


The present review covers the nuclides which are underlined in the figure and all the indicated reactions except the radioactive decays.

The two reaction sequences of importance to this fuel cycle are:



1·1



1·2

While fission and capture cross sections control the neutron balance of the breeder reactor based on this fuel cycle, the relatively long beta decay life time for 233-Pa (T_{y2} = 27d) and the hard gamma rays emitted by some of the products of the 232-U decay chain are other important nuclear parameters influencing the detailed technology of such a reactor.

A summary of data requests for the nine isotopes under review as per WRENDA 76/77 is shown in Table 1-I. The table indicates the number of requests for each cross section with

Table 1-I. Summary of data request for nine isotopes

Isotope	σ-(type)	WRENDA 76/77 request				Present status
		No. of request	Priority	Accuracy	Energy range	
^{231}Th, ^{232}Pa	-	-	-	-	-	No measurements are reported
^{232}Th	total	1	2	5-10%	-20MeV	More accurate measurements required
	(n,f)	4	2	3-5%	-20MeV	Requirements not fully met $^{235}U(n,f)$ ratio preferred 14MeV more accurate measurements required
	(n,γ)	2	1	3-5% 10%	-2 MeV 2-10MeV	Upto 1 MeV requirements not fully met 1-4MeV requirements met 4-14MeV no measurements are reported
	(n,2n)	1	1	10%	-10MeV	Requirements met
	$\overline{\nu}p$	-	-	-	-	Reported measurements with 2-4 % accuracy, 1·4-4 MeV and ≈15MeV
^{233}Th	All cross sections	1	2	5%	-20MeV	No measurements are reported Theoretical prediction exist with an accuracy of 15%
^{231}Pa	(n,f)	-	-	-	-	Reported measurements with 3-15% accuracy More accurate measurements required upto 1·5MeV
	(n,γ)	1	2	10%	-10MeV	No measurements are reported
^{233}Pa	(n,f)	1	2	5%	-20MeV	No measurements are reported
	(n,γ)	1	1	10%	-15 MeV	» »
	All other cross sections	1	2	5%	-20MeV	» » Theoretical prediction exist with an accuracy of 15%
^{232}U	(n,γ)	1	2	2-10%	-10MeV	No measurements are reported
	(n,f)	-	-	-	-	Reported measurements with 1·4-4% accuracy upto 1·5 MeV
^{233}U	total	1	2	5%	-20 MeV	Requirements met
	(n,f)	2	1	1·5-3%	0·01-15MeV	Requirments not fully met
	(n,γ)	3	1	3-20%	-10MeV	No measurements are reported
	(n,2n)	1	1	10%	-15MeV	» »
	$\overline{\nu}p$	1	1	0·5%	0·05-5MeV	Requirements not met
		1	2	1%	5-10MeV	Requirements not fully met
^{234}U	(n,f)	2	2	5-15%	-20MeV	Requirements met
	(n,γ)	3	2	5-15%	-20MeV	No measurements are reported
	(n,2n)	1	1	10%	-15MeV	» »

requested accuracies and also includes in the last column the information regarding whether and to what extent the request has been met. This column is the result of this review, thus this table can be considered as a summary of this whole paper.

In subsequent sections we take up each isotope individually. The pattern will be: a brief paragraph discussing the data followed by a table containing information about the data sources and including techniques and standards used as well as errors quoted. Wherever considerable data exist a graph showing the various data sets is included. The Thorium Isotopes are discussed in Section-2, Protactinium Isotopes in Section-3 and Uranium Isotopes in Section-4.

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2. THORIUM ISOTOPES

2.1 Thorium-231

From Fig. 1-1 it can be seen that this nuclide is produced through the (n,2n) reaction on 232-Th and is one of the steps in the alternate path for 232-U production. It is also produced by (n,γ) reaction on 230-Th which itself is produced by alpha decay of 234-U. However, the amount of 231-Th that is produced is small and considering the half life of 25.5 hrs, it does not seem to be significant enough to generate any WRENDA request and no measurements are reported in CINDA 76/77 (see the last paragraph under Thorium-233).

2.2 Thorium-232

For the Th-U cycle, 232-Th is the basic fertile isotope on which the technology of the whole fuel cycle rests, and hence is one of the two most important nuclides to be considered for this fuel cycle, the other being 233-U.

Referring to Fig. 1-1 we can see that the important reactions for 232-Th are (n,γ), (n,f) and (n,2n). In the fast energy region there are; two requests for (n,γ) cross section with required accuracies ranging from 3 to 10% and priority one, four requests for (n,f) cross section with 3 to 5% accuracy with priority two (ratio to 235-U fission is preferred) and one request for (n,2n) cross section with 10% accuracy and priority one. In addition there is one request for total, elastic and inelastic cross section with 5 to 10% accuracy and priority two.

2.2 (a) Total Neutron Cross Section

The status of the total cross section data has been recently reviewed for the INDC by us [MEHTA (1978)]. Most recent measurement has been that of WHALEN (1978) which was published just at the time when the report for INDC was

prepared and hence was not included in that report. These are transmission measurements performed from 0.1 to 5.0 MeV with statistical accuracy of $\lesssim$ 2%. The recent evaluation by MEADOWS (1978) includes Whalen's data. An independent evaluation of data on 232-Th is being carried out at B.A.R.C. and a preliminary technical report on evaluation of the total cross section [GARG (1979)] has been prepared. As the point data of Whalen are only recently made available from NDS, the evaluation is undergoing a revision to include this data.

The measured data exist upto 15 MeV and evaluated data have accuracies between 2 to 5%. Thus the present requirement for the total cross section data are met by available data. However, the presently specified target accuracies may not be adequate for optimised detailed calculation for an actual reactor, in which case more accurate measurements may be necessary in some specified energy range. Above 15 MeV deformed and spherical optical model prediction are available [MEADOWS (1978) and GARG (1979)].

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2.2 (b) Fission Cross Section

There are three recent reviews on the status of this cross section [MEADOWS (1978), PATRICK (1978) and MEHTA (1978)]. These between them give a good account of all the reported measurements which are summarised in Table 2.2-I. Most recent measurementshave been by POENITZ (1978) and NORDBERG (1978), which are not included in MEADOWS (1978) evaluation. Only preliminary data are reported for the more recent measurements[PLATTARED (1978) and SYME (1978)]. Most of the data measured from 1956 onwards are shown in Fig. 2.2-1 which is a copy of the curve shown by PATRICK (1978), which includes NORDBERG (1978) data but does not include POENITZ (1978) measurements.

Most of the measurements have used 235-U (n,f), 238-U (n,f) or 239-Pu (n,f) as reference while POENITZ (1978) measurement is based on 233-U (n,f) as a reference. The cross section derived from 232-Th/238-U and 232-Th/235-U ratios agree reasonably well when the recent ENDF/B-V evaluated values are used for the two reference cross sections [MEADOWS (1978)]. However, the measured absolute data are lower by about 15% than these values. BEHRENS (1977) measurement has the least quoted errors and covers the maximum energy range (0.7 to 32 MeV) and can be considered a very good shape measurement. NORDBERG (1978) data agree well with BEHRENS (1977) in the overlapping region. MEADOWS (1978) evaluation quotes accuracies varying from 4 to 10% from threshold to 20 MeV. Thus for this region the WRENDA 76/77 requirements are not fully met in terms of the measured accuracies (4-10%) compared to required accuracies of 3-5%. The 14 MeV data are used for normalisation between various sets which determine the shape over the whole energy range. There is some ground for more accurate measurements around this energy as the existing data exhibit large scatter.

Table 2·2-I Summary of ^{232}Th fission cross section measurements

Author Reference	Energy range (MeV) Number of points	Type of measurements	Error reported	Technique
Williams (1944) LA-520, 4603	3·4 - 5·85 3	Ratio	-	Charge particle reaction $^{232}Th(n,f)$; $^{235}U(n,f)$
Phillips (1948) LAMS-774, 4809	14 1	Ratio	8%	(D-T) reaction Photographic plates $^{232}Th(n,f)$; $^{238}U(n,f)$
Nyer (1950) LAMS-938, 50	14 1	Ratio	3%	(D-T) reaction Ionization chamber $^{238}U(n,f)$=1·13±0·03b standard
Uttley (1956) AERE-Np/R 1996	14·1 1	Ratio	5·2%	Back to back fission counter $^{238}U(n,f)$ = 1·14±0·078b standard
Henkel (1957) LA-2122, 5703	1·15-9 158 1·2-9·47 209	Ratio	-	Spiral fission chamber $^{235}U(n,f)$ standard
Berezin (1958) AE, 5, 659	14·6 1	Absolute	5·4%	$^{3}H(d,n)^{4}He$ reaction Ionization chamber-fission Associated α-counting-neutron Mass of deposition-α, counting
PROTOPOPOV (1958) AE, 4, 190	14.6 1	Absolute	5.7 %	Same as Berezin (1958)
KALININ (1958) 58GENEVA, 16/36	3.1 - 7.2 9 3 -10.9 23	Absolute		Ionization chamber Long counter
PANKRATOV(1960) AE, 9, 399	10.7 - 21.5 16	Absolute	3%	$D(d,n)^{3He}$ reaction and TOF Gas filled scintillation fission counter Long counter and telescope
BABCOCK (1961) BABCOCK (6110)	1.14 - 1.88 7 13 - 18 5	Ratio	8.35 % 5 - 22%	Charge particle reaction ^{238}U (n,f), BNL-325 (1958)

Table 2.2 - I Contd. Summary of ^{232}Th fission cross section measurements

Author / Reference	Energy range (MeV) Number of points	Type of measurement	Error reported	Technique
KATASE (1961) W. KATASE (6109)	13.5 - 14.8 3	Absolute	10 %	^{3}H(d, n) ^{4}He reaction Nuclear emulsion Associated α-counting
PANKRATOV (1963) AE, 14, 177	5.4 - 36.5 39	Absolute	5%, 5 - 27 MeV 10% >27 MeV	Same as Pankratov (1960)
ERMAGAMBETOV (1963) AE, 23, 20	0.5 - 3.0	Ratio	15 % at 0.6 MeV 3 %	^{3}H(p, n) ^{3}He reaction Ionization chamber ^{235}U(n,f) standard <840 keV ^{238}U(n,f) " >840 keV
RAGO (1967) HP, 13, 654	12.5 - 18 16	Ratio	5 %	^{3}H(d, n) ^{4}He reaction LAXAN, tracks, optical micro. ^{232}Th(n, f):^{236}U(n, f)
BEHKAMI (1968) ND / A118, 65	1.2 - 1.6 3	Ratio	6 - 8 %	^{7}Li(p, n) ^{7}Be reaction MAKROFOL - tracks ^{236}U(n, f) standard
IYER (1969) Roorke conf. 2 (1969) 289	14.1 1	Ratio	9 %	(D - T) reaction LEXAN - tracks ^{238}U(n, f)=1.20 b Mass of deposition, α-counting
BARRALL (1969) AFWL-TR-68-134	14.6 1	Absolute	8.9 %	(D - T) reaction LEXAN - tracks Na I(Tl) - ^{99}Mo (f.f.) ^{27}Al(n,α): 0.1207 b, standard
MUIR (1971) Knoxvill conf. 1 (1971) 292	0.598 - 2.96 104	Ratio	15 %	EXPLOSION Solid state detector ^{239}Pu(n, f), NSE, 32, (1968) 35 standard

Table 2.2 - I contd. - Summary of ^{232}Th fission cross section measurements

Author / Reference	Energy range (MeV) Number of points	Type of measurement	Error reported	Technique
SHPAK (1972) ZEP, 15, 323	13.5 – 14.8 10	Ratio	2 – 3 %	(D-T) reaction Glass detectors ^{238}Pu(n,f) standard
KONECNY (1972) ZP, 251, 400	1.1 – 1.9	Ratio	—	^{7}Li(p,n)^{7} Be reaction ^{235}U(n,f) standard 8 keV resolution
BLONS (1975) PRL, 35, 1749	1.21 – 5.01 638	Ratio	1 – 2	LINAC + TOF Gas scintillator ^{235}U(n,f), ENDF B/IV 3 keV resolution at 1.6 MeV
BEHRENS (1977) UCID – 17442	0.697 – 32.6 14.5	Ratio	1 – 2 % above 1.4 MeV	LINAC + TOF Back to Back Ionization chamber ^{232}Th(n,f): ^{235}U(n,f) data Mass of deposition -threshold method
NORDBORG (1978) Harwell conf.(1978)	4.6 – 8.8	Ratio	5 %	Charge particle reaction + TOF Back to Back fission chamber ^{232}Th(n,f): ^{235}U(n,f) data Mass of deposition-Weighing
BLONS (1978) PRL, 41, 1289	~1.6	Ratio	—	LINAC + TOF Gas scinillator ^{235}U(n,f) standard 2.3 keV resolution at 1.6 MeV
BLONS. Priv. comn.	9	Ratio	—	Same as BLONS (1978)
PLATTERED (1978) Priv. comn.		Ratio		LINAC + TOF Gas scintillator ^{235}U(n,f) ENDF/B IV standard
SYME (1978) Priv. comn.	1.2 – 2.0	Absolute	—	Fission neutron detection
POENITZ (1978) Ref. MEADOWS (1978)	1.2 – 8.5	Ratio	—	^{233}U(n,f) standard

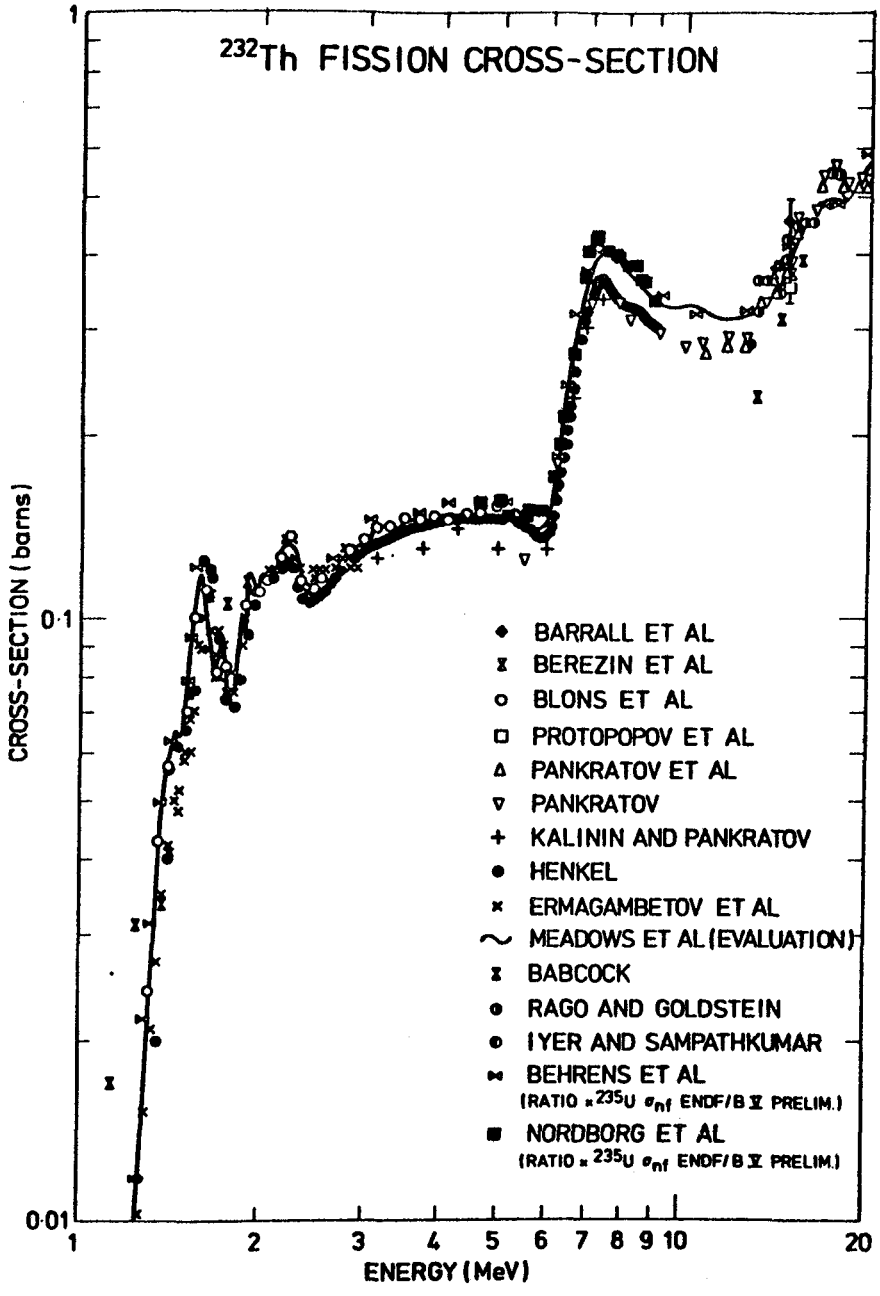

FIG. 2.2-I

Fine structure in the cross section at sub and near threshold has been observed by a number of workers. The new BLONS (1978) measurements have confirmed the details of this structure and removed the ambiguities. These data have been interpreted in terms of triple humped fission barrier by CARUNA (1977), BLONS (1978) and JARRY (1979). As the cross

section is very low, the details of the fine structure have little practical value from the reactor physics point of view, but such investigations extend our knowledge of the basic nuclear physics which will enable the fission cross section for the nearby important nuclides to be calculated with acceptable accuracies.

The fission spectrum averaged cross section has been measured by KOBAYASHI (1976,1977) and FEBRY (1972) which agree within quoted errors. However, MEADOWS(1978) has calculated this cross section using his own evaluation and Maxewellion type fission spectrum (Tn = 1.32 MeV) and has obtained a value which is lower by about 10% than the measured values.

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2.2 (c) Neutron Capture Cross Section

This cross section is of primary importance in the Th-U fuel cycle as it is basic to the feasibility of the breeder reactor, and yet it has been rather poorly known.

There are two WRENDA 76/77 requests for this cross section with 3 to 5% accuracy upto 2 MeV and 10% accuracy upto 10 MeV with priority one. There are a few more similar requests with lower priorities. Table 2.2-II summarises all the information on available data. MEADOWS (1978) evaluation has not included the data of KOBAYASHI (1978). As can be seen from the table, three different techniques are used in the measurements. BELANOVA [(1958), (1960), (1965)] has used spherical shell transmission technique. The difference between his 1958 and 1965 values exceeds six times the error quoted. There are no other measurements utilising this technique and thus no comparative values available to discriminate between the two sets. Thus these data can be considered uncoroborated and need not be included in any evaluation.

The other two techniques rely on the activation measurement and prompt capture gamma measurements respectively, both using suitable standards as reference. Standards used include 235-U (n,f), 238-U (n,γ), 10-B (n,α), 6-Li(n,α) and 127-I(n,γ). Most of the old (before 1970) measurements were based on beta counting and radiochemical separation and the standards used were poorly known. These data are very much discrepant with each other in the energy range 0.1 to 1.0 MeV. The ENDF/B-IV evaluation which was based on these data is considerably higher compared to the recent measurements of LINDNER (1976), MACKLIN (1977) and POENITZ (1978). Out of the earlier measurements only MISKEL (1962) and CHELNOKOV (1972) are in agreement with these recent data. Data from LINENBERGER (1946), STAVISSKII (1961), STUPEGIA (1963) and

Table 2.2-II Summary of ^{232}Th capture cross section measurements

Author Reference	Energy range (keV) Number of points	Type of measurements	Error reported	Technique
Linenberger (1946) LA-467	3 - 390 7	Ratio	10%	Activation Charge particle reaction $^{7}Li(p,n)$, $D(d,n)$ $^{235}U(n,f)$ standard
Macklin (1957) PR,107, 504	24 1	Ratio	20%	Activation Sb-Be source Chemical separation of ^{233}Pa, 310keV γ-ray from ^{233}Pa by NaI $^{127}I_{53}(n,\gamma)=0.820b$ standard
Belanova (1958) Fiz,34,574	25-830 3	Absolute	1-2%	Spherical shell transmission
Leipunskij (1958) Geneva 1958	200 1	Ratio	5%	Activation $^{127}I_{53}(n,\gamma)$ standard
Perkin (1958) PPS, 72, 505	14•5 Mev 1	Ratio	15%	Activation $^{27}Al_{13}(n,\gamma)$ standard
Barry (1959) PPS,74,685	300-1200 10	Ratio (600keV) Absolute	8%	Activation Charge particle reaction T(p,n) β-counting of ^{233}Th and ^{239}U with end window GM counter $^{238}U(n,\gamma)$ at 600keV standard Long counter $^{10}B(n,\alpha)$ Neutron monitor
Hanna (1959 JNE,8,197	100-1230 13	Absolute	8-10%	Activation β-counting of ^{233}Th with end window GM counter Fast flux monitored by proton recoil H(n,n')-standard
Belanova (1961) AE,8,549	220 1	Absolute	2%	Spherical shell transmission
Stavisskii (1961) AE,10,508	30-964 25 1•0-5•85 MeV 9	Ratio	3-10% -	Activation $^{127}I_{53}(n,\gamma)$ standard $^{235}U(n,f)$ standard

Table 2.2-II Contd. Summary of ^{232}Th capture cross section measurements

Author Reference	Energy range(MeV) Number of points	Type of measurements	Error reported	Technique
Miskel (1962) PR,128,2717	0·032-3·970MeV 26	Ratio	±10%	Activation Charge particle reaction $^{7}Li(p,n)$ β-Counting of ^{233}Pa with calibrated end window proportional counter chemical separation of ^{233}Pa $^{235}U(n,f)$ from LA-2124(1957)-standard
Tolstikov (1963) AE,15,414	5·5-102 10	Absolute	15-20%	Activation Charge particle reaction $^{7}Li(p,n)$ β-Counting of ^{233}Th with end window GM counter Long counter $^{10}B(n,\alpha)$ flux monitor
Moxon (1963) TRDWP/P-8	3 -143 keV 98	Absolute		Prompt gamma ray Time-of-flight, LINAC Moxon-Rae Detector for gamma ray $^{10}B(n,\alpha)$ neutron monitor
Stupegia (1963) JIN,25,627	191-1170 22	Ratio	7%	Activation β-Counting of ^{233}Th with end window proporional counter $^{235}U(n,f)$, BNL-325(1964) standard
Chaubey (1965) NP, 66,267	24 1	Ratio	10 %	Activation Sb-Be source β-Counting with end window GM counter $^{127}I_{53}(n,\gamma)$=0·820b standard
Belanova (1965) AE,19,3	24 1	Absolute	4 %	Spherical shell transmission Sb-Be source Four long counter to detect neutron
Koroleva (1966) AE,20,431	24 1	Absolute	7 %	Spherical shell transmission Sb-Be source Neutron detector through $^{127}I_{53}(n,\gamma)$ gamma detected with NaI
Forman (1971) CONF 710301,735	20ev-30keV 28	Absolute	±15%	Prompt gamma ray Underground nuclear explosion with time-of-flight Moxon-Rae detector for gamma ray $^{6}Li(n\alpha)$ neutron monitor

Table 2.2-II Contd. Summary of ^{232}Th capture cross section measurements

Author Reference	Energy range Number of points	Type of Measurements	Error Reported	Technique
Chelnokov (1972) YFI-13,6	0·2 - 34·6keV	Ratio	8-12%	Prompt gamma ray Lead-slowing down spectrometer -(D-T) reaction Gamma ray measurements with proportional counter $^{235}U(n,f)$ standard
Lindner (1976) NSE,59,384	0·121 - 2·73 MeV	Ratio	0·6 - 5·7%	Activation Charge particle reaction $^{3}H(p,n)^{3}He$ Radiochemical separation of ^{233}Pa. β-counting by 4 π proportional counter caliberated with $^{237}Np(\alpha)$ ^{233}Pa source $^{235}U(n,f)$ from ENDF/B-IV, standard, silicon surface barrier detector
Macklin (1977) NSE,64,849	2·6 - 800keV	Ratio	2% up to 100keV 2·5%, 100-450keV 5-10% above 450keV	Prompt gamma ray Time-of-flight, LINAC Liquid scintillator for γ-ray $^{6}Li(n,\alpha)$ neutron monitor Isotopically purified thorium
Yamamuro (1978) NST,15,637	24 keV 1	Absolute	9%	Prompt gamma ray Fe-filtered beam Liquid scintillator for gamma ray $^{10}B(n,\alpha)$, standard
Kobayashi (1978) PRELIMINARY	1keV-450keV 24 ,55,146keV 3	Ratio	3-5%	Prompt gamma ray Time-of-flight, LINAC Fe-Si filtered beam Liquid scintillator for γ-ray $^{10}B(n,\alpha)$ standard
Jain (1978) HARWELL Cont(1978)	3 50, 460, 680keV 3	Ratio	8%	Activation Charge particle reaction $^{7}Li(p,n)^{7}Be$ Ge(Li) detector, γ-rays from ^{233}Th decay $^{197}Au(n,\gamma)$ standard
Poenitz (1978) ANL/NDM-42	30keV-2·5 MeV 23	Ratio	3% 0·4 - 10·5% 4·7%	Prompt gamma ray, 58 - 850keV Charge particle reaction, 500keV-2 MeV White neutron source, 50 - 300keV Liquid scintillator for γ-ray $^{197}Au(n,\gamma)$ standard Activation above 240keV Ge(Li) detector, γ-rays from ^{233}Pa decay $^{235}U(n,f)$ standard $^{197}Au(n,\gamma)$ standard, 30keV

TOLSTIKOV (1963) are much higher, and HANNA (1959) data deviate too much from these recent measurements.

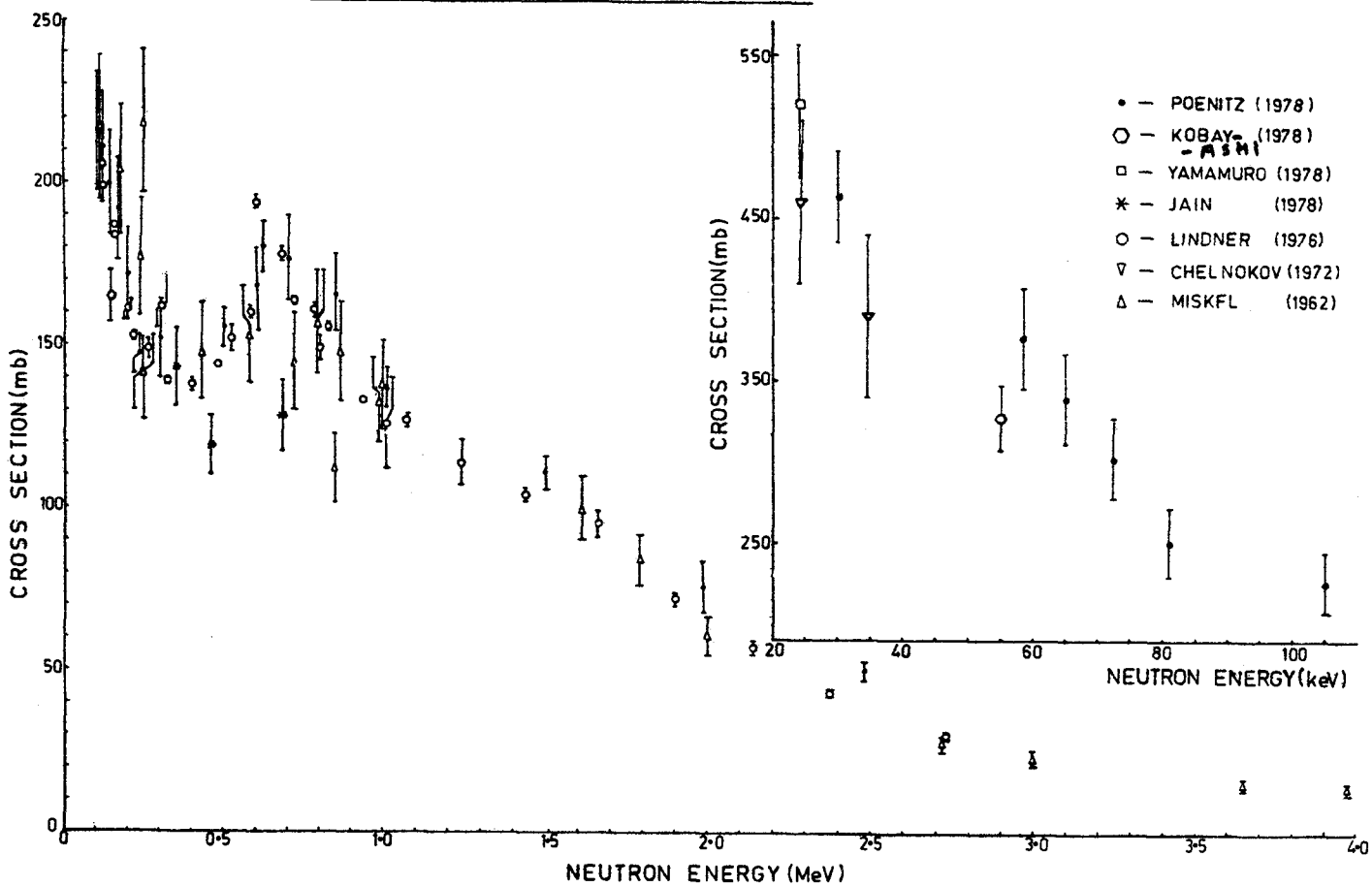
MACKLIN (1977) and POENITZ (1978) are the only two reported measurements based on prompt gamma technique. Preliminary results of KOBAYASHI (1978) also are obtained using prompt gamma technique. LINDNER (1976) and MACKLIN (1977) differ by 10-20%. POENITZ (1978) measurements, performed to settle this discrepancy, agree with LINDNER (1976) and are higher by about 10% than MACKLIN (1977) and also higher than MEADOWS (1978) evaluation. JAIN (1978) measurements at three energies agree with MACKLINS (1977) values within quoted errors but differ from LINDNER (1976) and POENITZ (1978) at 460 and 680 keV. Preliminary values of KOBAYASHI (1978) are also lower than POENITZ (1978) values. In Fig. 2.2-2 recent data are shown for the energy range 100 keV to 4 MeV.

Considering the scatter of data which is slightly more than the quoted errors on recent measurements between 400 keV to 1 MeV, one can conclude that the 3 to 5% accuracy requirement is not quite satisfied and more measurements are required.

Between 1 and 4 MeV there are three sets of measurements with accuracies better than 10% which agree within the quoted errors. Thus the required accuracies are satisfied in this region. However, no measurements exist between 4 and 14 MeV with one measurement PERKIN (1958) at 14.5 MeV. MEADOWS (1978) evaluation is just an "arbitrary interpolation" between 2.5 to 14 MeV. Again measurements in this region are required to produce a more reliable evaluation upto 15 MeV.

POENITZ (1978) measurements extend below 100 keV down to 30 keV. CHAUBEY (1965) and YAMAMURO (1978) have measured the cross section at 24 keV using photoneutron

Fig. 2.2-2 Capture cross section for ^{232}Th



source (Sb-Be) and Fe-filtered beam respectively which agree with the trend of Poenitz measurements. The measurements of CHELNOKOV (1972) include 24 and 34.5 keV data points and of KOBAYASHI (1978) the 55 keV point. These points are lower by 8 to 13% with respect to POENITZ (1978) data. The data below 100 keV are indicated in the insert to Fig. 2.2-2. All other measurements in this energy region are not reliable enough to be included in this graph. The main source of discrepancy in these earlier measurements could be attributed to uncertain standards. POENITZ (1978) measurement accuracies are quoted as 3% which meet the requirement. However, the discrepancy with CHELNOKOV (1972) and KOBAYASHI (1978) measurements indicate need for more corroborating measurements in this region.

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2.2 (d) (n,2n) and (n,3n) Cross Sections.

Reported measurements of (n,2n) cross section are summerised in Table 2.2-III. Apart from the measurement of KARIUS (1976) all other measurements are old. Evaluation of this data has been carried out at BARC by ANAND (1979).

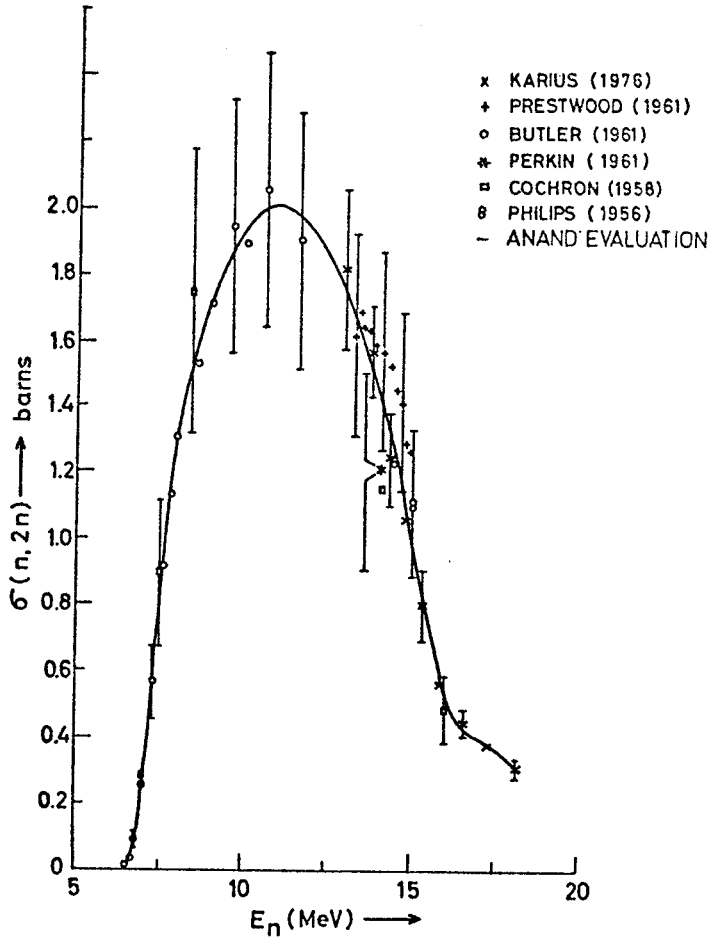
Table 2.2 - III Summary of $^{232}Th(n, 2n)$ cross-section measurements

Author / Reference	Energy range (MeV) Number of points	Type of measurement	Error reported	Technique
Phillips (1956) AERE-NP/R-2033	15 1	-	9 %	Activation $^{3}H(d,n)^{4}He$ reaction NaI(Tl) detector for γ-ray
Cochran (1958) WASH-1006, 22&1013, 34	7 - 16 5	-	9 - 12 %	Method not given
Halperin (1958) WASH-1006, 25	7 - 8.1 3	-		$^{238}U(n,f)$ standard
Tewes (1959) BAPS, 4, 445	8.4 - 15.1 13	Absolute	10 - 20 %	Activation $^{2}H(d,n)^{3}He$ reaction
Zisin (1960) AE, 8, 360	14.7 1	Ratio	23 %	Activation $^{3}H(d,n)^{4}He$ reaction 4π - β counting $^{238}U(n,f)$ standard
Prestwoud (1961) PR, 121, 1438	12.1 - 14.9 12	Ratio	10 %	Activation $^{3}H(d,n)^{4}He$ reaction Gamma-ray counting $^{27}Al(n,\alpha)^{24}Na$ flux monitor β-counting $^{238}U(n,f)$ standard
Butler (1961) CJC, 39, 689	6.5 - 20.4 18	Ratio	5 - 10 %	Activation $^{3}H(d,n)^{4}He$, $^{2}H(d,n)^{3}He$ reaction $^{32}S(n,p)$ standard
Perkin (1961) JNE, 14, 698	14.1 1	Absolute	5 %	Activation NaI(Tl) detector for γ-ray $^{27}Al(n,\alpha)^{24}Na$-flux monitor Geiger-counter for β
Batchelor (1965) NP, 65, 236	7 1	-	-	Derived from η measurement using time of flight and organic scintillation detector
Karius (1976) NEANDC(E) 172, 5	13 - 18.1 9	-	10 %	Activation $^{3}H(d,n)^{3}He$ reaction Ge(Li) detector for γ-rays

Some of the data required renormalization and reassessment of the errors. Similarly some older measurements as well as a few data points in some reported sets have to be rejected on various grounds. The selected data, after renormalization and reassignment of errors, are plotted in Fig.2.2-3. The line through the data is the evaluation generated by a SPLINE fit and the error estimated for the evaluation is ±7.5%. Thus the requirements for the (n,2n) data are fully met.

ANAND (1979) evaluation is compared with that of MEADOWS (1978) and VASILIU (1979) in Fig. 2.2-4. There are no reported measurements for the (n,3n) cross section and only theoretical prediction has to be used.

Fig 2.2-3 (n,2n) cross section for ^{232}Th



A semiempirical expression has been developed by JINGHAN (1978) to calculate (n,2n) cross section which predicts the cross section with a maximum deviation of 10% around the peak value between 10 and 13 MeV. This expression has been utilised to calculate the (n,3n) cross section. Considering agreement between the measured and calculated (n,2n) cross section it is expected that the (n,3n) cross sections are predicted with an uncertainty of 10 to 15%. These are shown in Fig. 2.2-5.

Fig.2.2-4 ^{232}Th σ(n,2n) evalution

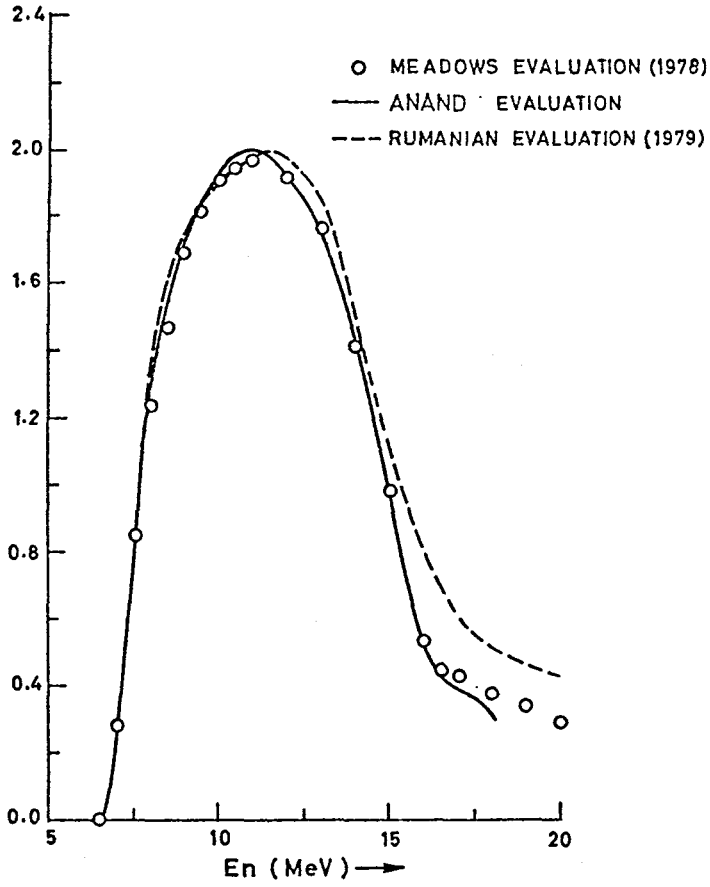
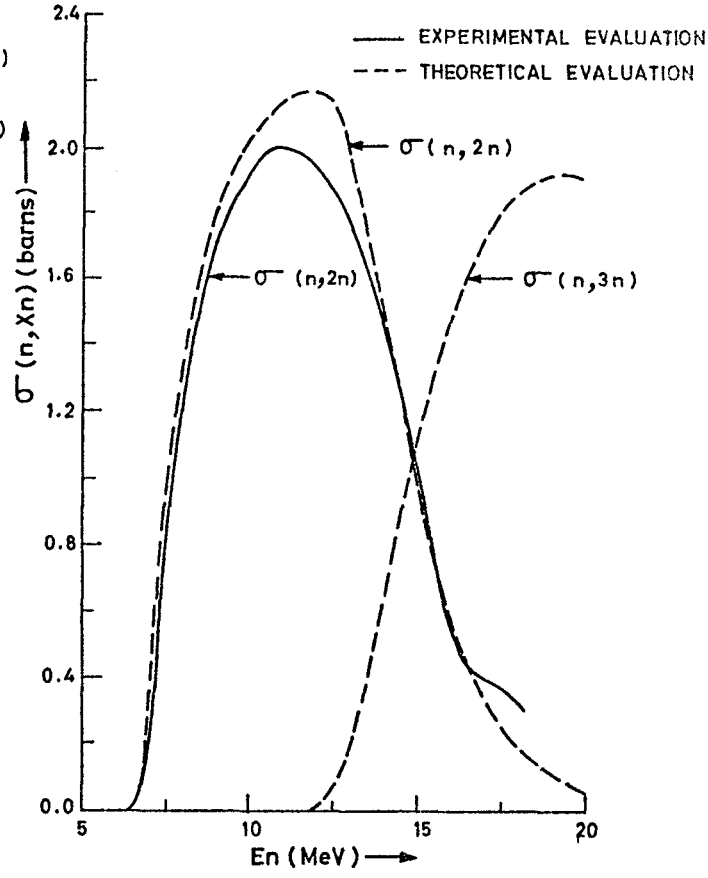


Fig 2.2-5 ^{232}Th:- σ (n, 2n) & σ(n,3n)



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2.2 (e) Prompt Neutrons emitted per fission ($\bar{\nu}_p$)

The neutron produced by fast fission of 232-Th contribute marginally to the neutron balance in the reactor system.

There are no WRENDA 76/77 request for this number. However, there are a few reported measurements which are summarised in the Table 2.2-IV. CARUNA (1977) is the most recent one with seven data points between 1.35 and 2.1 MeV and one point at 16 MeV with accuracy of 1 to 3%. Recently evaluated value for 252-Cf spontaneous fission $\bar{\nu}_p = 3.745$ is used as a standard. The available data are shown in Fig. 2.2-6. HOWERTON (1977) has calculated this number empirically for the energy range 1.39 to 4 MeV. The values differ by about 9% from the measurement at lower energy. CARUNA (1977) has made a linear least square fit to these data. There is an indication of a peak around 1.4 MeV which CARUNA (1977) has attempted to interpret in terms of double or triple humped fission barrier.

Table. 2.2-IV Summary of ^{232}Th- $\bar{\nu}_p$ measurements

Author Reference	Energy range(MeV) Number of points	Type of Measurement	Error Reported	Technique
Smith (1959) PR,115,1242	1·40 1	Ratio	8%	$^{7}Li(p,n)^{7}Be$ reaction $^{238}U, \bar{\nu}$ =2·63 standard
Minov (1961) B,SPN,177	2·3-15·7 3	Ratio	3-4%	Proportional counter ^{235}U $\bar{\nu}$ =2·426 standard
Conde (1961) NSE,11,397	3·60-14·9 2	Ratio	3-4%	$D(d,n)^{3}He$ and $T(d,n)^{4}He$ reaction Coincidence between fission fragments(f,f) and fission neutron(f,n) liquid scintillation tank $^{252}Cf,sf,\bar{\nu}$ =3·79 standard
Conde (1965) AE,29,33	1·42-14·9 9	Ratio	1·5-4%	Same as Conde (1961)
Mather (1965) NP 66,149	1·39-4·02 4	Ratio	2-4%	Charged particle reaction Fission chamber - fission Liquid scintillation counter for neutron $^{252}Cf\,sf, \bar{\nu}$ = 3·782 standard
Prokhorova (1967) SNP,7,579	1·48-3·27 7	Ratio	2-4%	$^{3}H(p,n)$ reaction Coincidence between f,f(fission chamber) and f,n(BF_3-counter) ^{235}U $\bar{\nu}_{th}$=2·414 standard
Caruna (1977) NP/A-285,217	1·35-2·1 7	Ratio	1·2-1·5% 2·73% at 1·35 MeV 2% at 16 MeV	$^{3}H(p,n)^{3}He$ and $^{3}H(d,n)^{4}He$ reaction Coincidence between f,f(fast ionisation chamber) f,n(liquid scintillation) $^{252}Cf, sf, \bar{\nu}$ = 3·745 standard

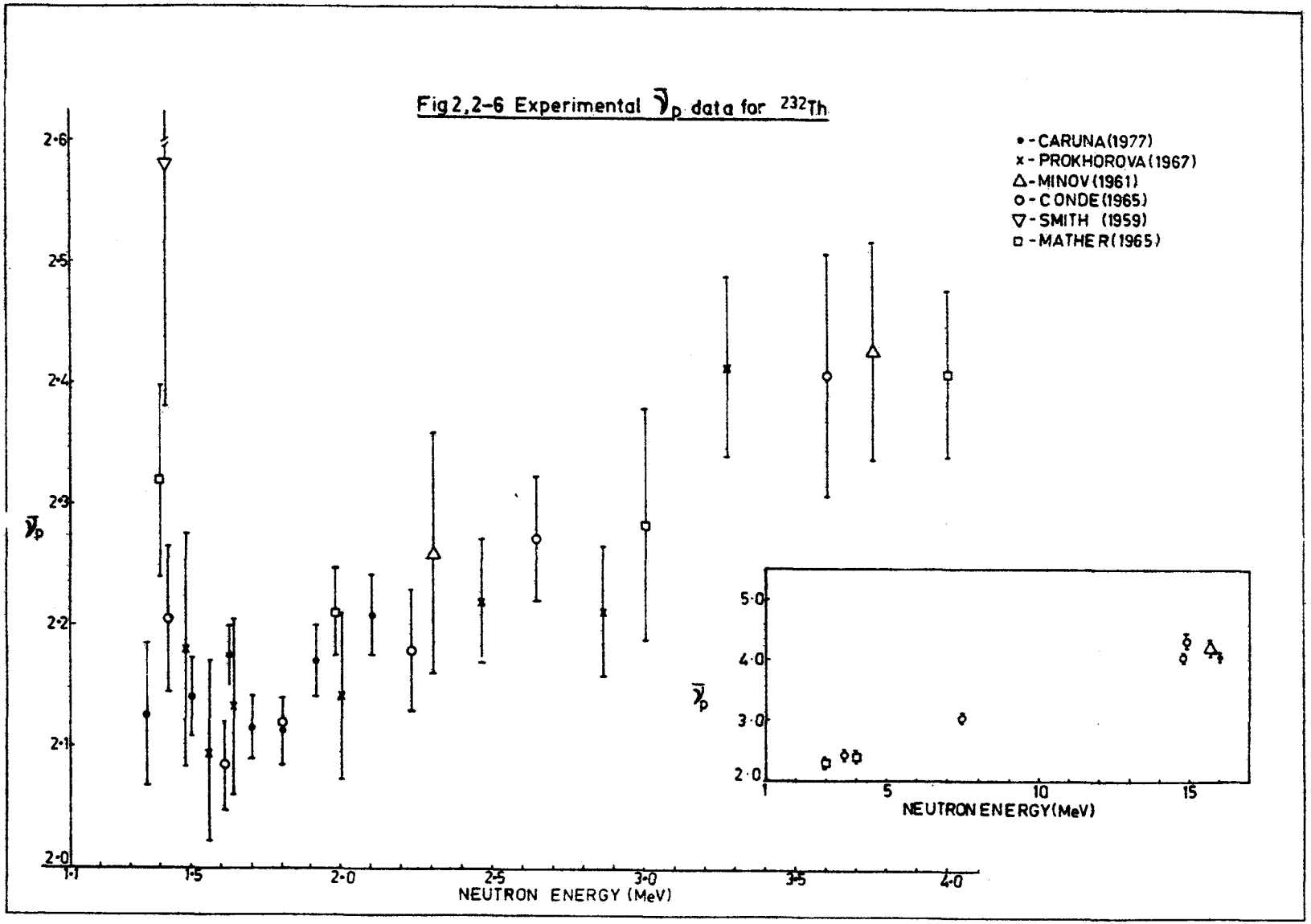
Fig 2,2-6 Experimental $\bar{\nu}_p$ data for ^{232}Th
• - CARUNA (1977)
x - PROKHOROVA (1967)
△ - MINOV (1961)
○ - CONDE (1965)
▽ - SMITH (1959)
□ - MATHER (1965)
$\bar{\nu}_p$
2·6
2·5
2·4
2·3
2·2
2·1
2·0
1·1
1·5
2·0
2·5
3·0
3·5
4·0
NEUTRON ENERGY (MeV)
5·0
4·0
3·0
2·0
1
5
10
15
NEUTRON ENERGY (MeV)

References

CARUNA (1977)

Caruna J., Boldeman J.W. and Walsh R.L.
Nucl. Phys. A285 (1977) 217

HOWERTON (1977)

Howerton R.J., Nucl. Sci. Eng., 62 (1977) 438

2.3 Thorium-233

This nuclide is produced by the neutron capture reaction on 232-Th and is the first important step towards production of the fissile isotope 233-U through the β^- decay of 233-Th. There is only one request in WRENDA for total; elastic, inelastic capture and fission cross sections with a required accuracy of 5% and priority two. There are no measurements reported in the fast energy region, which is understandable in view of the short half life of 22.2 min.

The only way to obtain required cross sections for both 231-Th and 233-Th is to estimate them theoretically. Utilising various systematics established for the neighbouring nuclides, CRAMER (1970) has estimated fission cross sections for both of this nuclides utilising the fission probabilities obtained through (t,pf) reaction on 230-Th and 232-Th and the compound nucleus formation cross section based on optical model. BEHERENS (1978) has similarly predicted fission cross section for 233-Th from systematics. Recently at B.A.R.C. a semiempirical expression has been developed and used to predict the fission cross section for 233-Th with an accuracy of about 15% [JINGHAN (1979)]. A more basic calculation has been done by JARRY (1977) involving more input information. Predicted cross section in this case is lower by about 15% compared to the semiempirical calculation.

References

CRAMER (1970)

Cramer J.D. and Britt H.C., Nucl. Sci. Eng., 41 (1970) 177

BEHRENS (1978)

Behrens J.W., Nucl. Sci. Eng. 65 (1978) 464

JINGHAN (1979)

Jinghan M.L., Anand R.P., Gupta S.K. and Mehta M.K. (To be published)

JARRY (1977)

Jarry J.
CEA-N-1971 (1977)

3. PROTACTINIUM ISOTOPES

3.1 Protactinium-231

From Fig. 1.1-1 we see that 231-Pa is produced by β^- decay of 231-Th following the (n,2n) reaction on 232-Th. 231-Pa is relatively stable and decays by alpha emission ($T_{1/2}$ = 3.25 x 10^4 yrs). Neutron capture reaction on this isotope produces 232-Pa which on β^- decay leads to the production of 232-U which pauses fuel handling problems. From basic physics point of view it can be noted that this nuclide has the smallest level spacing in this region of the periodic table.

The reactions of importance are (n, γ) and (n,f). There is only one WRENDA 76/77 request for capture cross section from 0.025 eV to 10 MeV with 10% accuracy and priority two.

There are no reported measurements for capture cross section for fast neutrons. However, there are some thermal measurements and the recent one reported by KOBAYASHI (1974) gives a value of 201 $\pm$ 6 barns. It can be seen that this cross section is quite high, especially compared to the cross section for 232-Th (7.35 $\pm$ 0.21 barns), and hence plays an important role.

Table 3.1-I Summary of ^{231}Pa fission cross-section measurements

Author / Reference	Energy range (MeV) Number of points	Type of measurement	Error reported	Technique
Williams (1944) LA-150, 4410	0.43-3.0 15	Ratio	3 to 9%	Ionization chamber $^{235}U(n,f)$, BNL-325(1965) standard ^{231}Pa $T_{\frac{1}{2}}$ = 32480y, α-counting used
Dubrovina (1964) J. Dok, 157, 561	0.133-1.73 49	Absolute	4 to 6 % above 0 5MeV	Ionization chamber ^{239}Pu also measured
Muir (1971) C.71KNOX, 1.292	0.1-2.965 374	Ratio	19% above threshold	Underground nucler explosion and time of flight Solid state detectors $^{239}Pu(n,f)$ NSE, 32(1968), 35- standard
Kobayashi (1975) RIK, 8,10	2.12-7.65 10	Absolute	6.6 to 13%	Charge particle reaction on(d,d) and(p,t) Silicon detectors $^{115}In(n,n')^{115m}In$- neutron flux moniter JNE, 27(1973) 741, standard ^{231}Pa-α counting
Iyer (1972) B.A.R.C-628	14 MeV 1	Ratio	10 %	Charge particle reaction (d,t) Fission track detector ^{238}U (n,f) standard
Sicre (1973)	0.1-1.3	Ratio	4 to 12% above threshold	Charge particle reaction $^{7}Li(p,n)$ Two Makrofel fission fragment detector ^{235}U (n,f) and ^{238}U(n,f) NSE 32(1968) 35, standard 10-15 keV resolution

The only cross section measurements in the fast region are for fission cross section and are summarised in Table 3.1-I. IGARASI (1975) has reviewed this nuclide in his review paper at the first TND advisory group meeting. There are some recent measurements which have been published subsequently [SICRE (1974), KOBAYASHI (1975)]. Data upto 1.4 MeV are shown in Fig. 3.1-1 which is taken from SICRE (1974). WILLIAMS(1944) and SICRE (1974) measurements seem to agree with each other, while DUBROVINA (1964) measurements are higher by 4 to 18%, the maximum discrepancy being between 0.8 to 1 MeV. MUIR (1971) data are even higher (7 to 35%) with respect to SICRE's measurements. In the high energy region KOBAYASHI (1975) has measured the cross section from 2.12 to 7.65 MeV and one measurement at 14 MeV has been reported by IYER (1972). The quoted errors are around 10%. Considering the discrepancy between the existing data sets, remeasurements are required especially upto 1.5 MeV. All data show peaks at around 300, 550 and 870 keV.

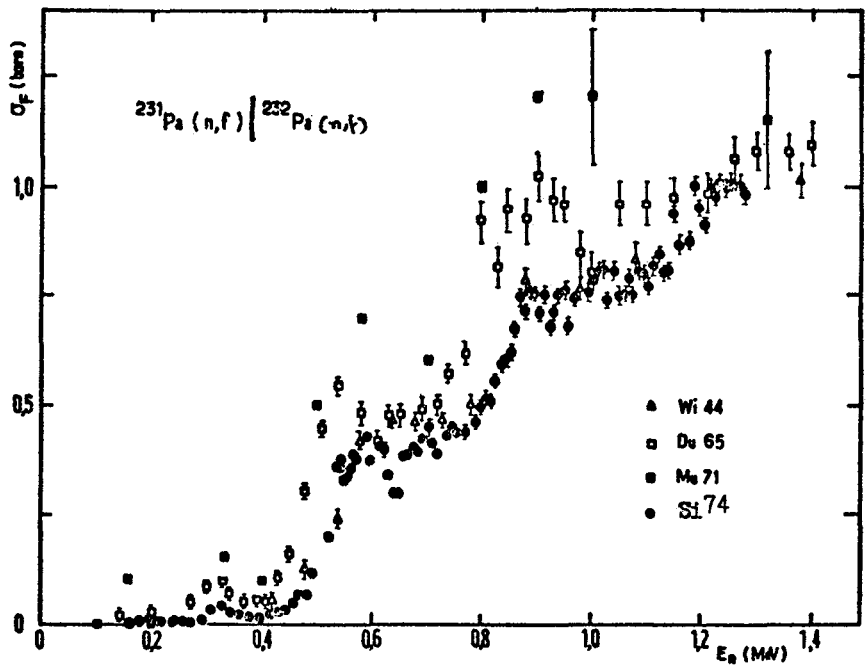

Fig.3.1-I The ^{231}Pa:^{232}Pa fission cross section ratio

These, along with the subthreshold fine structure observed by MUIR (1971) and SICRE (1974) could be interpreted in terms of the double humped fission barrier. Again, as discussed in the case of 232-Th, such interpretations are useful to determine the barrier parameters in this region.

There is one recent integral measurement by KOBAYASHI (1977) where he has compared the measured value (1087 ± 68 mb) with calculated values using various measured differential data. MUIR (1971) data yielded integral value (1040 mb) comparable to the measured one, while those of DUBROVINA (1964) and WILLIAMS (1944) yielded values lower by 8.5% and 21% respectively. No integral calculation is done with SICRE (1974) data.

There is one evaluation by DRAKE (1967), requoted by HINKELMANN (1970), which includes only WILLIAMS (1944) and DUBROUINA (1964) fission data and other cross sections are predicted using theoretical models.

References

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Sicre A., Barreau G., Chastel R. et al.
Proc. of a Symp. on Physics and Chemistry of Fission, at Rochester, Vol. I, IAEA-Vienna (1974) 71

KOBAYASHI (1975)

Kobayashi K., Kimura I., Gotoh H. and Yagi H.
Annu. Rep. Res. Reactor Inst., Kyoto Univ., 8 (1975) 10

WILLIAMS (1944)

Williams J.H., LA-150 (1944)

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Dubrovina S.M., Shigin V.A., Doklady Akad. Nauk, SSSR-157 (1964) 561

MUIR (1971)

Muir D.W., Veseer L.R., Conf. -710301, 3rd Conf. on Neutron Cross Sections and Technol., at Knoxville Vol. I (1971) 292

IYER (1972)

Iyer R.H., Sagu M.L. and Sampathkumar R. BARC-628 (1972) 94

KOBAYASHI (1977)

Kobayashi K., Kimura I., Annu. Rep. Res. Reactor Inst. Kyoto Univ. 10 (1977) 1

DRAKE (1967)

Drake M.K. and Nichols P.F., GA-7462 (1967)

HINKELMANN (1970)

Hinkelmann B. KFK-1186 (1970)

3.2 Protactinium-232

This isotope is formed by the capture reaction on 231-Pa and decays to 232-U. Because of the short half life of 1.32 days it does not remain long enough and hence the neutron cross sections for 232-Pa are not of much importance.

There are no WRENDA 76/77 requests for this nuclide.

Cross section measurements on such a short lived isotope would be difficult and would not be justified in view of the lack of general requirements. No measurements are reported in the fast energy region. However, one capture cross section measurement for thermal neutron has been reported by SMITH (1956) indicating a value of 760 ± 100 barns even higher than that for 231-Pa.

Reference

SMITH (1956)

Smith R.R.: Phys. Rev. 101 (1956) 1053

3.3 Protactinium-233

This nuclide is formed by the β^--decay of 233-Th ($T_{1/2}$ = 22.2 m) formed by capture reaction on 232-Th and is the intermediate step towards production of 233-U to which it decays by β^--emission with a half life of 27 days. Because of this relatively long half life, it creates special problems for the technology. Neutron capture by 233-Pa would generate a two fold loss towards the production of 233-U as a neutron would be lost as well as a parent nucleus for production of 233-U also will be lost.

There is one request for capture cross section with 10% accuracy and priority one and one request with 5% accuracy and priority two. There is only one request with 5% accuracy and priority two for fission and all other cross sections. There are no reported measurements which are difficult because of the relatively short half life. Theoretical calculations based on systematics and semiempirical expressions have been done at our laboratory for (n,2n), (n,3n) and fission cross sections which have been predicted with estimated uncertainties of 10 to 15% [JINGHAN (1978), JINGHAN (1979)]. OHTA(1973) have performed optical model calculationsto estimate all cross sections in the range 0-15 MeV.

References

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OHTA (1973)

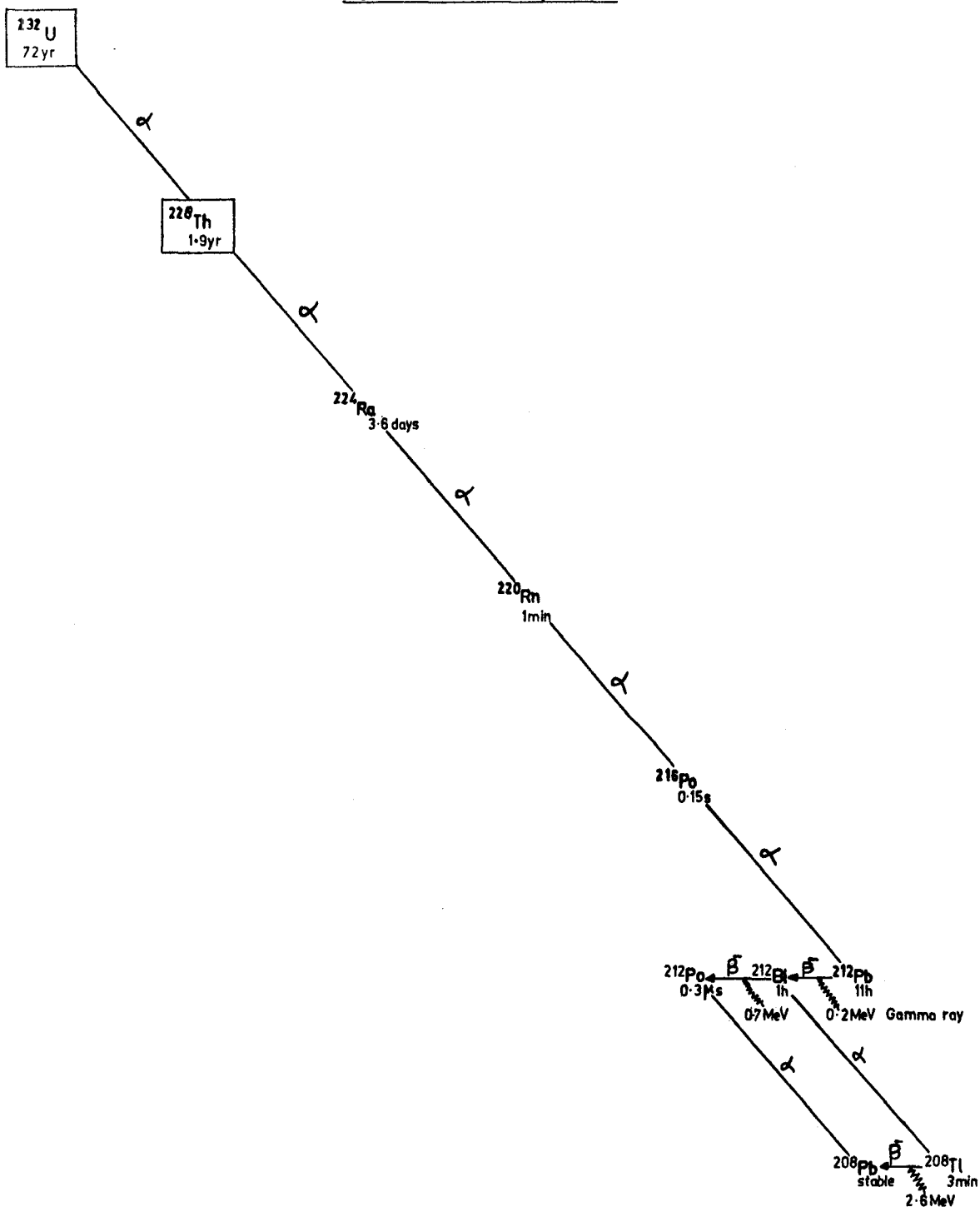
Ohta Masao and Miyamoto Keiji
Nucl. Sci. Tech. 10 (1973) 583

4. URANIUM ISOTOPES

4.1 Uranium-232

The importance of this isotope in this fuel cycle is mainly because of its nuisance value due to the hard gammas emitted by its decay products. The decay chain of 232-U is shown in Fig. 4.1-I. This nuclide is produced

Fig 4.1-1 ^{232}U decay chain



in the reactor by two main reaction sequences indicated by expressions 1.1 and 1.2. The actual amount of 232-U contained in the recycled fuel depends on the reactor type and neutron spectrum. This is one of a few even-mass nuclides which undergo thermal fission and has very striking resonance structure which are well resolved and hence easy to analyse.

There is one WRENDA 76/77 request for capture cross section from 0.5 keV to 10 MeV with 2 to 10% accuracy and priority two. There are no reported capture measurements in the fast energy region. There are two fission cross section measurements by FARELL (1970) for 10 eV-21 keV and by VUROTNIKOV (1971) for 0.1 to 1.5 MeV. These have been included in the earlier review by IGARASI (1975). There is no new information to be added to that review.

DRAKE (1967) has predicted capture and inelastic cross sections using theoretical models as discussed in the case of 231-Pa.

References

FARRELL (1970)

Farrell J.A. : LA-4420 (1970)

VOROTNIKOV (1970)

Vorotnikov P.E., Dubrovina S.M., Otroshchenko G.A., Shivin V.A., Davydov A.V. and Palshin E.S.
J. YF. 12 (1970) 474

DRAKE (1967)

Drake M.K., Nichols P.F. : GA-7462 (1967)

4.2 Uranium-233

There is no need to stress the importance of this nuclide for this fuel cycle. Like the other important nuclide 232-Th, the important cross section are (n,γ), (n,f), (n,2n).

There are three WRENDA 76/77 requests for the capture cross section with accuracy ranging from 3% to 20% with priority one. In addition the Japan [JERI-M-8062(1979)] list of requested data includes capture cross section between 1 and 20 MeV with 10% accuracy. There are some more lower priority requests in WRENDA 76/77 for similar accuracies. For fission cross section there are two requests in WRENDA 76/77 with 1.5 to 3% accuracy and priority one between 10 keV and 15 MeV (ratio to 235-U fission is preferred). WRENDA 76/77 has one request for (n,2n) cross section with 10% accuracy with priority one from threshold to 15 MeV and similarly Japan request list also include (n,2n) cross section upto 20 MeV with similar accuracy. There is one request with priority two for the total cross section with 5% accuracy upto 20 MeV. There is one request for prompt neutron emitted per fission ($\bar{\nu}_p$) with 0.5% accuracy and priority one from 50 keV to 5 MeV and one more request with priority two with 1% accuracy upto 10 MeV.

No measured data are reported for the capture and (n,2n) cross sections in this energy region. There is one measurement for fission spectrum averaged (n,2n) cross section by KOBAYASHI (1973). Measurements are reported for fission and total cross section and for $\bar{\nu}_p$ which are discussed in the following subsections.

4.2(a) Neutron total cross section

The most recent measurement has been that of POENITZ (1978). These are transmission measurement performed from 40 keV to 4.5 MeV with statistical uncertainty of 1.5%. These measurements are done with the same technique as used for 232-Th and referred to in that subsection. They are compared by POENITZ (1978) with earlier ones of STUPEGIA (1962) - from 10 keV to 1.6 MeV, FOSTER (1971) -

between 2.5 and 15 MeV with an accuracy of 2%, and GREEN (1971) - between 0.5 and 10 MeV. The data are higher by 5 to 10% compared to the older measurements of STUPEGIA (1962), but agree with later measurements of FOSTER (1971) and GREEN (1971). The ENDF/B-IV evaluation is lower by about 4 to 9%. POENITZ (1978) has referred to a private communication from MADLAND (1978) who has evaluated this cross section by fitting (1971) data with optical model. The measured data are 1 to 3% higher below 400 keV and 1 to 2% higher between 3 and 4 MeV compared to this evaluation. These latest data seem to meet the required and requested accuracy of 5%. Model calculation based on fits to these data should suffice in yielding the cross section for higher energy with sufficient accuracy.

References

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Foster D.G. and Glasgow D.W.
Phys. Rev., C3 (1971) 576

GREEN (1971)

Green L.
Proc. Third Conf. Neutron Cross Sections and Technology, Knoxville, Tennessee, 1971, CONF-710301 1 (1971) 325

4.2 (b) Fission Cross Section

PATRICK (1978) has reviewed the status of the data and there is no further information to be added to his

review. Table 4.2-I is a summary of all measurements. PATRICK(1978) has compared various ratio measurements. He has also multiplied the ratio measurement of CARLSON (1978) with the ENDF/B - V, 235-U (n,f) values and compared the results with absolute measurements of POENITZ (1978), GWIN (1976), NETTER (1956), ALLEN (1957), SMITH (1957) and KALENIN (1963). He finds that the recent ratio measurements agree within 2 to 3% from 100 keV upto about 7 MeV but at higher energy the spread is a little larger. The ratio measurements of CARLSON (1978), properly converted, agree with POENITZ (1978) within 3%, but around 3 MeV the difference is about 5% with POENITZ data being lower. Thus the quality of data suggests an overall accuracy no better than 3% when proper evaluation is carried out,which does not quite meet the required and requested accuracies.

References

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Patrick B.H., Review Paper "Fast Fission Cross Sections of the major transactinium isotopes" Proc. Int. Conf. on Neutron Physics and Nuclear Data for Reactors and other Applications, Harwell September 1978 (to be published)

CARLSON (1978)

Carlson G.W. and Behrens J.W.
Nucl. Sci. Eng., 66 (1978) 205

POENITZ (1978)

Poenitz W.P., ANL/NDM-36 (1978)

GWIN (1976)

Gwin R., Silver R., Ingle W. and Weaver H.
Nucl. Sci. Eng., 59 (1976) 79

NETTER (1956)

Netter F., Julien J., Corge C. and Ballini R.
J. Phys. et Rad., 17 (1956) 565

Table 4.2 - I Summary of ^{233}U fission cross section measurements

Author / Reference	Energy range (MeV) Number of points	Type of measurement	Error reported	Technique
William (1944) LA - 520	3.40 - 5.85 3	Ratio	-	Charged particle reaction $^{233}U(n,f)$: $^{235}U(n,f)$ data
Nyer (1950) LAMS-938	14 1	Ratio	-	Ionization chamber $^{238}U(n,f)$ standard
Lamphere (1956) PR, 104, 1654	0.005 - 3 96	Ratio	2 %	Charged particle reaction Back to back fission chamber Mass of deposition by α-counting $^{233}U(n,f)$: $^{235}U(n,f)$ data
Smith (1957) BAP. Soc. 2,196	2 - 10 19	Ratio Absolute	5 %	Charged particle reaction Back to back fission chamber $^{233}U(n,f)$: $^{238}U(n,f)$ data Using CH foil
Uttley (1956) AERE-NP/R-1996	14.1 1	Ratio	6 %	Back to back fission chamber $^{238}U(n,f) = 1.14 \pm 0.038$ standard
Allen (1957) PPS, 70A, 573	0.030 - 3 25	Absolute	1.5 %	Charged particle reaction Back to back fission chamber Normalised to 500 keV absolute value
Henkel (1957) LA-2114	0.003 - 6.95 49	Absolute	-	Ionization chamber Long counter
Kalinin (1958) 58 GENEVA. 16, 136	3.05 - 8.35 13	Absolute	-	Ionization chamber Long counter
Pankratov (1963) AE, 14, 177	9.05 - 21.6 10	Absolute	-	Time of flight
White (1967) JNE, 21, 671	1 - 14.1 4	Ratio	2 %	Charged particle reaction Back to back fission chamber $^{235}U(n,f)$ BNL-325 (1965) standard
Nesteron (1968) AE, 24, 185	0.485 - 2.5 4	Absolute	1 - 2 %	Charged particle reaction Ionization chamber and glass detector Normalized to thermal ratio

Table 4.2-I Contd. Summary of ^{233}U fission cross section measurements

Author / Reference	Energy range (MeV) No. of points	Type of measurements	Error reported	Technique
Pfletschiger (1970) NSE, 40, 375	0.005 - 1.01 49	Ratio	1.5 - 3 %	Charged particle reaction+TOF 4π-Argon filled gas Scintillation chamber Deposition mass by α-counting $^{233}U(n,f):^{235}U(n,f)$ data
Lehto (1970)	0.2 - 24 keV 26	Ratio	2 - 3 %	Slowing down lead spectrometer Back to back fission chamber $^{233}U(n,f):^{235}U(n,f)$ data
Meadows (1974) NSE, 54, 317	0.144 - 7.37 20	Ratio	1 %	Charged particle reaction Double ionization chamber(f.f.) Deposition mass by α-counting and thermal irradiation $^{233}U(n,f):^{235}U(n,f)$ data
Gwin (1976) NSE, 59, 79	0.005 - 0.2 12	Absolute	5 - 8 %	LINAC + TOF Ionization chambers, $^{10}Bo(n,\alpha)$ neutron monitor
Carlson (1978) NSE, 66, 205	0.001 - 30 107	Ratio	2 - 4 %	LINAC + TOF Ionization chambers (f.f.) Deposition mass by threshold method $^{233}U(n,f):^{235}U(n,f)$ data
Fursov (1978) AE, 44, 236	0.024 - 7.4 52	Ratio	1.2 - 1.4 %	Charged particle reaction Ionization chamber and Glass detector Normalized to thermal ratio (0.9293) $^{233}U(n,f):^{235}U(n,f)$ data
Poenitrg (1978) ANL / NDM - 36	0.130 - 8 52	Absolute	2 - 3 %	Charged particle reaction+TOF Back to back ionization chamber Deposition mass by α-counting and isotopic dilution method 3 Black neutron detector
James (1978) AERE PR/NP25 Priv. Commun.	0.1 - 20	Ratio	0.8 - 2.5%	Harwel synchrocyclotron Two gas scintillation chamber back to back

ALLEN (1957)

Allen W.D. and Ferguson A.T.G.
Proc. Phys. Soc., 70-A (1957) 573

SMITH (1957)

Smith R.R., Henkel R.L. and Nobler R.A.
Bull. Am.Phys. Society, 2 (1957) 196

KALENIN (1963)

Kalinin S.P. and Pankratov V.M., Proc. 2nd U.N. Int. Conf. Peaceful Uses of Atomic Energy, 16 (1958) 136

4.2 (c) Prompt Neutrons emitted per fission ($\bar{\nu}_p$)

There are a number of measurement between 100 keV to 2 MeV, only two measurements below 100 keV, one measurement at 3 MeV, three at 4 MeV and three measurements around 14 MeV. These are summarised in Table 4.2-II and shown in Fig. 4.2-1. Between 200 keV to 2 MeV, but for one point of HOPKINS (1963) at 1.08 MeV, the agreement between various measurements is within 1% as compared to the required accuracy of 0.5%. More data are required below 200 keV to confirm the dip indicated by BOLDEMAN (1976) data point at 150 keV and subsequent rise shown by NURPEISOV(1973) data point at 80 keV and SERGACHEV (1972) at 70 keV. The three data points at 4 MeV differ by 3% from each other. Same is the case for three data points at 14 MeV. The required accuracy is 1 to 3% in this energy range. Thus although the 4 and 14 MeV measurements satisfy the requirement marginally, more measurements are required to fill the gaps between 2 to 4 MeV and 4 to 14 MeV. Recently HOWERTON (1977) has calculated this number empirically upto 4 MeV. His values differ by 1 to 6% from the measured values.

References

HOPKINS (1963)

Hopkins J.C. and Diven B.C.
Nucl. Phys., 48 (1963) 433

Table 4.2 - II Summary of ^{233}U - ν_p measurements

Author / Reference	Energy range (MeV) Number of points	Type of measurement	Error reported	Technique
SMIRENKIN (1958) AE, 4, 188	4 - 15 2	Ratio	4 - 5 %	Coincidence counting ^{233}U, $\overline{\nu}_{th}$ = 2.497
PROTOPOPOV (1959) AE, 5, 71	14.8 1	Ratio	10 %	Ionization chamber ^{233}U, $\overline{\nu}_{th}$ = 2.52
FLEROV (1961)	14 1	Absolute	5.7 %	Spherical shell transmission
HOPKINS (1963) NP, 48, 433	0.28 - 3.93 5	Ratio	1.5 - 1.7 %	Charged particle reaction Coincidence between double fission chamber (f. f.) and liquid scintillator tank (f. n) ^{252}Cf. Sf. $\overline{\nu}_p$=3.771 standard
MATHER (1965) NP, 66, 149	0.96 - 4.0 4	Ratio	1.6 %	Same as HOPKINS (1963) ^{252}Cf. Sf. $\overline{\nu}_p$= 3.782
BOLDEMAN (1970) JNE, 25, 321	0.3 - 1.870 7	Ratio		Same as HOPKINS (1963) ^{252}Cf. Sf. $\overline{\nu}_p$= 3.782
SERGACHEV (1972) YF, 16, 475	0.07 - 2.14 19	Absolute	0.6 - 0.8 %	Charged particle reaction ^{7}Li (p, n), (d-d) and (p-T) Coincidence between Silicon detector (f. f.)
KOLOSOV (1972) AE, 32, 83	0.07 - 1.56 15	Ratio	0.6 - 0.8 %	Method not given Relativ to $\overline{\nu}$ for ^{233}U at thermal energy

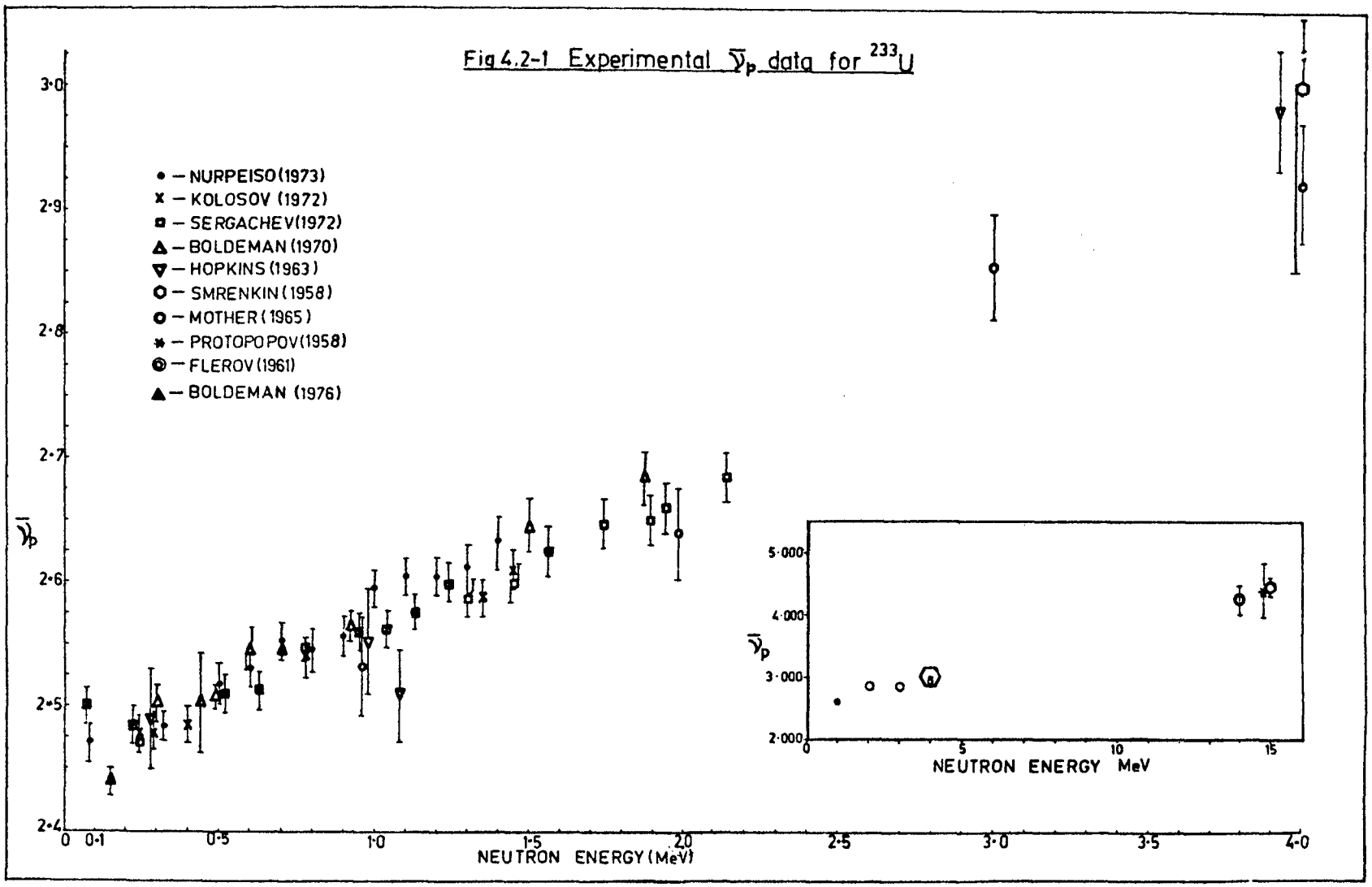
Fig 4.2-1 Experimental $\bar{\nu}_p$ data for ^{233}U
• — NURPEISO (1973)
× — KOLOSOV (1972)
▫ — SERGACHEV (1972)
△ — BOLDEMAN (1970)
▽ — HOPKINS (1963)
○ — SMRENKIN (1958)
○ — MOTHER (1965)
✱ — PROTOPOPOV (1958)
◎ — FLEROV (1961)
▲ — BOLDEMAN (1976)
$\bar{\nu}_p$
NEUTRON ENERGY (MeV)
NEUTRON ENERGY MeV

BOLDEMAN (1976)

Boldeman J.W., Bertram W.K. and Walsh R.L.
Nucl. Phys. A265 (1976) 337

NURPEISOV(1973)

Nurpeisov B., Nesterov V.G., Provkhorova L.I.,
Smirenkin G.N. : Atomnaya Energiya 34 (1973) 49

SERGACHEV (1972)

Sergachev A.I., Dojachenko N.P., Kovalov A.M.
and Kuzpminov B.D. : J.Y.F, 16 (1972) 475

HOWERTON (1977)

Howerton R.J. : Nucl. Sci. Engineering, 62 (1977)438

4.3 Uranium-234

This is one of the two long lived (T_{y2} = 2.5 x 10^5 yrs) important nuclides produced in this fuel cycle, the other being 233-U (T_{y2} 1.6 x 10^5 yrs). It is a fertile nuclide like 232-Th but does not affect the conversion ratio for 233-U production. It has a fission threshold lower than 232-Th and plays a role in detailed reaction calculations.

There are three WRENDA 76/77 requests for (n,γ) and two for (n,f) cross section with accuracies 5 to 15% upto 20 MeV and priority two. There is one request for (n,2n) and (n,3n) cross section with accuracy of 10% upto 15 MeV with priority one.

IGARASI (1975) has reviewed this nuclide at the last Advisory Group meeting. There are no reported capture and (n,2n) and (n,3n) measurements. A number of (n,f) measurements are reported and IGARASI (1975) has reviewed the status upto 1974 in his paper at the last Advisory Group meeting. Two recent measurements have been reported by BEHRENS (1977) between 0.1 to 30 MeV and MEADOWS (1978) from 0.6 to 9.84 MeV. The latter measurement quotes an

accuracy of 1.5% while BEHREN (1977) data have accuracies ranging from 1 to 4%. All the measurements are summarised in Table 4.3-I. Comparison of MEADOWS (1978) data with all the other measurements, except for those of BABCOCK (1961) is shown in Fig. 4.3-I which is taken from MEADOWS (1978). All measurements have comparable errors. LAMPHERE (1962) data have the same shape but are lower by 5%. One data point at 2.25 MeV of WHITE (1967) is lower by 5%. BEHREN (1977) data are consistently lower by about 2% between 1 and 3 MeV and by lesser difference between 8 and 10 MeV. However, in the 3 to 6 MeV region the difference is almost 5%. This difference is larger than the quoted systematic errors can account for. Considering the requested accuracies of 5 to 15%, the existing new data can be considered to be satisfactory, but a proper reevaluation of the data is necessary. Earlier evaluation by DAVEY (1966) is based on older data.

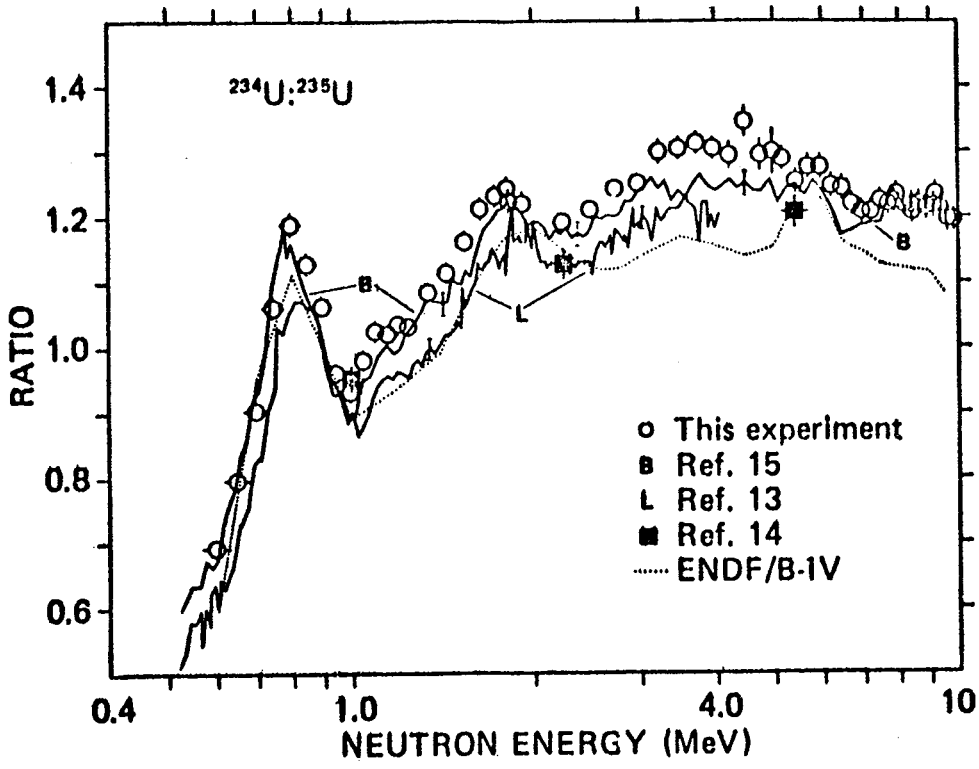

Fig.4.3-I. The $^{234}U:^{235}U$ fission cross-section ratio.

Table 4.3-I. Summary of ^{234}U fission cross-section measurements

Author / Reference	Energy range (MeV) Number of points	Type of measurement	Error reported	Technique
Babcock (1961) EXFOR 12294004, 5	13 - 18 5 0.35 - 1.88 10	Ratio	6 - 25 % 8 - 25 %	Charge particle reaction $^{12}C(d,n)$ $^{238}U(n,f)$, BNL-325 (1958) standard
Lamphere (1962) NP, 38, 561	1.350 - 4.05 91 0.136 - 0.606 28 0.501 - 0.756 5 0.565 - 1.33 4.0	Ratio	1 - 2 %	Charge particle reaction $^{7}Li(p,n)$, $^{3}H(p,n)$ Back to back fission chamber $^{235}U(n,f)$, BNL-325 (1965) standard
White (1967) JNE 21, 671	0.067 - 0.5 4 1 - 14.1 3	Ratio	3 - 4 %	Charge particle reaction Back to back fission chamber $^{235}U(n,f)$, BNL-325 (1965) standard
Behrens (1977) NSE, 63, 250	0.104 - 33.7 155	Ratio	4% 104-250 keV 1-2% 0.3-12 MeV 4% above 12 MeV	Time of flight, LINAC Back to back fission chamber $^{234}U(n,f):^{235}U(n,f)$ ratio data reported Threshold method for mass of deposition
Meddows (1978) NSE, 65, 171	0.598 - 9.84 58	Ratio	~ 1.5 %	Charged particle reaction Back to back fission chamber $^{234}U(n,f):^{235}U(n,f)$ ratio data reported α-Counting or thermal fission ratios for mass of deposition

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Present Status, Critical Comparison and Assessment of Different Evaluations and Files of Neutron Cross-Section Data for Selected Actinides

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Abstract

This review is limited to fission and capture cross sections of ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{244}Cm and ^{245}Cm. Brief survey is presented concerning neutron nuclear data evaluation at major laboratories, on the basis of their contribution to this review and available literatures. Intercomparison is made among evaluated data, and the present status of the data is assessed by comparing with users' needs.

1. Introduction

Since the first IAEA meeting[1] on the transactinium isotope nuclear data (TND) held at Kernforschungszentrum Karlsruhe in 1975, many evaluation works have been performed, especially for the higher plutonium, americium and curium isotope nuclear data. Measurements of the cross sections for transactinium isotopes have been also made vigorously at many laboratories. Some of them were reported at the meetings held recently at Brookhaven National Laboratory and at Atomic Energy Research Establishment Harwell. Although the proceedings of these meetings are not yet received by the authors, some topics will be picked up in this review from the copies of the contributed papers to the meetings.

The present review is mainly based on the works performed at the following laboratories: Argonne National Laboratory (ANL), Atomic Energy Research Establishment Harwell (HAR), Brookhaven National Laboratory (BNL), Centre d'Etudes de Bruyères-le-Châtel (BRC), Centre d'Etudes Nucleaires de Cadarache (CAD), Comitato Nazionale Energia Nucleare Bologna (BOL), Hanford Engineering Development Laboratory (HED), Israel Atomic Energy Commission (ISL), Japan Atomic Energy Research Institute (JAE), Kernforschungszentrum Karlsruhe (KFK), Lawrence Livermore Laboratory (LRL), Los Alamos Scientific Laboratory (LAS), Nippon Atomic Industry Group Co. Ltd. (NIG), Oak Ridge National Laboratory (ORL) and Savannah River Laboratory (SRL).

Laboratory codes in parentheses are quoted from CINDA and WRENDA.

The evaluated nuclear data libraries or files*) cited in this review are ENDF/B, ENDL, JENDL, KEDAK and UKNDL. ENDF/B includes evaluations made at ANL, HED, LAS, LRL, ORL, SRL and other institutes and laboratories in USA. A special purpose file of TND in the newest version of ENDF/B (ENDF/B-V) has been informed recently for this review work. A new version of ENDL (ENDL 78) was also presented to this review. JENDL-2 is scheduled to release at the end of 1979, and the present status is at the stage of the data storage to the files. In the next chapter, nuclides included in these libraries and files will be shown. Also, a comparison will be made between users' needs for the nuclear data and the status of the evaluated data files.

In this review, the capture and fission cross sections of ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{244}Cm and ^{245}Cm are selected to do comparison and assessment of the evaluated data. Nuclear data for ^{240}Pu, ^{241}Pu and ^{242}Pu were newly evaluated[2] at KFK. Evaluations for these higher plutonium isotope nuclear data were also performed at BRC[3], HED[4,5], LAS[6], BOL[7,8], NIG[9,11,12] and JAE[10-12]. The present review will make comparison of these data in graphic form in chapter 3.

Nuclear data for ^{241}Am in UKNDL were revised recently[13], and were presented for this review. New evaluations of americium and curium isotope nuclear data were made at HED[4,5,14], BOL[15,16], CAD[17], and SRL[18-20]. Evaluations at BOL, CAD and SRL are mainly for the resonance parameters. Old evaluations[21-23] for ^{241}Am and ^{243}Am at JAE are presented in this review. Evaluations for ^{244}Cm and ^{245}Cm nuclear data were also made at JAE[24,25]. New measurements on ^{245}Cm fission cross section at RPI[26] were presented for this review.

New evaluations for ^{232}Th and ^{237}Np nuclear data were contributed to this review from ANL[27] and ISL[28], respectively. Also, many experimental information were presented from KFK[29-34].

2. Status of Evaluations and Files.

At the previous meeting, Yiftah made many valuable recommendations concerning nuclear data evaluations, one of which was "the world transactinium nuclear data evaluation program" to be sponsored and coordinated by the IAEA. This idea has led to the formation of the IAEA Coordinated Research Programme on the Intercomparison of Evaluations of Actinide Neutron Nuclear Data, and has stimulated nuclear data evaluations of the transactinium isotopes.

Yiftah reported in his previous review paper[1] that, out of 72 transactinium nuclides which have longer half-lives than one day, 24 isotopes had been made evaluations of their nuclear data. Today, the evaluated nuclear data for 48 isotopes are compiled in the big nuclear

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*) Although UKNDL-73 data may be old, they are quoted to show the present status of the latest version of the big files.

data files or libraries. Table 1 shows the nuclides in each evaluated nuclear data library.

Users' needs for the nuclear data are shown in WRENDA 76/77.[35] Table 2 shows the requested quantities in WRENDA 76/77, except for the Japanese requests which are quoted from the newest Japanese List of Requests for Nuclear Data.[36] These are not always the requests for evaluation. It is also shown in Table 2 whether the evaluated nuclear data libraries include the data files of nuclides requested in WRENDA 76/77. Except for ^{245}Pu and ^{244}Am, the requested nuclides are filed, at least, in one of these libraries. Some nuclides in Table 1 do not appear in Table 2. They are ^{228}Th, ^{230}Th, ^{231}Th, ^{234}Th, ^{239}U, ^{240}U, ^{243}Pu, ^{244}Pu, ^{241}Cm, ^{248}Cm, ^{249}Cf, and ^{253}Cf. This may imply that the evaluation of the transactinium isotope nuclear data is ahead of the users' needs concerning nuclides. However, at the previous meeting, these 12 nuclides were not assigned first priority for doing evaluation of their nuclear data. Table 2 shows that the users' needs concentrate on the data of the fission and capture cross sections for the higher plutonium, americium and curium isotopes.

It was stressed at the previous meeting that the evaluated nuclear data of higher plutonium isotopes ^{240}Pu, ^{241}Pu and ^{242}Pu should be revised and updated at regular intervals of two to three years. Since 1975, there have been many evaluation works for these three isotopes.

In this review, the fission and capture cross sections for these three nuclides are taken into account selectively as well as those for ^{241}Am, ^{243}Am, ^{244}Cm and ^{245}Cm which were also stressed to be evaluated in the previous meeting. The followings are brief survey of evaluation works for these seven isotopes in each laboratory, on the basis of referring to their reports.[2-25]

KFK (Kernforschungszentrum Karlsruhe)

Recent evaluation at KFK was reported at the BNL meeting. According to ref.2), the capture cross sections of ^{240}Pu were obtained on the basis of the experimental data of Hockenbury et al.[37] and Weston and Todd.[38] The evaluated capture cross sections in keV region were in good agreement with the recent experimental data of Wisshak and Käppeler.[29] The new evaluated data were about 30 - 50 % higher than the old evaluation.

The capture cross sections of ^{241}Pu were evaluated on the basis of the experimental data by Weston and Todd.[39] The new evaluation was lower than the old version. The data of ^{242}Pu capture cross section in KEDAK were revised from 500 eV to 200 keV by using the experimental data of Wisshak and Käppeler.[29] The new evaluation was 30 - 50 % higher than the old version. The capture cross sections for ^{240}Pu and ^{242}Pu were transcribed from the figures given in ref.2) for comparison with other evaluated data in the next chapter.

HED (Hanford Engineering Development Laboratory)

Mann and Schenter[4,5,14] made evaluations on nuclear data above 1 keV of 16 transactinium isotopes: ^{234}U, ^{236}U, ^{237}Np, ^{236}Pu, ^{237}Pu, ^{238}Pu, ^{242}Pu, ^{244}Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{241}Cm, ^{242}Cm, ^{243}Cm, ^{244}Cm and ^{248}Cm. The fission cross sections of ^{242}Pu were evaluated on the basis of the experimental data of Fomushkin et al.[40,41], Bergen and Fullwood[42], Auchampaugh et al.[43], and Behrens et al.[44], above 100 keV. The statistical model calculations[45] were used below 100 keV where the uncertainties of the experimental data were large. The new evaluation agreed well with ENDF/B-IV from 200 keV to 2 MeV, but was lower about 50 % below 200 keV and 2 - 6 MeV regions.

The capture cross sections of ^{242}Pu were calculated by a statistical model code HAUSER*4.[45] The radiative width for the calculation was normalized to the experimental data of Hockenbury et al.[46] The new evaluation was about a factor of 2 higher than the ENDF/B-IV data below 1 MeV.

The low energy capture and fission cross sections were taken from SRL evaluation.[47]

The fission cross sections of ^{241}Am were obtained by the statistical model calculation below 100 keV. The cross-section curve passed near the data of Bowman et al.[48] and of Shpak et al.[49] The evaluation above 400 keV was made by following the experimental data of Shpak et al., Seeger et al.[50], Fomushkin et al.[40,41], and Iyer and Sampathkumar.[51]

The capture cross sections of ^{241}Am as well as the branching to the ^{242}Am ground and isomeric states were calculated by using HAUSER*4. The radiative width for the calculation was normalized so that the calculated capture cross sections might fit the data of Weston and Todd.[52]

The fission cross sections of ^{243}Am were evaluated on the basis of the data of Seeger[53] and of Fomushkin et al.[41] The new evaluation was about 20 % higher than the ENDF/B-IV data over the threshold rise and plateau regions. The capture cross sections of ^{243}Am were obtained by the HAUSER*4 calculations. The low energy fission and capture cross sections were from SRL evaluation.[47]

For ^{244}Cm fission cross sections, HED evaluation followed the experimental data of Moore and Keyworth.[54] The data of Koontz and Barton[55], and of Fomushkin and Gutnikova[40] at 14 MeV were also used. The capture cross sections were from HAUSER*4 calculations. The low energy fission and capture cross sections were from SRL evaluation.[56]

LAS (Los Alamos Scientific Laboratory)

Madland and Young[6] evaluated the nuclear data of ^{242}Pu from 10 keV to 20 MeV. Except for the fission and capture cross sections, only nuclear model calculations were used to derive the evaluated data. These data were combined with the data below 10 keV from the evaluation by Mann and Schenter.[5]

The capture cross sections were obtained on the basis of the statistical model calculations. The experimental data by Hockenbury et al.[46] were used in normalizing the calculated data. They mentioned in ref. 6) that, in spite of normalizing to the same experimental data, the result of the LAS evaluation deviated from that of HED.

The fission cross sections were evaluated by using the experimental data of Auchampaugh et al.[43] in the energy region of 10 - 100 keV, and the data of Behrens et al.[57] from 100 keV to 20 MeV. The evaluations were made for the (n,f), (n,n'f) and (n,2nf) reactions using the Hill-Wheeler approach with single-hump, one-dimensional fission barriers. Parameters for the fission barriers were optimized by fitting the calculated cross sections to the experimental data mentioned above. The result of LAS evaluation was similar to that of HED.

BRC (Centre d'Etudes de Bruyères-le-Châtel)

Jary et al.[3] gave their preliminary evaluation of ^{242}Pu to this review. They performed the evaluation mainly based on the deformed optical and statistical models with parameters obtained by the use of ^{232}Th, ^{238}U and ^{240}Pu experimental data. The evaluated data were obtained in the energy region of 10 keV - 20 MeV, and were combined with the data of ENDF/B-IV below 10 keV.

The barrier heights and the effective numbers of fission channels were obtained by adjusting the calculated fission cross sections to the experimental data.[44,57] In this calculation, the neutron transmission coefficients were obtained from the coupled channel optical model calculations. The radiative widths were adopted from the values given by Lynn[58] for ^{242}Pu and the data of Auchampaugh et al.[59] for ^{240}Pu.

The results of the evaluated fission cross sections were in good agreement with the experimental data for ^{240}Pu and ^{242}Pu. For the capture cross sections, the evaluation was lower than the experimental data for ^{240}Pu below 200 keV. The evaluated capture cross sections for ^{242}Pu were in agreement with the experiment around 50 keV, but lower below 30 keV.

BOL (Comitato Nazionale Energia Nucleare, Bologna)

Menapace et al.[7,8,16] performed evaluation for ^{241}Pu, ^{242}Pu and ^{242}Cm neutron cross sections in the resonance region. Maino et al.[15] also made evaluation for ^{241}Am.

The cross sections for ^{241}Pu were treated by Reich-Moore formalism in the resolved resonance region from 0.26 to 104 eV, and by the statistical model from 104 eV to 40 keV of the unresolved resonance region. The resonance parameters were taken from the experimental data by Blons and Derrien.[60] The spin assignment was made by assuming the average radiative width to be 40 meV. The unresolved resonance parameters were chosen so

as to reproduce the capture and fission cross sections, and the alpha-values measured by Weston and Todd.[61] The average level spacing, neutron strength functions and scattering radius were assumed as the following values: $\overline{D}$ = 0.83 eV, $S_0 = 1.18 \times 10^{-4}$, $S_1 = 2.2 \times 10^{-4}$, $S_2 = 3.4 \times 10^{-4}$ and R' = 9.6 fm, respectively.

The resolved resonance parameters for ^{242}Pu were evaluated from 0 to 1.3 keV. Except for the fission widths, the resonance parameters were mainly from Poortmans et al.[62] The fission widths were deduced from the fission areas given by Auchampaugh et al.[43], and by Bergen and Fullwood.[42] The complete set of parameters given by Auchampaugh and Bowman[63] were also accepted. The parameters of the bound level were chosen in order to reproduce a thermal capture cross section of 18.5 barns.[64] Menapace et al. adopted the radiative width of 25 meV which reproduced well the total and capture cross sections from 5 to 90 keV. Subthreshold fission structure was discussed, and the fission widths of 0.94 meV at 474.6 eV and of 256 meV at 762.5 eV were adopted. Recommended average resonance parameters thus obtained were as follows: D_{obs} = 15 eV, $S_0 = 1.15 \times 10^{-4}$, $S_1 = 2.7 \times 10^{-4}$, $\overline{\Gamma}_\gamma$ = 25 meV and R' = 9.6 fm.

Maino et al.[15] chose the resolved resonance parameters for ^{241}Am mainly from the works of Derrien and Lucas[65], and Weston and Todd.[66] They tabulated the parameters up to 150 eV. The parameters for a bound level were adopted from Kalebin[1]. The parameters for the lowest two resonances were from Weston and Todd.

The unresolved resonance parameters were given in the energy region of 150 eV - 10 keV. They were obtained so as to reproduce the total cross sections by Derrien and Lucas, the capture cross sections by Weston and Todd, and the fission cross sections by Gayther and Thomas[67], and Shpak et al.[49] The following parameters were assumed in order to search for the unresolved resonance parameters: $\overline{D}$ = 0.58 eV, $S_0 = 0.95 \times 10^{-4}$, $S_1 = 2.5 \times 10^{-4}$, and $S_2 = 0.94 \times 10^{-4}$.

CAD (Centre d'Etudes Nucleaires de Cadarache)

According to ref.17), a great effort had been made at Cadarache for making new computer codes and improving the existing codes for evaluation of the actinide neutron cross sections. In the resonance region, both single-level and multilevel formalisms were used, and the average resonance parameters were also evaluated by a computer code. The unresolved resonance parameters were calculated on the basis of the Hauser-Feshbach formalism with input of the neutron strength functions or neutron transmission coefficients.

Derrien et al.[17] made evaluation of the resonance parameters for ^{241}Am. Their recommended resonance parameters in the energy region of 1 - 50 eV were based on the experimental data by Derrien and Lucas.[65] The absorption cross sections of Weston and Todd[66], the total cross

sections reported by Kalebin[1], and the fission cross sections of Gayther and Thomas[67] were also taken into account. From 50 to 150 eV, only the data of Derrien and Lucas were available. The absorption cross section at 0.0253 eV was reproduced by the single-level Breit-Wigner formula with their recommended resonance parameters, along with negative levels and a smooth background of $20.5/\sqrt{E}$.

Derrien et al.[17] reported their evaluation for the corss sections from 1 keV to 1 MeV. The statistical model calculations were performed with the following parameters: D_0 = 0.55 eV, $\overline{\Gamma}_\gamma$ = 43.7 meV, $S_0 = 0.94 \times 10^{-4}$, $S_1 = 2.54 \times 10^{-4}$, $S_2 = 0.94 \times 10^{-4}$, $S_3 = 2.54 \times 10^{-4}$ and R' = 9.36 fm.

SRL (Savannah River Laboratory)

Recent evaluations of neutron cross sections at SRL were for ^{242}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm, ^{248}Cm and ^{249}Bk. Results for ^{244}Cm, ^{246}Cm and ^{248}Cm were reported in ref.18).

The experimental data used for the evaluation of ^{244}Cm in the resonance and thermal regions were collected from the measurements by Coté et al.[69], Berreth et al.[70] and Simpson et al.[71] The cross sections below 525 eV were calculated by the single-level Breit-Wigner formula. A bound level was taken into account. The unresolved resonance region was defined from 525 eV to 10 keV. The cross sections above 10 keV were taken from ENDF/B-IV, and were joined to the cross sections below 10 keV.

Evaluation of ^{245}Cm neutron cross sections was recently performed below 10 keV, using the recent experimental data by Browne et al.[72] and by Moore and Keyworth.[54] The resolved resonance parameters were given for 38 S-wave resonances and one bound level from 10^{-5} eV to 60 eV. The unresolved resonance parameters were given from 60 eV to 10 keV. A reasonable match was obtained between the calculation with these parameters and the recent fission measurements of Nakagome and Block[26].

ORL (Oak Ridge National Laboratory)

Evaluation for ^{240}Pu and ^{241}Pu were performed by Weston and his coworkers. Weston[73] reviewed the microscopic neutron cross sections for ^{240}Pu, ^{241}Pu and ^{242}Pu in the resonance region.

Though there were some discrepancies among the experimental data in the higher resonance region, their evaluations might be performed on the basis of recent measurements by Weston and Todd[38], Hockenbury et al.[37] and Wisshak and Käppeler[30] for ^{240}Pu capture cross section, and by Weston and Todd[61] for ^{241}Pu capture cross section. For the fission cross section of ^{241}Pu, there were many measurements with reasonable certainty below 20 eV. From 100 eV to 40 keV, the agreement between experimental fission cross sections was only about 10 %. Taking these data discrepancies into account, they adopted the data by Weston and Todd[61] for their evaluation of the fission cross sections of ^{241}Pu.

JAE (Japan Atomic Energy Research Institute)

Evaluation works on neutron nuclear data in Japan have been carried out for compilation of Japanese Evaluated Nuclear Data Library (JENDL). The first version[12] of JENDL (JENDL-1) has been already released, and the second version (JENDL-2) is now at the stage of compilation.

Evaluations[10-12, 21-25] for ^{241}Pu, ^{241}Am, ^{243}Am, ^{244}Cm and ^{245}Cm nuclear data were made at JAE. Kikuchi[10-12] made evaluation of ^{241}Pu nuclear data for JENDL-1. Selecting some reliable experimental data from old measurements and adding recent data, he performed reevaluation for JENDL-2. He selected the fission cross sections by Weston and Todd[61], Blons[74], Migneco et al.[75], James[76], and Carlson et al.[77] in order to obtain a weighted mean cross section from 100 eV to 1 keV. He gave a weight factor of 0.5 to the data of Migneco et al. and of James, and a factor of 1.0 to the other data. From 1 to 10 keV, he averaged the data by Weston and Todd[61], and by Blons.[74] Taking the data by Carlson et al.[77] into account, he modified slightly the average cross sections. Above 10 keV, he obtained the evaluated cross sections by following the experimental data of Weston and Todd, Blons, Carlson et al., Szabo et al.[78], Carlson and Behrens[79], and Käppeler and Pfletschinger[80]. The last two experiments of these were the ratio measurements relative to the fission cross sections of ^{235}U. He used Matsunobu's evaluation[81] of ^{235}U fission cross sections which will be compiled in JENDL-2 file.

The capture cross sections of ^{241}Pu were obtained from 100 eV to 250 keV by multiplying the data of relative measurements[61] by the fission cross sections[81] of ^{235}U. Above 250 keV, he calculated the capture cross sections with the statistical model.

The fission cross sections of ^{241}Am were overestimated below 300 keV in the old evaluation[21], because the evaluation was much dependent on the experimental data of Seeger et al.[50] which were erroneously high below several hundred keV. Structure shown in the data might be also erroneous. The data of JENDL-1[12,22] were obtained by multiplying the old data by an energy dependent factor to reduce the high values below 100 keV. The recent experimental data[33,68], however, reveal no such structure as that shown in Seeger et al. Therefore, reevaluation is necessary to improve the data in keV region. Besides, some valuable experimental data[1,67,82,83] are reported in thermal and MeV regions. In particular, the total cross sections[83] are useful to determine a set of the optical potential parameters. The reevaluation at JAE has started with looking for a new set of the potential parameters.

There are similar drawbacks[23] in ^{243}Am fission cross sections evaluated at JAE. The evaluation was dependent on the experimental data by Seeger[53] which showed large fission cross sections below 10 keV. A structure near 150 keV is doubtful. Reevaluation is going to be performed by taking a recent experiment[84] into account.

The capture cross sections of ^{241}Am and ^{243}Am were obtained by the statistical model calculations. The results were in good agreement with the experimental data for ^{241}Am by Weston and Todd[52]. The resolved resonance parameters for ^{241}Am were mainly taken from Derrien and Lucas[65]. For the resolved resonance parameters of ^{243}Am, the data by Simpson et al.[85] were adopted. Fictitious large fission widths were added in order to reproduce large erroneous fission cross sections below 10 keV. This is one of the drawbacks to be improved in the reevaluation.

Resolved resonance parameters for ^{244}Cm were taken from Moore and Keyworth[54] above 20 eV. The lowest two levels and a negative level were adopted from Benjamin et al.[18] The resolved resonance parameters were given below 1 keV. The cross sections were calculated with the single-level Breit-Wigner formula and appropriate background cross sections. The fission cross sections above 1 keV were obtained by the least-squares method based on the experimental data by Moore and Keyworth, Koontz and Barton[55], and Fomushkin et al.[41] The capture cross sections were calculated by the statistical model. The following parameters were used in the calculation: $\overline{\Gamma}_\gamma$ = 37 meV and $\overline{D}$ = 14.0 eV.

Resonance parameters for ^{245}Cm were given in the energy region below 60 eV. From 20 to 60 eV, the parameters were taken from Moore and Keyworth[54], and the cross sections were calculated by the Reich-Moore formula. Below 20 eV, the parameters were from Browne et al.[72], and the cross sections were obtained by the single-level Breit-Wigner formula. The calculated cross sections were joined smoothly around 20 eV. In order to save the computer time, it is desirable that the resonance cross sections are calculated by the single-level formula. In JENDL, the resonance parameters of ^{245}Cm were given for the single level formula, and the differences between multilevel and single-level cross sections were added as the background cross sections.

The fission cross sections above 50 eV were obtained by the least-squares method based on the data by Moore and Keyworth. The capture cross sections were calculated by the statistical model with the parameters $\overline{\Gamma}_\gamma$ = 40 meV and $\overline{D}$ = 1.8 eV. The evaluated fission cross sections from 100 eV to 30 keV seem to be a little smaller than the recent experimental data[26] at RPI.

NIG (Nippon Atomic Industry Group Co. Ltd.)

Murata[11,12] made evaluation of ^{240}Pu neutron cross sections above 1 keV for JENDL-1. He gave the smooth fission cross section below 10 keV by averaging the experimental data of Byers et al.[86] and of Migneco and Theobald.[75] Between 10 keV and 4 MeV, he obtained the fission cross sections by using many ratio measurements and the JENDL-1 fission cross sections of ^{235}U evaluated by Matsunobu.[11] Above 4 MeV, he estimated the cross sections by means of the statistical theory of fission.

As to the capture cross sections for JENDL-1, Murata calculated the cross sections by using the statistical model, and then modified them so as to pass through the experimental data by Weston and Todd[52] from 30 to 120 keV.

Murata revised[9] his evaluation of the fission cross sections above 9 keV for JENDL-2. He used recent experimental data of ratio measurements for the fission cross sections by Behrens et al.[57] and Wisshak and Käppeler.[31] He averaged the data by three or five data points and multiplied them by the fission cross sections of ^{235}U obtained by Matsunobu.[81]

For the capture cross sections, he revised his old evaluation by using the recent ratio experiment by Wisshak and Käppeler[29,30] in addition to the data by Hockenbury et al.[37] and Weston and Todd.[38] He used the capture cross sections of Au in ENDF/B-IV in order to deduce the ^{240}Pu capture cross sections from the ratio data by Wisshak and käppeler. He obtained the values of the capture cross sections in the region from 30 keV to 50 keV, and normalized the calculated cross sections to these data. He added the direct capture component above 5 MeV.

For the resonance parameters of ^{242}Pu, Murata and Kawai[9] selected 131 levels below 1.3 keV by examining the experimental data reported by 1975. They obtained the neutron widths with weighted average method. The values of their neutron widths were similar to those by Auchampaugh and Bowman[63], or by Poortman et al.[62] They also obtained the radiative widths by the weighted average method for the levels to which some experimental data were given. An average value of these evaluated radiative widths was 24.2 meV. This value was used for the levels not given the radiative widths. For the fission widths, they obtained the evaluated values by taking account of the fission area.

Using the evaluated resonance parameters mentioned above, they calculated the thermal cross sections and confirmed that the capture cross section agreed well with the experimental data. For the fission and elastic scattering cross sections, however, agreement was not good. They added the background cross sections in order to reproduce the experimental data.

Average resonance parameters and the thermal cross sections are as follows: $\overline{D}$ = 13.04 eV, $S_0 = 0.85 \times 10^{-4}$, $\overline{\Gamma}_\gamma$ = 24.2 meV, R' = 9.6 fm, $\sigma_{n,\gamma}$ = 18.43 (b), $\sigma_{n,f}$ = 0.013 (b), σ_{el} = 8.2 (b).

Above resonance region, they obtained the fission cross sections of ^{242}Pu on the basis of the experimental data by Auchampaugh et al.[43] and Behrens et al.[57] They examined a trend of the average fission cross sections from 370 eV to 110 keV by using the fission areas given by Auchampaugh et al. They assumed that the average fission cross sections were given by a sum of Lorentzian shape resonances with the areas mentioned above and with the half widths of 0.5 keV in the region of 1 - 6 keV,

and of 0.1 keV in 6 - 100 keV. The fission cross sections thus obtained were normalized to the cross sections above 100 keV which were obtained from the data of ratio measurement by Behrens et al. The ratio data above 100 keV were averaged by five data points, and were multiplied by the fission cross sections of ^{235}U evaluated by Matsunobu.[81)]

For the capture cross sections of ^{242}Pu, they calculated the cross sections with Hauser-Feshbach theory and normalized them to the experimental data by Hockenbury et al.[46)] They added the direct component of the capture cross section above 5 MeV.

HAR (Atomic Energy Research Establishment Harwell)

Evaluation of neutron cross sections for ^{241}Am was carried out in the energy range from 10^{-5} eV to 15 MeV. The total, capture, fission, elastic and inelastic scattering, (n,2n) and (n,3n) cross sections, $\bar{\nu}$ and the fission neutron spectrum were included. The result was incorporated in UKNDL.

Also, evaluation of ^{243}Am neutron cross sections will be completed in near future.

LRL (Lawrence Livermore Laboratory)

Table 1 shows that ENDL-78 includes 30 transactinium isotopes, excluding big three nuclides. The evaluation methods for each quantity of each isotope are described in UCRL-50400 Vol. 15 part D.[87)] The newest version of ENDL was presented to this review. Some parts of the data are illustrated in the next chapter.

Summaries of the evaluations for each isotope are given in Table 3-1 ∿ 3-7.

3. Comparison of Evaluated Data

As we saw in the previous chapter, there are some available evaluated data for each quantity. Generally speaking, trend of evaluated data is much dependent on experimental data. For the quantity with no experimental data, the evaluated data by different authors are apt to deviate with each other. Deviation of the data depends on also the different methods of the evaluation. In this chapter, we see the trend of different evaluated data with some graphs. We also show the maximum differences among the data in graphic forms for the capture and fission cross sections in each energy interval of which boundaries are given as follows:

$$(1.0,\ 1.5,\ 2.0,\ 3.0,\ 4.0,\ 5.0,\ 6.0,\ 8.0) \times 10^{n}, \qquad (1)$$

where n is an integer.

^{240}Pu: Evaluations of the capture cross sections were recently made at KFK, ORL, NIG and LRL. Figs. 1 and 2 show the data of various files including UKNDL-73 which may be old today. Histogram in Fig. 1 shows

the average cross sections in the resonance region. The energy intervals were taken by following the rule given in Eq. (1). The JENDL-2 data evaluated at NIG were not yet completed below 1 keV. The KEDAK-NEW data in Fig. 2 were transcribed from Ref. 2). The evaluation at ORL must have been included in the general purpose file of ENDF/B-V which is restricted within a limited use, and hence it is not shown in the figures. With the exception of UKNDL-73, the average, maximum and minimum values of the capture cross sections are illustrated in Fig. 3 in the histograms.

The fission cross sections were evaluated recently at LRL and NIG. No information was reached to the present authors about new evaluation for ENDF/B-V. Hence, the ENDF/B-IV data were shown in Figs. 4 and 5, together with the data of KEDAK-3, UKNDL-73, JENDL-1 as well as the recent evaluations of ENDL-78 and JENDL-2. Although the differences between the old and recent evaluations are large, the differences between the recent works become small. Since there were many congruous experimental data above 100 keV, agreement was good among the evaluated data. Fig. 6 shows the average, maximum and minimun values of the fission cross sections.

^{241}Pu: Recent evaluations for the capture cross sections were performed at KFK, ORL, JAE and LRL, while the fission cross sections were evaluated at ORL, JAE and LRL. Resolved and unresolved resonances were obtained by BOL members through their evaluations in the energy region from 0.26 eV to 40 keV.

In Figs. 7 and 8, the capture cross sections are shown. However, the recent data obtained at KFK, ORL and BOL are not included, because no data have been reached to the authors. The JENDL-2 data were only prepared in the energy region between 100 eV and 250 keV. There are some discrepancies among ENDL-78, ENDF/B-IV and JENDL-1 or -2. In particular, large differences exist in MeV energy region. Fig. 9 shows the average, maximum and minimum values of the capture cross sections exclusive of the data of UKNDL-73.

The fission cross sections are illustrated in Figs. 10 and 11. The JENDL-2 data were not yet completed except the energy region above 100 eV. Among the recent evaluations, the ENDL-78 has a different trend from the other evaluations in the energy region between 400 eV and 30 keV. Agreement is good above 100 keV. Fig. 12 gives the average, maximum and minimum values.

^{242}Pu: Many evaluation works have been made recently for the capture and fission cross sections. However, the full evaluations were performed at only NIG and LRL. Evaluations at BOL were for the resonance parameters below 1.3 keV. At KFK, HED, LAS and BRC, only cross sections above resonance region were obtained by using the optical and statistical model calculations in addition to the use of the experimental data.

Figs. 13 and 14 show the capture cross sections. The KEDAK-NEW data were transcribed from Ref. 2). The ENDF/B-V data must have been based on the evaluations at HED and LAS. Except for some large values of ENDL-78, agreement would be good below 10 keV. Disagreement is rather large in the MeV region. This is mainly due to whether or not the evaluations include direct capture component. The average, maximum and minimum values are illustrated in Fig. 15.

The fission cross sections are shown in Figs. 16 and 17. There are large discrepancies among JENDL-2, ENDF/B-V, ENDL-78 and KEDAK-3 below 100 keV. In particular, they are very different with each other below 50 eV. Above 200 keV, agreement is good. Fig. 18 shows the average, maximum and minimum values exclusive of the UKNDL-73 data which may be based on the old experimental data. The minimum values below 10 keV are zero, because the data in KEDAK-3 and BRC files are zero.

^{241}Am: The present authors received information from six laboratories concerning the evaluations of ^{241}Am capture and fission cross sections. The full evaluations were made at HAR, LRL and JAE. The evaluations at HED were performed for the data above 1 keV region. The resonance parameters were investigated at BOL and CAD.

Figs. 19 and 20 show the capture cross sections. The evaluations made at HED must have been included in the ENDF/B-V file. The JENDL-1 data are higher than the other data, because the higher thermal value was accepted from the compilation of the BNL 325, 3rd edition. Above 1 MeV, the discrepancies are large among four evaluations. Global situation is revealed in Fig. 21 which shows the average, maximum and minimum values of the evaluated capture cross sections.

The fission cross sections are shown in Figs. 22 and 23. The evaluations at HED were probably included in the ENDF/B-V file. The ENDL-78 data followed the experimental data by Seeger et al.[50] The JENDL-1 data are smaller than the ENDL-78 data below 50 keV, but still have some structures. Discrepancies among the evaluations are large below a few hundreds keV, in particular, from 1 eV to 200 keV. Fig. 24 reveals the largest discrepancies in each energy interval.

^{243}Am: There are three works which have been recently evaluated at HED, JAE and LRL. The full evaluations were made at JAE and LRL. The evaluations at HED were probably included in the ENDF/B-V file.

Figs. 25 and 26 show the capture cross sections. Agreement is good below 300 eV, if the UKNDL-73 data were excepted from the comparison. Above 300 eV, however, there are large disagreements among JENDL-2, ENDF/B-V and ENDL-78. Fig. 27 reveals the global situation.

Fission cross sections are displayed in Figs. 28 and 29. ENDF/B-V gives the zero values below 200 eV and UKNDL-73 gives no values below 10 keV, while JENDL-2 and ENDL-78 follow the experimental data by Seeger[53] which included some errors. Fig. 30 shows very large differences between the maximum and minimum values below 300 keV.

^{244}Cm: Four recent evaluation works were informed to the authors. The full evaluations were performed at JAE and LRL. Resolved and unresolved resonance parameters were investigated at SRL below 10 keV. The evaluation works at HED and SRL were probably included in the ENDF/B-V file.

Figs. 31 and 32 show the capture cross sections. The JENDL-2 data are slightly higher in the thermal region than the data of ENDF/B-V and ENDL-78. Discrepancy is large above 2 keV. Fig. 33 illustrates the average, maximum and minimum values of the evaluated data.

Fission cross sections are given in Figs. 34 and 35. Discrepancies are not so large above 1 keV, but are large below 1 keV. The JENDL-2 and ENDL-78 data are larger than the ENDF/B-V data in the thermal region. Fig. 36 illustrates the global situation of the discrepancies.

^{245}Cm: The resolved and unresolved resonance parameters were evaluated at SRL below 10 keV. The full evaluations were performed at JAE and LRL.

Figs. 37 and 38 shows the capture cross sections. The ENDF/B-V and ENDL-78 data are almost in good agreement. The JENDL-2 data are smaller than the other two below 1.5 eV and higher from 20 eV to 200 eV. Above 10 keV, the ENDF/B-V and ENDL-78 are the same values. Fig. 39 shows the average, maximum and minimum values. Difference is large between 300 eV and 100 keV.

Figs. 40 and 41 display the fission cross sections. The ENDF/B-V and ENDL-78 have the same values above 10 keV. Some differences exist among three files below 150 eV. The largest discrepancies are illustrated in Fig. 42.

Above mentioned comparison showed that there were some significant discrepancies among evaluated data. In order to express numerically these discrepancies (or accuracies), the average values and standard deviations were calculated for each quantity in each energy interval given in Eq. (1), and the accuracy was expressed in two standard deviations divided by the average value; for the i-th energy interval, the standard deviation is

$$\Delta\sigma_i = \{ \frac{1}{N} \sum_j (\sigma_i^J - \bar{\sigma}_i)^2 \}^{1/2} \qquad (2)$$

where j stands for the j-th evaluated file, N is the number of the files, and $\bar{\sigma}_i$ is the mean value of the data in the i-th energy interval. The accuracy of the evaluated data is defined as follows:

$$A_i = (2 \cdot \Delta\sigma_i / \bar{\sigma}_i). \qquad (3)$$

These statistical considerations must be based on the random sampling. Here, we assume that the randomness is satisfied in the selection of the evaluated data files. The selected files are those given in the graphs shown in the above discussions, but the data of UKNDL-73 and KEDAK-NEW are rejected. The former data are too old, and the latter include some errors made at the transcription from the graphs.

Table 4 shows the ranges of the quantities given in Eq. (3), and compare them with the users' requests. It is not always clear whether the users' requests are given in Eq. (3) or not. So, the data in Table 4 should be taken into account as reference data than comparable ones with each other.

From table 4 as well as graphs, the following causes may be extracted concerning discrepancy of the evaluated data.

^{240}Pu: Capture. Discrepancy below 100 eV is due to the large values of KEDAK-3. Different trends of ENDL-78 and JENDL-2 cause the large discrepancy in MeV region.

Fission. Discrepancy below 100 keV is due to the differnet trends of different evaluations. This depends on the selection and treatment of the experimental data in each evaluation.

^{241}Pu: Capture. Different evaluations have different trends in the whole energy region. Scarce experiments cause this discrepancy.

Fission. Except for the different trend of ENDL-78 below 100 keV, agreement is almost good.

^{242}Pu: Capture. Large discrepancies exist in some energy intervals below 1 keV, but not in the whole energy region. Different evaluations have different trends in MeV region.

Fission. Discrepancies below 100 keV are due to the very different trends of different evaluations.

^{241}Am: Capture. Different trends exist among different files below 100 eV and in MeV region. JENDL-1 has large values in the thermal region.

Fission. JENDL-1 and ENDL-78 were affected by the large values of Seeger et al. These make the discrepancies among different evaluations large.

^{243}Am: Capture. ENDL-78 shows different trend from ENDF/B-V and JENDL-2 above 300 eV. JENDL-2 does not have the direct capture component in MeV region.

Fission. Three evaluations have entirely different trends with each other below 100 keV.

^{244}Cm: Capture. Different evaluations have different trends above 1 keV. Thermal value of JENDL-2 is larger than those of the other two.

Fission. Three evaluations show different trends almost in the whole energy range, except the energy region from 300 to 600 keV.

^{245}Cm: Capture. JENDL-2 shows different trend from the other two.

Fission. Three evaluations have different trends, except the data from 10 to 400 keV.

4. Conclusions and Recommendations

This review was limited to the capture and fission cross sections for seven isotopes. There were many evaluation works even for these limited quantities. In particular, many works were recently performed for the plutonium isotopes and ^{241}Am. Some evaluations were also carried

out for ^{243}Am and the curium isotopes.

Comparison of these evaluations showed that significant discrepancies existed in the resonance and MeV energy regions for some nuclides. When there were experimental data, evaluations were strongly dependent on the experiments. Therefore, the evaluations were in agreement with each other for the quantities in the energy range where the experimental data were not dispersive. On the contrary, the evaluations were discrepant in case where the experimental data were dispersive or there were no experimental data. These latter cases are still common for the transactinium neutron nuclear data. For these data, analyses should be carefully performed in order to remove any unreasonable discrepancies from the evaluated data. Precise experiments are also required for these data.

Examples for the former case of being in good agreement are found in the fission cross sections of ^{241}Pu, ^{242}Pu, ^{244}Cm and ^{245}Cm, and also in the capture cross sections of ^{241}Am. According to Table 4, there are many energy intervals in which the users' required accuracies are numerically satisfied, in particular, for the above mentioned quantities. However, it is not clear whether the users' required accuracy is defined in Eq. (3) or not. So, it is necessary that the definition should be made clear for the accuracy or discrepancy of the data, so that the comparison may be easily performed between the evaluated data and the users' requirements.

Most evaluations used the optical and statistical model calculations. However, the optical potential parameters used in the transactinium isotope nuclear data evaluations are not always reliable, because the parameters are those for the lighter actinides and are not tested for the present nuclides for which no experimental data are available on the total cross sections, elastic scattering cross sections and their angular distributions. In order to get the reliable optical potential parameters, it is necessary, at least, that the measurements of the total cross sections should be promoted. The experimental total cross sections are also useful not only to determine the upper values of some partial cross sections but also to evaluate the total cross section themselves.

Finally, it is recommended that the similar review should be made for the other quantities of the present seven isotopes as well as for the other transactinium isotope nuclear data. This should be helpful for promoting future evaluation work.

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TABLE 1. TRANSACTINIDES IN EVALUATED NEUTRON DATA LIBRARIES

	ENDF/B-V	ENDF/B-IV	ENDL-78	UKNDL-73	KEDAK-3	JENDL-2	JENDL-1
TH-228						X	
230	X					X	
231			X				
232	X	X	X	X		X	X
233			X			X	
234						X	
PA-231	X						
233	X	X		X		X	X
234						X	
U- 232	X						
233	X	X	X	X		X	
234	X	X	X	X		X	
236	X	X	X	X		X	X
237	X		X			X	
239			X	X			
240			X	X			
NP-237	X	X	X			X	
238	X						
239						X	X
PU-236	X						
237	X					X	
238	X	X	X	X	X	X	
240	X	X	X	X	X	X	X
241	X	X	X	X	X	X	X
242	X	X	X	X	X	X	
243	X		X				
244	X						
AM-241	X	X	X	X		X	X
242	X					X	
242M	X	X	X			X	
243	X		X			X	
CM-241	X						
242	X		X			X	
243	X		X			X	
244	X	X	X	X		X	
245	X		X			X	
246	X		X				
247	X		X				
248	X		X				
BK-249	X		X				
CF-249	X		X				
250	X		X				
251	X		X				
252	X		X				
253	X						
ES-253	X						

Table 2. *Requested Quantities Registered on WRENDA 76/77*

It is also denoted whether libraries have the files of requested nuclides.

	^{232}Th	^{233}Th	^{231}Pa	^{233}Pa	^{234}Pa	^{232}U	^{233}U	^{234}U	^{236}U	^{237}U	^{237}Np	^{238}Np	^{239}Np
K E D A K													
U K N D L	Y			Y			Y	Y	Y				
E N D F / B	Y		Y	Y		Y	Y	Y	Y	Y	Y	Y	
E N D L	Y	Y					Y	Y	Y	Y	Y		
J E N D L	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y		Y
Total Cross Section	X	X		X	X		X	X					
Elastic Cross Section	X	X		X	X		X	X					
Differential Elastic	X												
Inelastic Cross Section	X	X		X	X		X	X					
Energy Diff. Inelastic	X						X		X				
Angular Diff. Inelastic							X						
(n, 2n) Cross Section	X						X	X		X	X		
(n, 3n) Cross Section	X							X					
Fission Cross Section	X	X		X	X		X	X	X	X	X		X
Capture Cross Section	X	X	X	X	X	X	X	X	X	X	X	X	X
Absorption Cross Section				X									
Alpha							X						
Eta							X						
Nu-bar							X		X				
Delayed Neutrons							X		X				X
Fission Yield							X						
Resonance Data	X			X			X		X				
Photon Production Data							X						

Table 2: (cont.)

	^{236}Pu	^{237}Pu	^{238}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{245}Pu	^{241}Am	^{242}Am	^{242m}Am	^{243}Am	^{244}Am
K E D A K			Y	Y	Y	Y						
U K N D L			Y	Y	Y	Y		Y			Y	
E N D F / B	Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	
E N D L			Y	Y	Y	Y		Y		Y	Y	
J E N D L			Y	Y	Y	Y		Y	Y	Y	Y	
Total Cross Section				X	X			X	X	X		
Elastic Cross Section												
Differential Elastic												
Inelastic Cross Section				X	X							
Energy Diff. Inelastic				X								
Angular Diff. Inelastic				X								
(n, 2n) Cross Section			X		X							
(n, 3n) Cross Section												
Fission Cross Section		X	X	X	X	X	X	X	X	X	X	
Capture Cross Section		X	X	X	X	X		X	X	X	X	X
Absorption Cross Section	X				X			X			X	
Alpha					X							
Eta					X							
Nu-bar			X	X	X	X		X		X	X	
Delayed Neutrons				X	X	X						
Fission Yield					X							
Resonance Data				X	X			X	X	X	X	
Photon Production Data				X	X	X		X				

Table 2: (cont.)

	^{242}Cm	^{243}Cm	^{244}Cm	^{245}Cm	^{246}Cm	^{247}Cm	^{249}Bk	^{250}Cf	^{251}Cf	^{252}Cf	^{253}Es
K E D A K											
U K N D L			Y								
E N D F / B	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
E N D L	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	
J E N D L	Y	Y	Y	Y							
Total Cross Section				X	X	X	X	X			
Elastic Cross Section											
Differential Elastic											
Inelastic Cross Section											
Energy Diff. Inelastic											
Angular Diff. Inelastic											
(n, 2n) Cross Section											
(n, 3n) Cross Section											
Fission Cross Section	X	X	X	X		X		X	X		X
Capture Cross Section	X	X	X	X	X	X	X	X	X	X	
Absorption Cross Section											
Alpha											
Eta											
Nu-bar	X		X						X		
Delayed Neutrons											
Fission Yield											
Resonance Data	X										
Photon Production Data											

Table 3-1. Summary of Evaluations for ^{240}Pu Capture and Fission Cross Sections.

^{240}Pu	Capture Cross Section	Fission Cross Section
K F K	Evaluations were based on Hockenbury et al.(37), Weston and Todd(38), Wisshak and Käppeler(29). New data were 30 ∿ 50 % higher than old version.	
O R L	Evaluations might be based on Weston and Todd(38), Hockenbury et al.(37), Wisshak and Käppeler(30).	
N I G	Statistical model calculation was normalized to the average values from 30 to 50 keV obtained from Wisshak and Käppeler(29,30), Hockenbury et al.(37), Weston and Todd (38). ENDF/B-IV Au(n,γ) cross section was used.	Evaluated data in 1 ∿ 9 keV were obtained by averaging the experimental data by Byers et al.(86), Migneco and Theobald (75). Above 9 keV, the evaluation was based on Wisshak and Käppeler(31), and Behrens et al.(57). They averaged the data by three or five points and then multiplied by Matsunobu's ^{235}U fission cross section.
L R L	Between 4 and 350 keV, fitting to the experimental data was used. Above 350 keV, the data were obtained from systematics.	Between 4 and 160 keV, the data were obtained by averaging over the experimental data. Above 160 keV, ratio data of Behrens and Carlson were normalized to ENDL ^{235}U fission cross section.

Table 3-2. Summary of Evaluations for ^{241}Pu Capture and Fission Cross Sections.

^{241}Pu	Capture Cross Section	Fission Cross Section
K F K	Evaluation was based on Weston and Todd(39). New data were lower than old version.	
B O L	In 0.26 ∿ 104 eV, they obtained the resolved resonance parameters with Reich-Moore formalism. In 104 eV ∿ 40 keV, unresolved resonances were analysed with statistical model. The evaluations were based on the resonance parameters by Blons and Derrien(60), alpha values by Weston and Todd(61).	
O R L	Evaluation might be based on Weston and Todd(61).	Many experimental data were used below 20 eV. From 100 eV to 40 keV, Weston and Todd(61) were the dominant data.
J A E	In 100 eV ∿ 250 keV, Weston and Todd(61) were multiplied by Matsunobu's ^{235}U fission cross sections. Above 250 keV, statistical model calculation was used.	From 100 eV to 1 keV, evaluation was based on Weston and Todd(61), Blons(74), Migneco et al.(75), James(76), and Carlson et al.(77). In 1 ∿ 10 keV, Weston and Todd(61), and Blons(74) were used. Above 10 keV, Weston and Todd(61), Blons(74), Carlson et al.(77), Szabo et al.(78), Carlson and Behrens(79), and Käppeler and Pfletschinger(80) were used.
L R L	Evaluated data were mainly from systematics, because of the absence of experimental data.	They averaged over the experimental data.

Table 3-3. Summary of Evaluations for ^{242}Pu Capture and Fission Cross Sections.

^{242}Pu	Capture Cross Section	Fission Cross Section
K F K	Evaluated data were revised from 500 eV to 200 keV by using Wisshak and Käppeler(29). New evaluation was 30 ∿ 50 % higher than old version.	
H E D	Statistical model calculation was normalized to Hockenbury et al.(46). New evaluation was higher than ENDF/B-IV.	Evaluation for $E_n \geq 100$ keV was based on Fomushkin et al.(40,41), Bergen and Fullwood(42), Auchampaugh et al.(43), and Behrens et al.(44). Statistical model was used in 1 keV $\leq E_n <$ 100 keV.
L A S	In the region of 10 keV $\leq E_n \leq$ 20 MeV, statistical model calculation was normalized to Hockenbury et al.(46).	The data in 10 ∿ 100 keV were Auchampaugh et al.(43), and in 100 keV ∿ 20 MeV, Behrens et al.(57). Statistical model calculation with single hump, one dimensional barrier was made.
B R C	In 10 keV $\leq E_n \leq$ 20 MeV, deformed optical and statistical model calculation was performed with radiative width by Lynn(58).	Deformed optical and statistical model calculation was adjusted to Behrens et al.(44,57). The data were obtained from 10 keV to 20 MeV.
B O L	Resolved resonances from 0 to 1.3 keV were determined with the parameters from Poortmans et al.(62), Auchampaugh et al.(43), Bergen and Fullwood(42), and Auchampaugh and Bowman(63).	
N I G	Statistical model calculation was normalized to Hockenbury et al.(46). Direct component was added. They selected 131 resonance levels below 1.3 keV. Weighted average method was used for selection of resonance parameters.	Below 100 keV, evaluation was based on Auchampaugh et al.(43), and Behrens et al.(57). They averaged the cross sections by assuming Lorentzian shape resonances with areas given by Auchampaugh et al. Above 100 keV, they averaged the ratio data of Behrens et al. by five points, and multiplied by Matsunobu's ^{235}U fission cross sections.
L R L	Above 75 eV, evaluated data were from systematics.	Above 75 eV, they averaged over the experimental data. Ratio data of Behrens, and Browne and Carlson were normalized to ENDL ^{235}U fission cross section.

Table 3-4. Summary of Evaluations for ^{241}Am Capture and Fission Cross Sections.

^{241}Am	Capture Cross Section	Fission Cross Section
H E D	Statistical model calculation was normalized to Weston and Todd(52). Branching to ^{242}Am ground and isomeric states was also obtained.	In $1 \leq E_n < 100$ keV, statistical model was used so as to pass through the points near Bowman et al.(48), Shpak et al.(49). For $E_n \geq 100$ keV, evaluated data were obtained by following Shpak et al.(49), Seeger et al.(50), Fomushkin et al.(40,41), Iyer and Sampathkumar(51).
B O L	Resolved resonance parameters were from Derrien and Lucas(65), Weston and Todd(66). Bound level was accepted from Kalebin(1). Unresolved resonances were from 150 eV to 10 keV.	
C A D	For $l \sim 50$ eV, resonance parameters from Derrien and Lucas(65), Weston and Todd(66), Kalebin(1), Gayther and Thomas(67).	
J A E	Statistical model calculation was in good agreement with Weston and Todd(52).	Least-squares fit was applied to the experimental data. They reduced the data by Seeger et al.(50) below 100 keV, but the evaluation was much dependent on higher values below 300 keV.
	Resolved resonance parameters were mainly from Derrien and Lucas(65) below 150 eV.	
H A R	New evaluation from 10^{-5} eV to 15 MeV was performed for total, capture, fission, elastic and inelastic scattering, (n,2n) and (n,3n) cross sections, $\bar{\nu}$, fission spectrum. Branching of radiative capture cross section to form the ground and isomeric states of ^{242}Am was also obtained.	
L R L	Between 10 and 350 keV, the data were from Weston and Todd(66). Above 350 keV, evaluation was from systematics. Splitting the capture cross sections into the components to the ground and metastable states of ^{242}Am was obtained.	Above 1 keV, ratio data of Behrens and Browne(82) were normalized to ENDL ^{235}U fission cross section.

Talbe 3-5. Summary of Evaluations for ^{243}Am Capture and Fission Cross Sections.

^{243}Am	Capture Cross Section	Fission Cross Section
H E D	Statistical model calculation was used.	Evaluation was based on Seeger(53), and Fomushkin et al.(41). New data were 20 % higher than ENDF/B-IV.
J A E	Statistical model calculation was used.	Least-squares fit to the experimental data was used. Results were much dependent on Seeger(53). Below 10 keV, the data were too high values.
	Resolved resonance parameters by Simpson et al.(85) were adopted.	
L R L	Below 1 keV, the data were from SRL evaluation. Above 1 keV, evaluation was from systematics.	Below 1 keV, the data were from SRL evaluation. Between 1 keV and 4 MeV, averages over the experimental data were used. Above 4 MeV, the data were from systematics guided by 14.5 MeV data.

Table 3-6. Summary of Evaluations for ^{244}Cm Capture and Fission Cross Sections.

^{244}Cm	Capture Cross Section	Fission Cross Section
H E D	Statistical model calculation was used.	Evaluated data were obtained by following Moore and Keyworth (54). At 14 MeV, evaluation was based on Koontz and Barton (55), Fomushkin and Gutnikova(40).
S R L	Below 525 eV, they adopted the resonance parameters by Coté et al.(69), Berreth et al.(70), Simpson et al.(71). Single-level Breit-Wigner formula was used. Unresolved resonance region was defined from 525 eV to 10 keV.	
J A E	Statistical model calculation was used. Resolved resonance parameters were prepared below 1 keV: they were from Moore and Keyworth(54) above 20 eV, and from Benjamin et al.(18) for the lowest two levels and a negative level.	Above 1 keV, least-squares fit was applied to Moore and Keyworth(54), Koontz and Barton(55), Fomushkin et al.(41).
L R L	Below 1 keV, the data were from SRL evaluation. Between 1 and 10 keV, they averaged over experimental data. Above 10 keV, evaluation was from systematics.	Below 1 keV, the data were from SRL evaluation. Between 1 keV and 3 MeV, they averaged over the experimental data. Above 3 MeV, the data were from systematics and from a few points of 14.5 MeV data.

Table 3-7. Summary of Evaluations for ^{245}Cm Capture and Fission Cross Sections.

^{245}Cm	Capture Cross Section	Fission Cross Section
S R L	Below 60 eV, 38 S-wave resonances and one bound level were adopted. Data were from Browne et al.(72), Moore and Keyworth (54). From 60 eV to 10 keV, unresolved resonances were defined. Reasonable match was attained with Nakagome and Block (26).	
J A E	Statistical model calculation was made. Resonance parameters by Moore and Keyworth(54) were accepted from 20 to 60 eV, and the data by Browne et al.(72) were below 20 eV.	Above 50 eV, least-squares fit was applied to Moore and Keyworth(54).
L R L	Below 1 keV, SRL evaluation was adopted. From 1 keV to 20 MeV, evaluation was from systematics.	Below 20 eV, SRL evaluation was adopted. From 20 eV to 2.8 MeV, evaluation was based on Physics - 8 data with some smoothing of the data from 10 keV to 2.8 MeV. Above 2.8 MeV, evaluation was obtained by using nuclear systematics.

Table 4. Comparison between required accuracies (R) and deviation of evaluated data (E).

Majority of required accuracies is shown in parentheses, in %.

			$0 - 10^2$	$10^2 - 10^3$	$10^3 - 10^5$	$10^5 - 10^6$	$10^6 - 2 \times 10^7$ (eV)
^{240}Pu	capture	R	3	5 - 7 (5)	5 - 10 (10)	5 - 10 (10)	10
		E	1.4 - 199	16 - 27	19 - 53	21 - 40	40 - 231
	fission	R	10	9 - 10	2 - 10 (5)	2 - 10 (5)	2 - 10 (5)
		E	2.8 - 215	8.3 - 126	21 - 90	6.1 - 31	4.0 - 18
^{241}Pu	capture	R	3 - 8	3 - 10	3 - 10 (10)	8 - 10 (10)	8 - 10
		E	3.3 - 191	23 - 59	12 - 49	23 - 61	72 - 218
	fission	R	1 - 10 (5)	1 - 10 (5)	1 - 10 (5)	1 - 10 (5)	1 - 10 (10)
		E	0.9 - 83	5.6 - 49	2.7 - 35	1.4 - 3.4	2.5 - 26
^{242}Pu	capture	R	3 - 5	8 - 10	5 - 20 (10)	8 - 20 (10)	10 - 20 (10)
		E	2.6 - 281	10 - 182	19 - 42	24 - 38	35 - 207
	fission	R	1 - 5	1 - 5	1 - 10 (10)	1 - 10 (10)	10
		E	135 - 395	138 - 243	42 - 188	5.9 - 19	1.9 - 15

Table 4: (cont.)

			$0 - 10^2$	$10^2 - 10^3$	$10^3 - 10^5$	$10^5 - 10^6$	$10^6 - 2 \times 10^7$ (eV)
^{241}Am	capture	R	5 - 15 (10)	10 - 20 (10)	5 - 20 (10)	5 - 20 (10)	5 - 20
		E	8.8 - 67	8.3 - 24	8.0 - 18	21 - 66	61 - 215
	fission	R	10 - 15	10 - 20	3 - 20	3 - 15	3 - 15
		E	4.1 - 134	117 - 235	49 - 270	15 - 320	3.1 - 10.6
^{243}Am	capture	R	5 - 20	5 - 20	5 - 30	5 - 30	5 - 20 (10)
		E	0.23- 28	1.5 - 100	59 - 112	108 - 155	40 - 184
	fission	R	20	20 - 30	20 - 30	20 - 30	10 - 30 (20)
		E	161 - 283	141 - 150	44 - 140	9.0 - 27	3.2 - 31
^{244}Cm	capture	R	10	10 - 50 (10)	10 - 50 (10)	10 - 50 (10)	10 - 20 (10)
		E	0.2 - 174	8.9 - 99	11 - 102	69 - 90	22 - 155
	fission	R	10	10 - 50	5 - 50	5 - 50	5 - 50
		E	52 - 195	16 - 109	4.4 - 60	2.8 - 59	9.9 - 27
^{245}Cm	capture	R	10 - 20 (10)	10 - 50	10 - 50	20 - 50	20
		E	3.8 - 125	22 - 69	47 - 107	5.4 - 50	11 - 141
	fission	R	5 - 50	5 - 50 (10)	5 - 50 (10)	10 - 50	10 - 50
		E	4.6 - 131	9.3 - 48	0.93- 34	0.16 - 3.5	0.0 - 32

FIG. 1 Neutron Cross Section ^{240}Pu CAPTURE ENERGY 0.01(eV) - 10.00(keV)

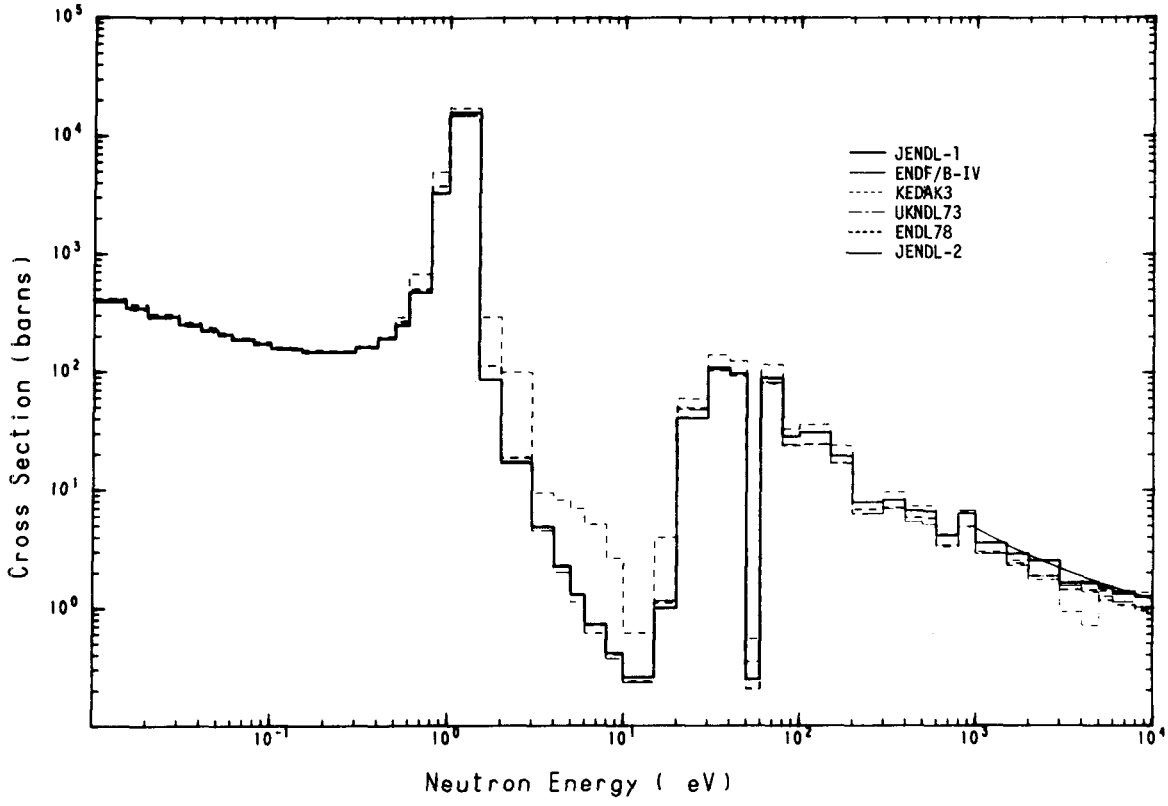


FIG. 2 Neutron Cross Section ^{240}Pu CAPTURE ENERGY 10.00(keV) - 20.00(MeV)

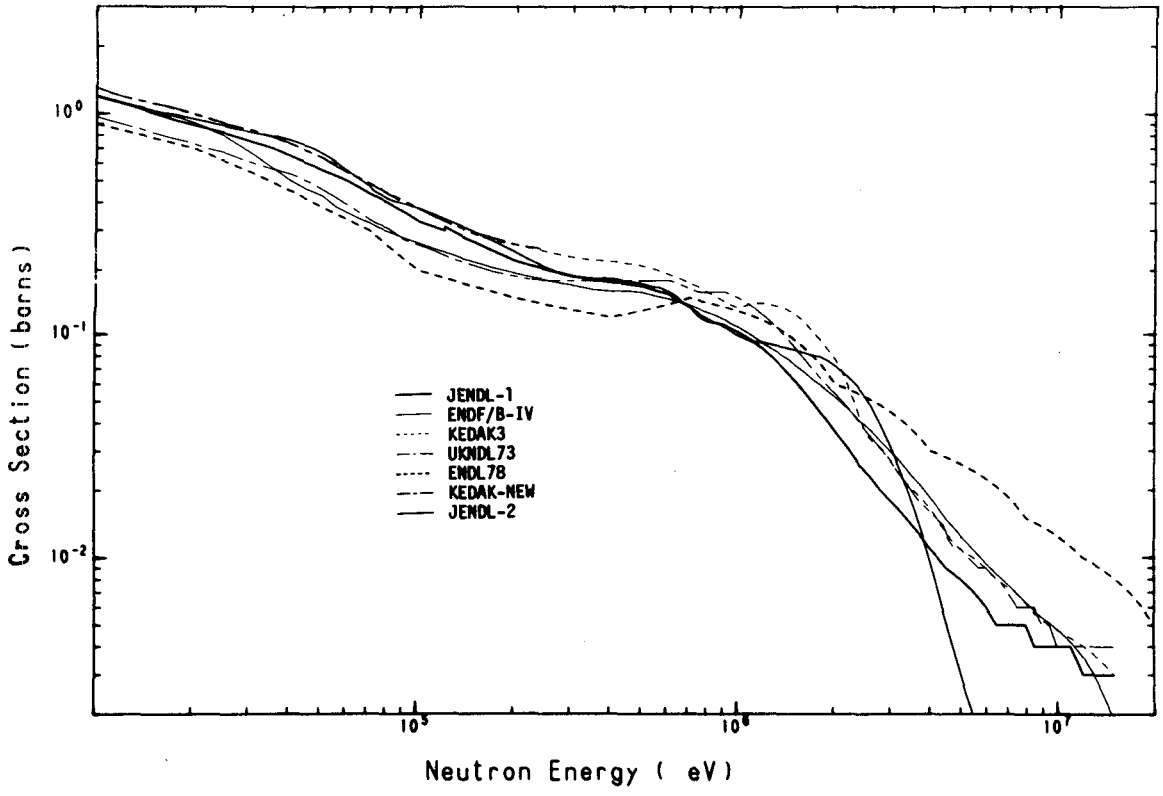


FIG. 3 Neutron Cross Section ^{240}Pu CAPTURE ENERGY 0.01(eV) - 20.00(MeV)

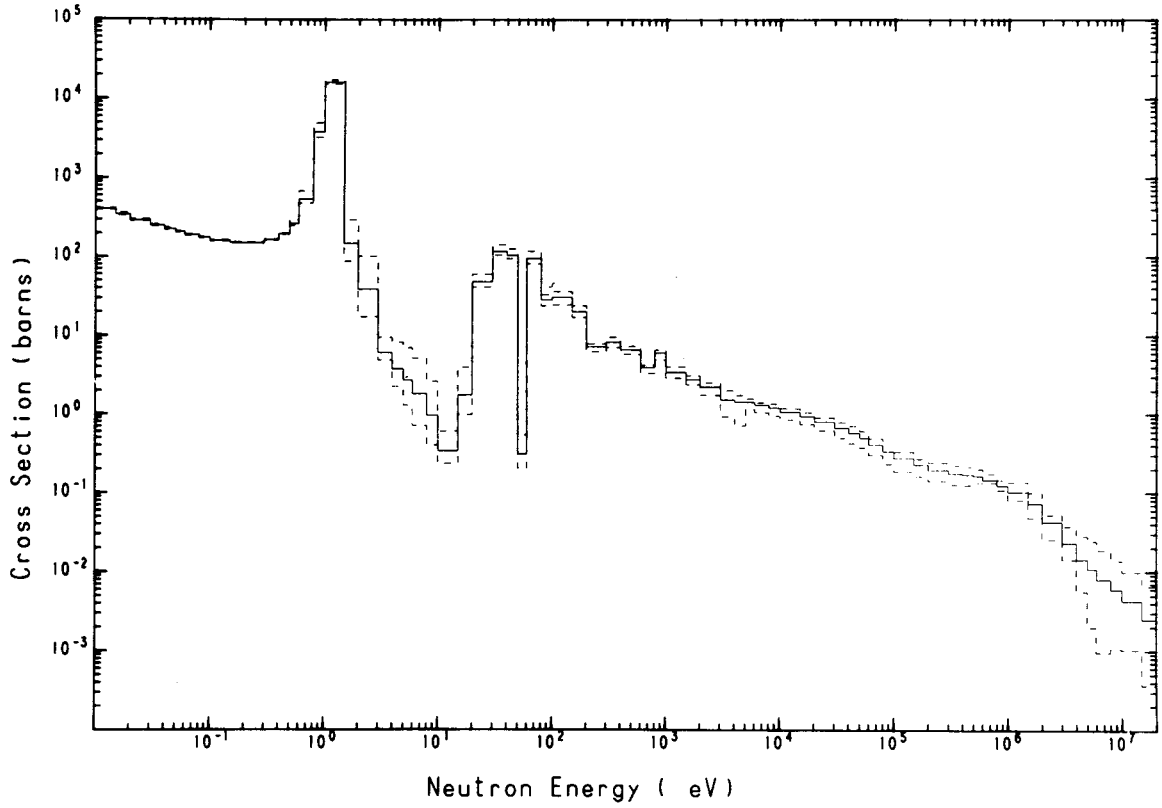


FIG. 4 Neutron Cross Section ^{240}Pu FISSION ENERGY 0.01(eV) - 10.00(keV)

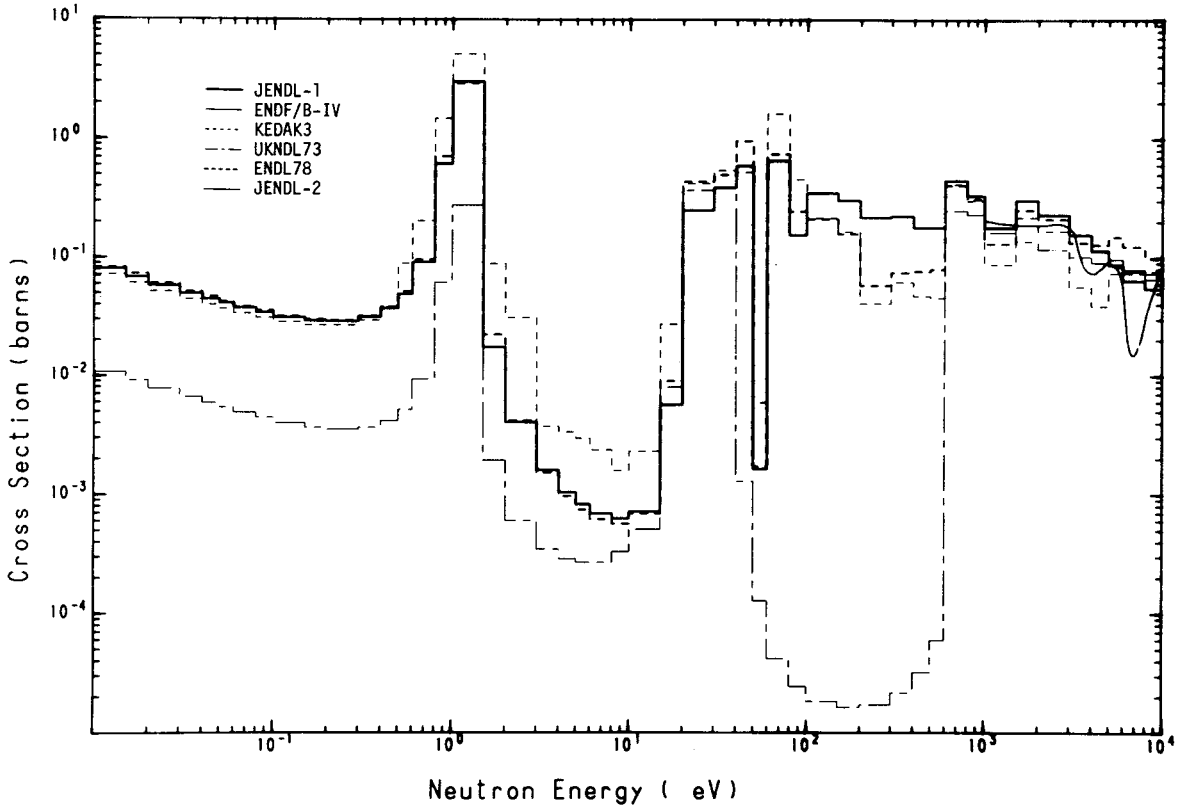


FIG. 5 Neutron Cross Section ^{240}Pu FISSION ENERGY 10.00(keV) - 20.00(MeV)

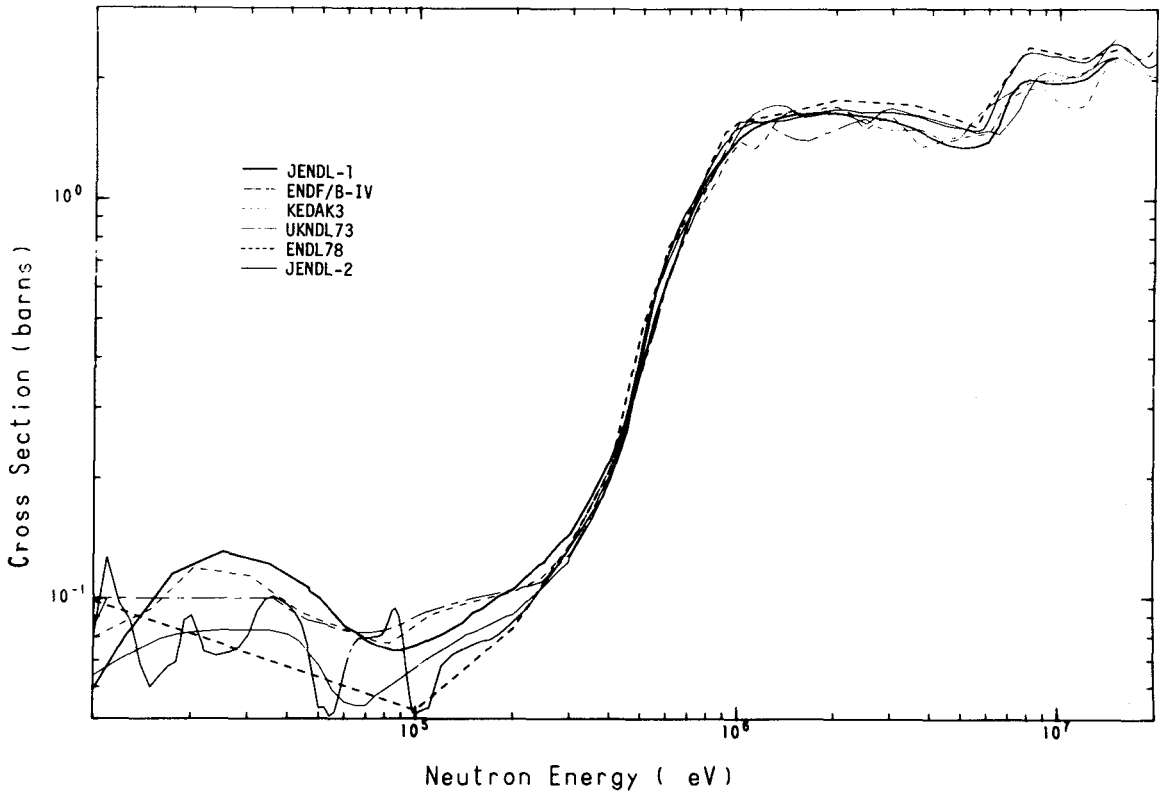


FIG. 6 Neutron Cross Section ^{240}Pu FISSION ENERGY 0.01(eV) - 20.00(MeV)

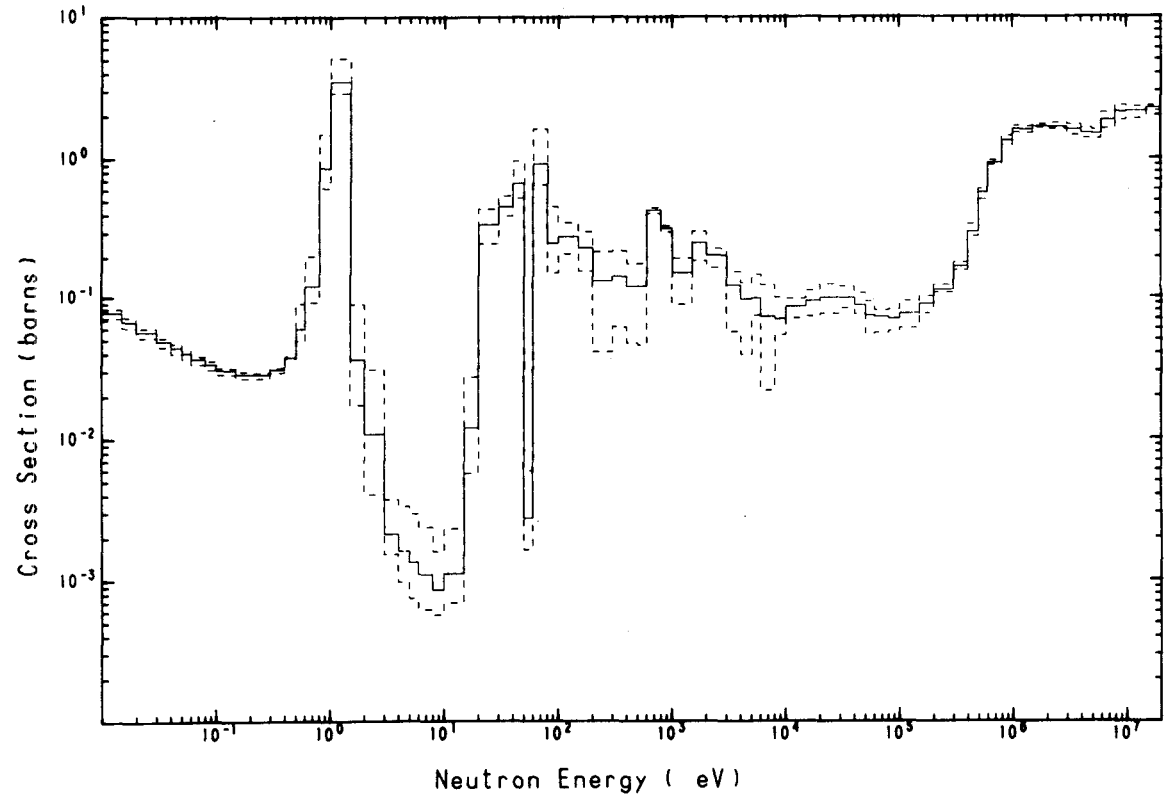


FIG. 7 Neutron Cross Section ^{241}Pu CAPTURE ENERGY 0.01(eV) - 1.00(keV)

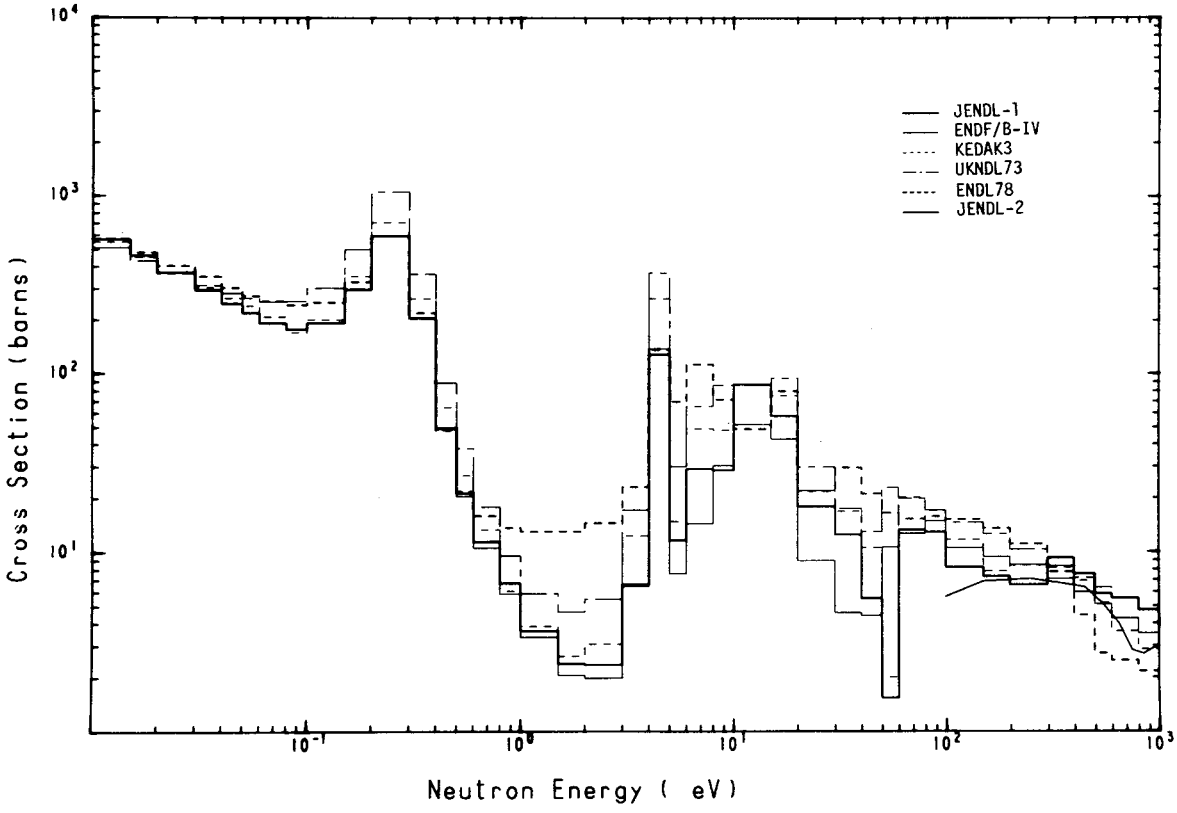


FIG. 8 Neutron Cross Section ^{241}Pu CAPTURE ENERGY 1.00(keV) - 20.00(MeV)

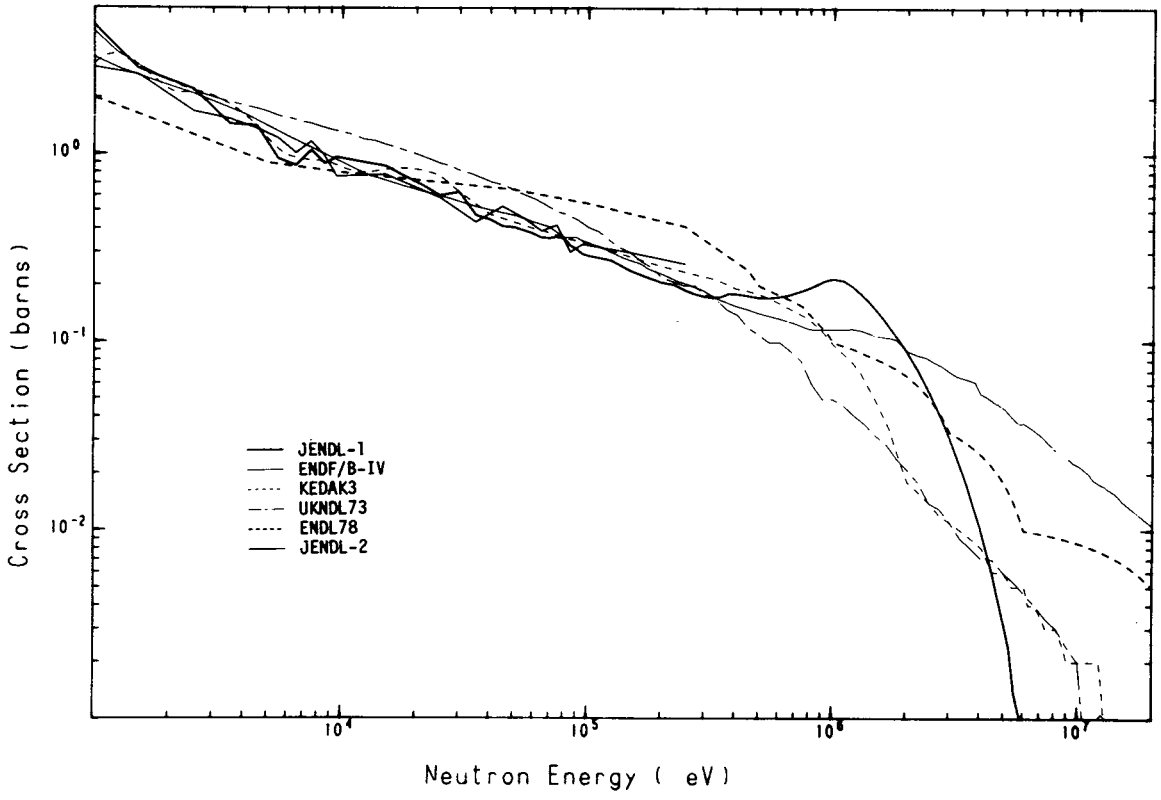


FIG. 9 Neutron Cross Section ^{241}Pu CAPTURE ENERGY 0.01(eV) - 20.00(MeV)

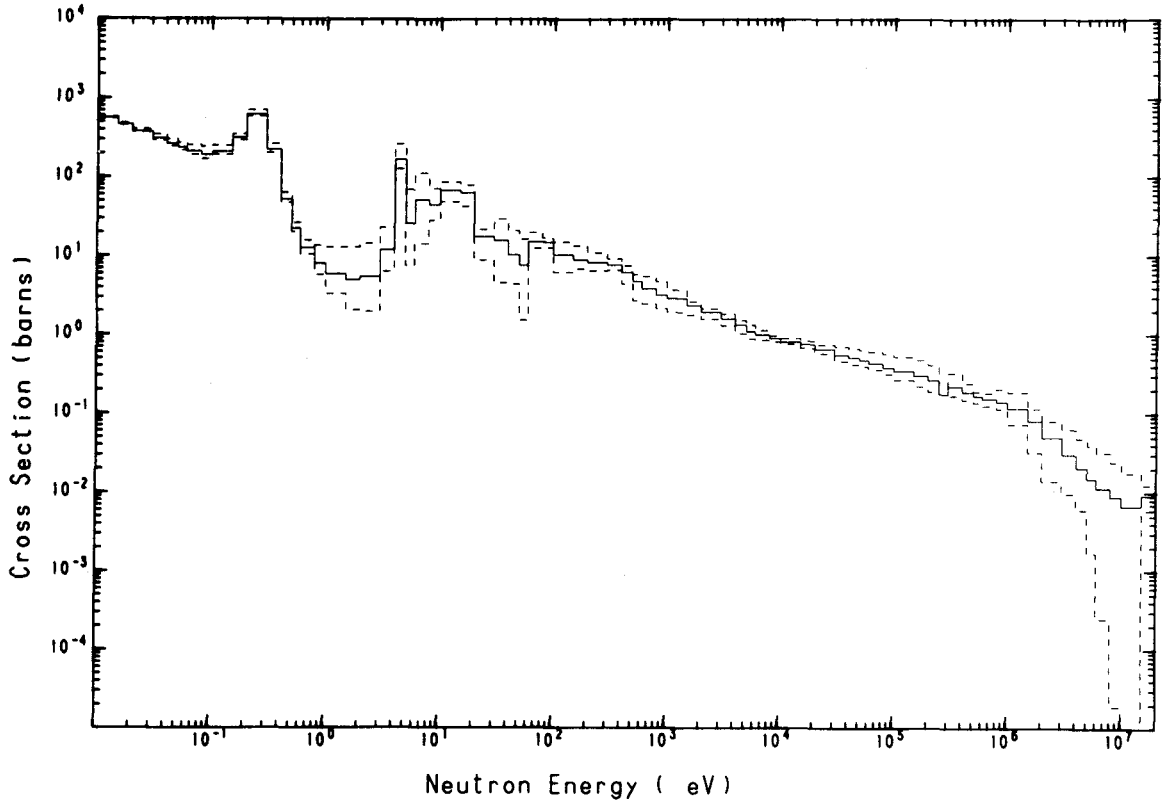


FIG. 10 Neutron Cross Section ^{241}Pu FISSION ENERGY 0.01(eV) - 1.00(keV)

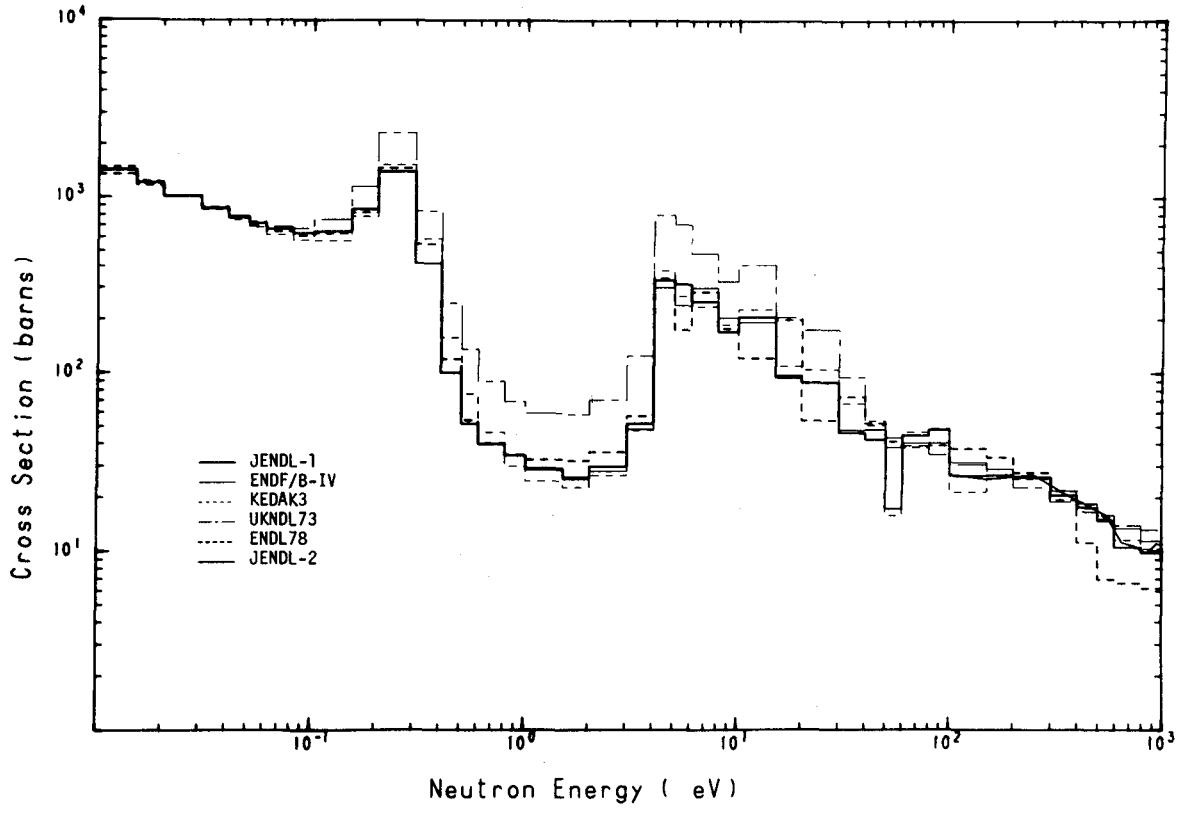


FIG. 11 Neutron Cross Section ^{241}Pu FISSION ENERGY 1.00(keV) - 20.00(MeV)

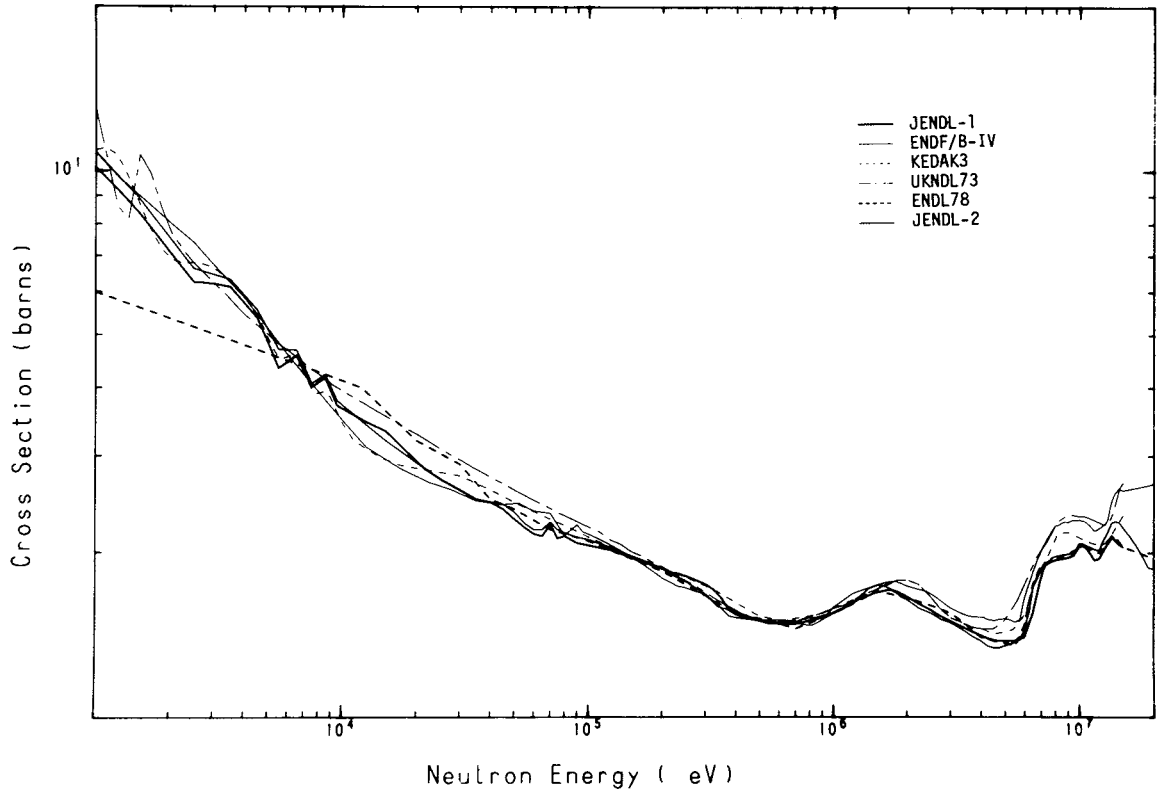


FIG. 12 Neutron Cross Section ^{241}Pu FISSION ENERGY 0.01(eV) - 20.00(MeV)

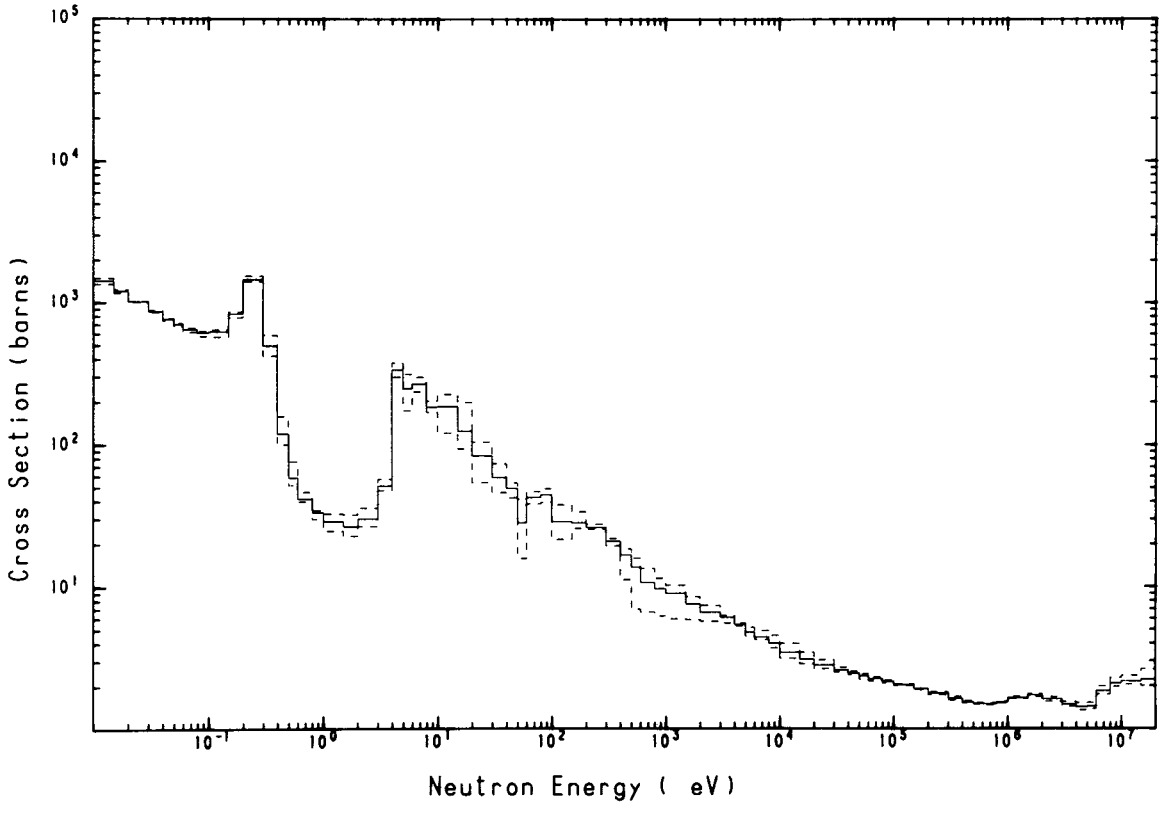


FIG. 13 Neutron Cross Section ^{242}Pu CAPTURE ENERGY 0.01(eV) - 10.00(keV)

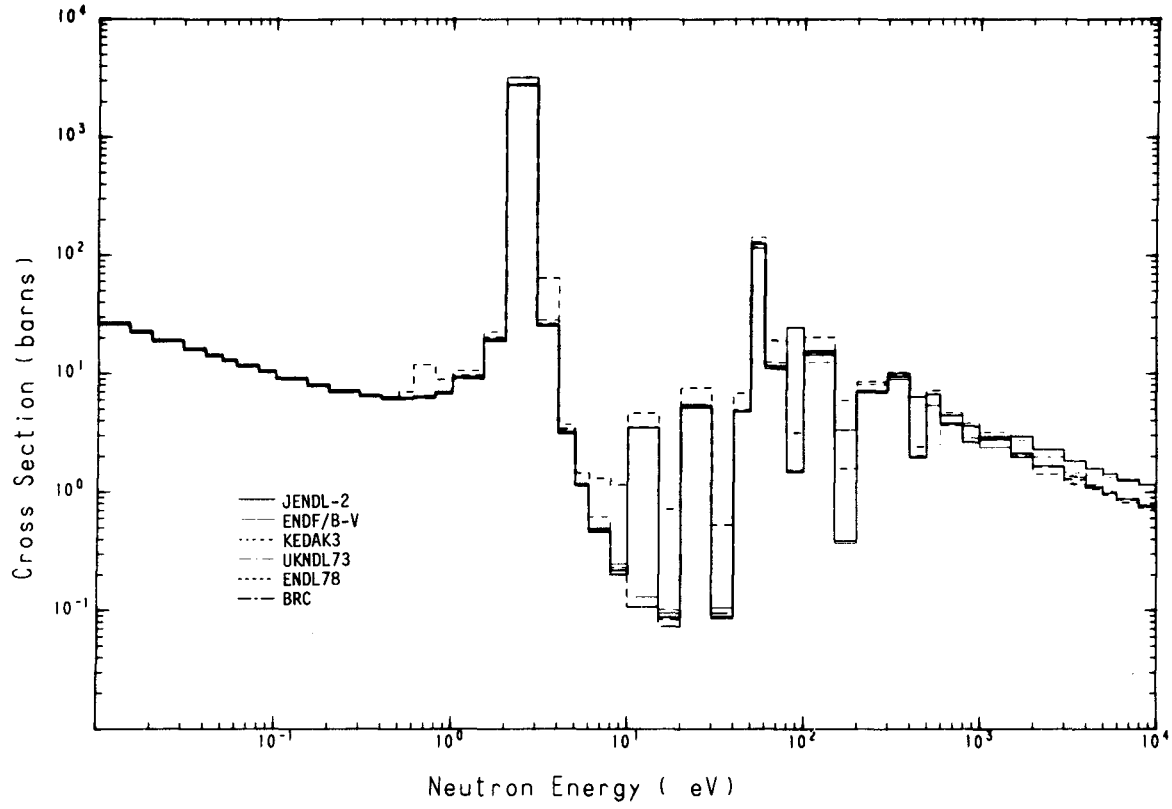


FIG. 14 Neutron Cross Section ^{242}Pu CAPTURE ENERGY 10.00(keV) - 20.00(MeV)

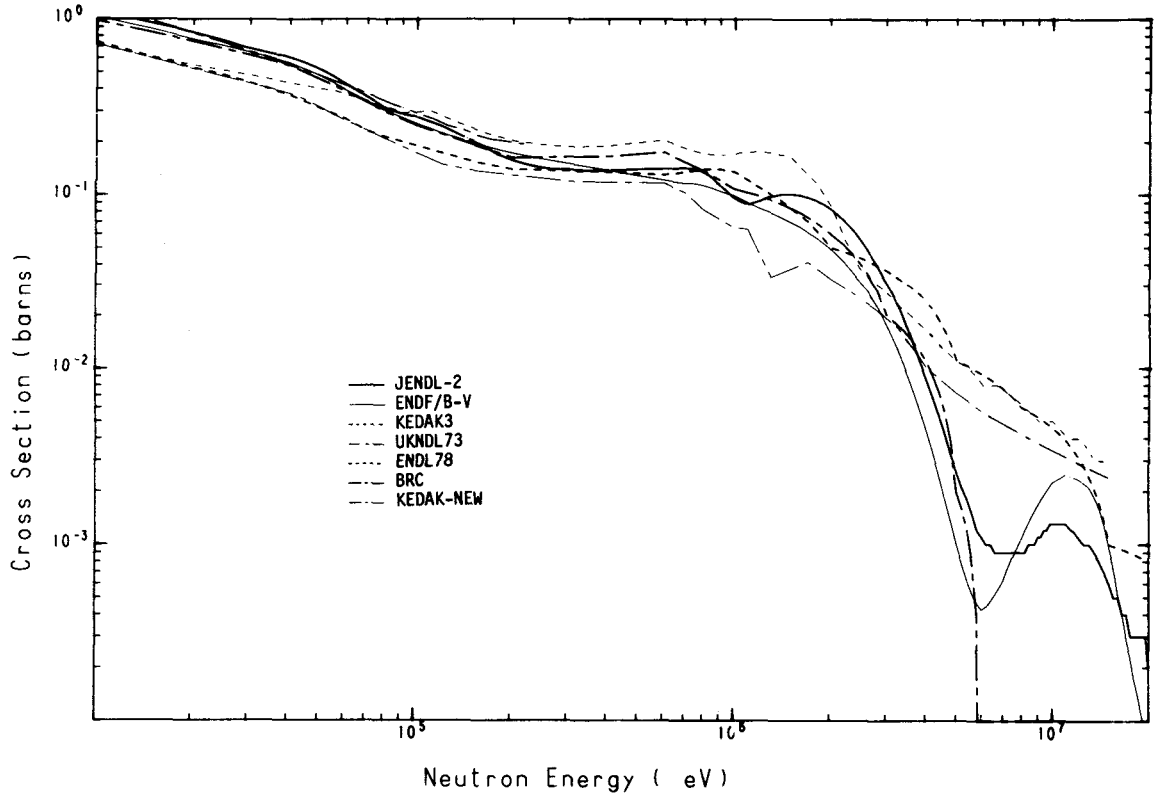


FIG. 15 Neutron Cross Section ^{242}Pu CAPTURE ENERGY 0.01(eV) - 20.00(MeV)

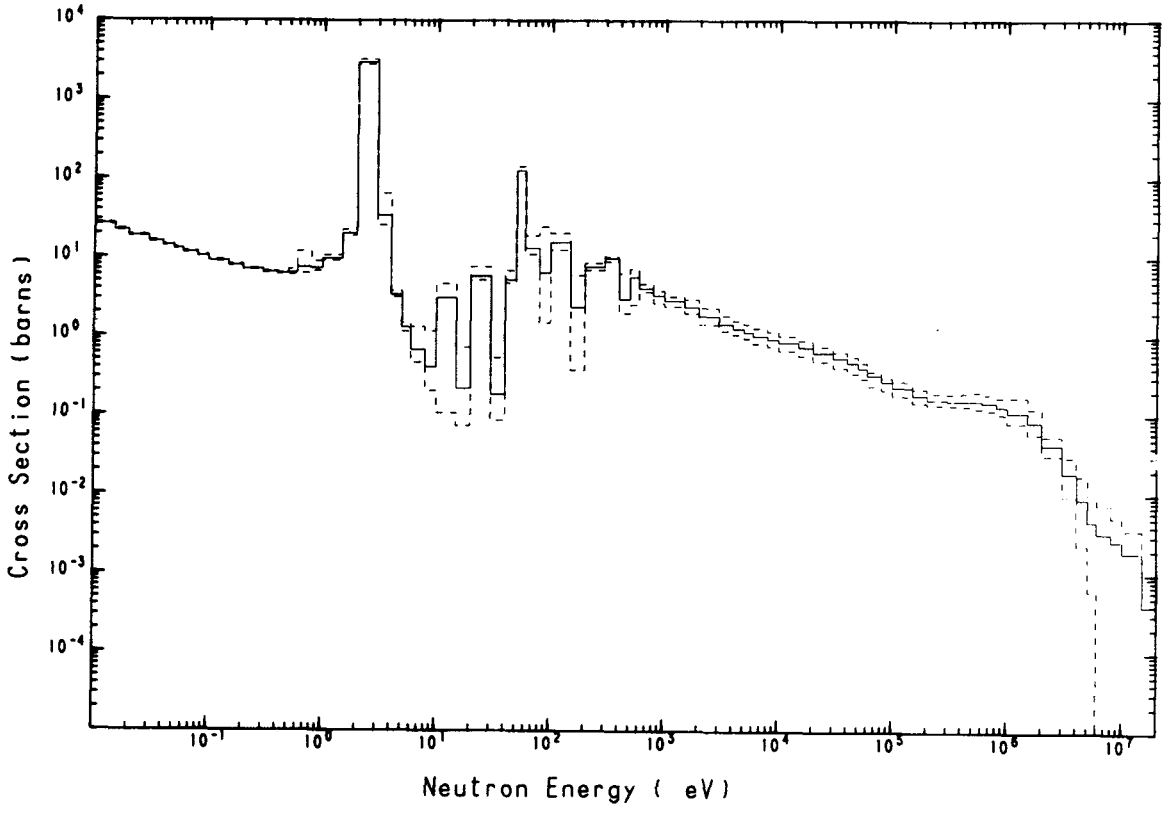


FIG. 16 Neutron Cross Section ^{242}Pu FISSION ENERGY 0.01(eV) - 10.00(keV)

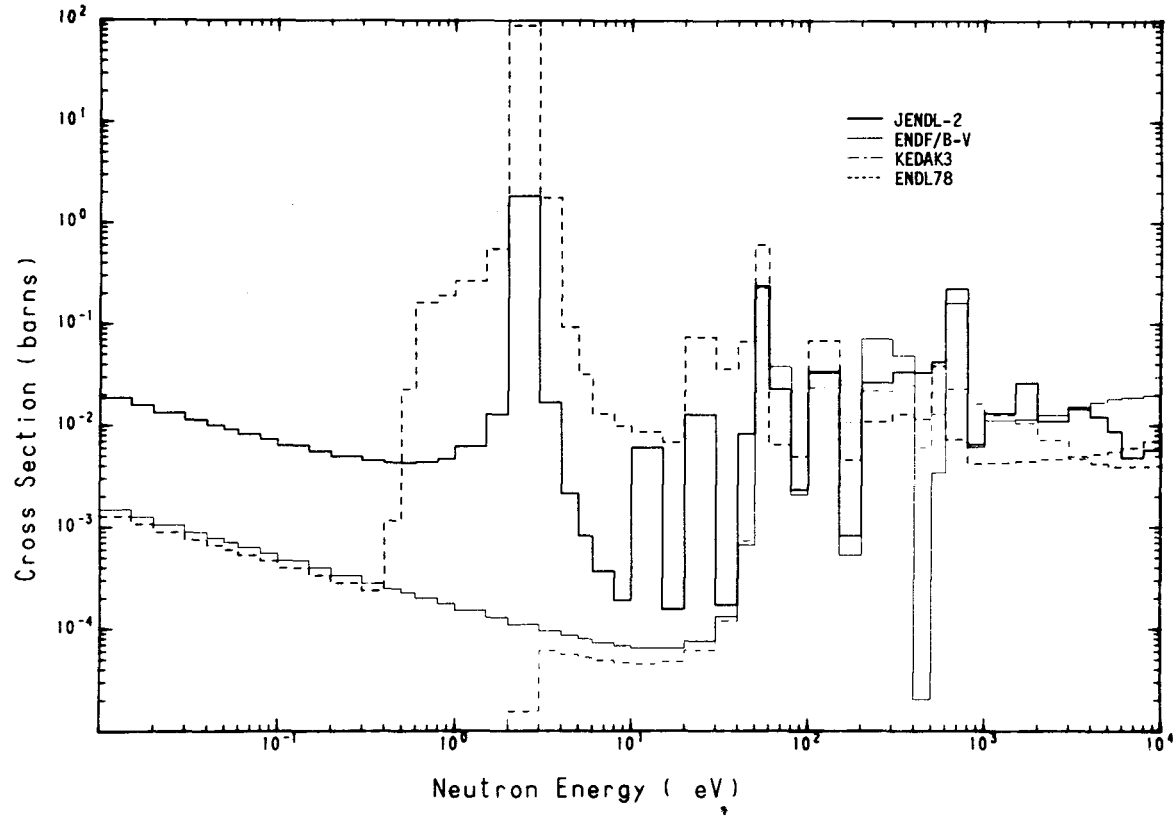


FIG. 17 Neutron Cross Section ^{242}Pu FISSION ENERGY 10.00(keV) - 20.00(MeV)

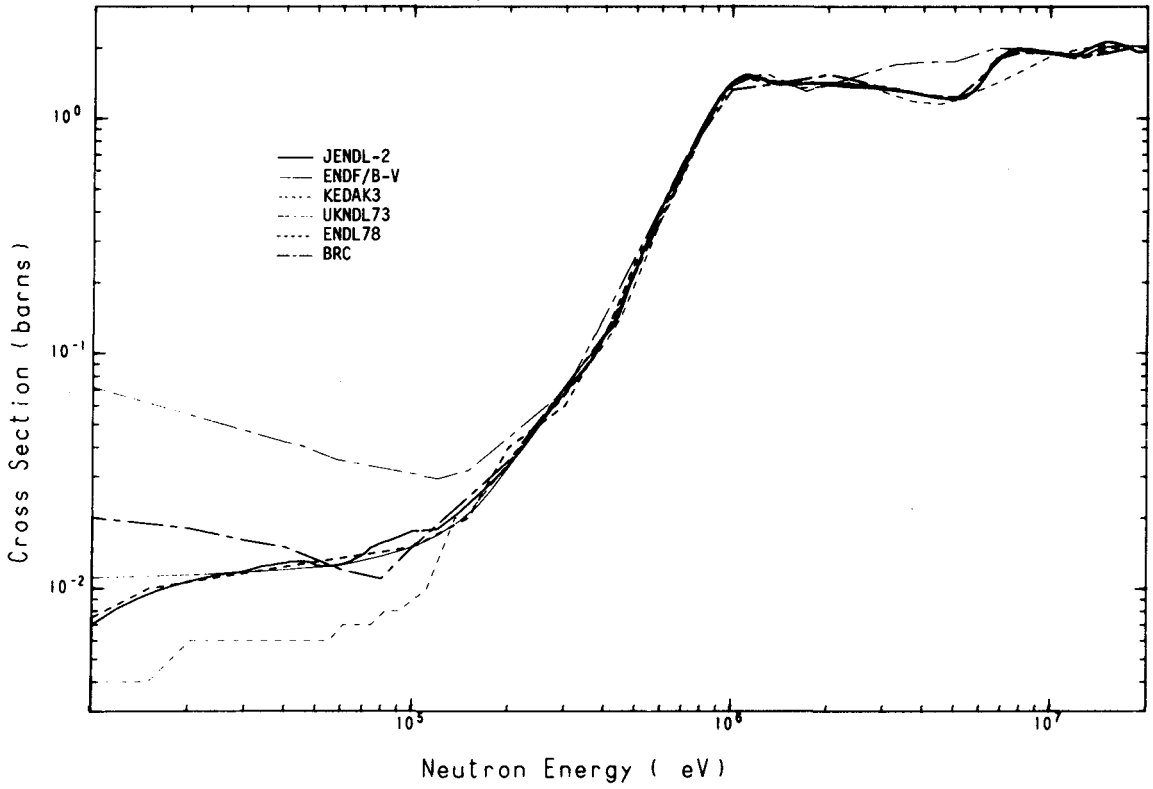


FIG. 18 Neutron Cross Section ^{242}Pu FISSION ENERGY 0.01(eV) - 20.00(MeV)

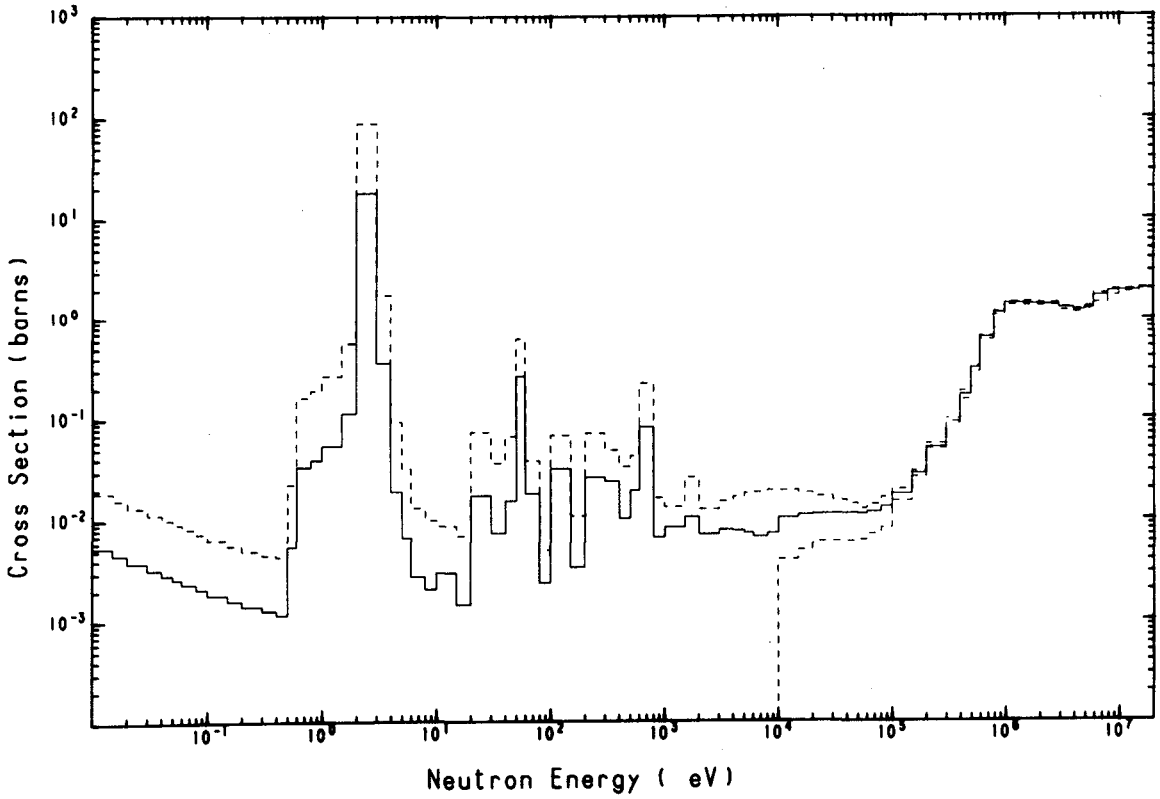


FIG. 19 Neutron Cross Section ^{241}Am CAPTURE ENERGY 0.01(eV) - 1.00(keV)

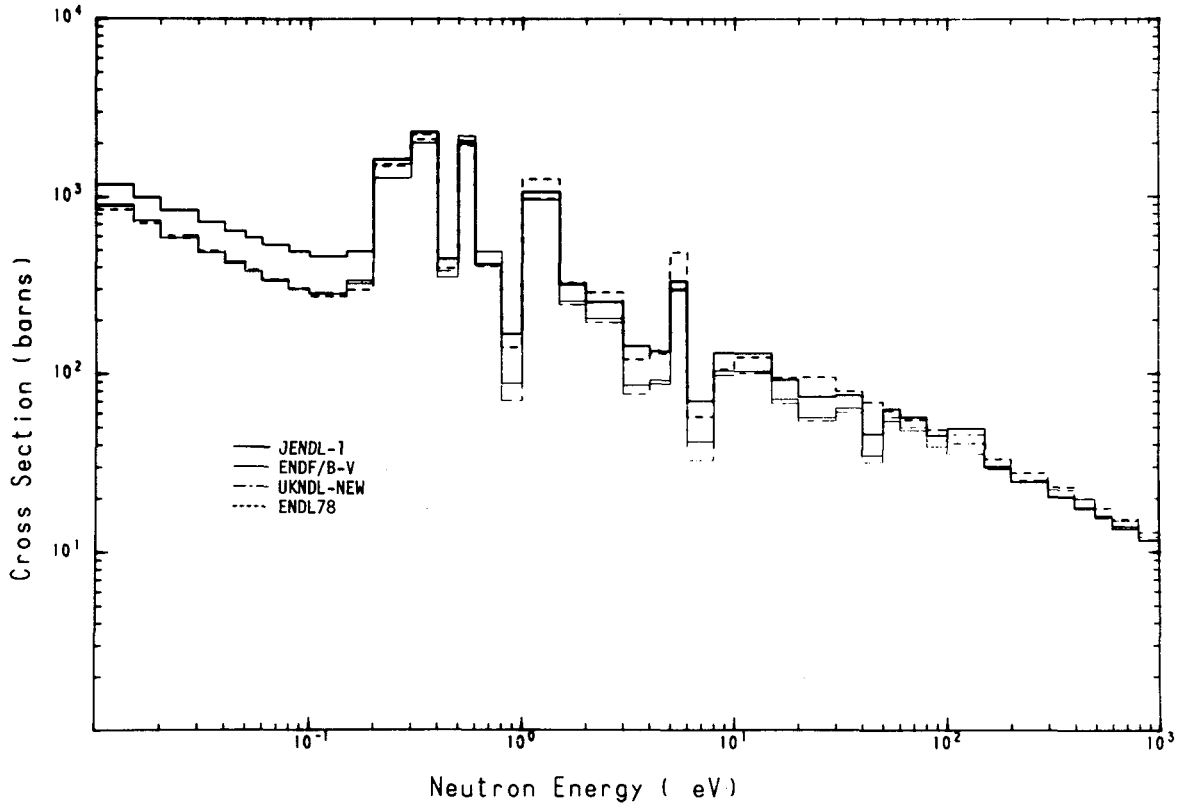


FIG. 20 Neutron Cross Section ^{241}Am CAPTURE ENERGY 1.00(keV) - 20.00(MeV)

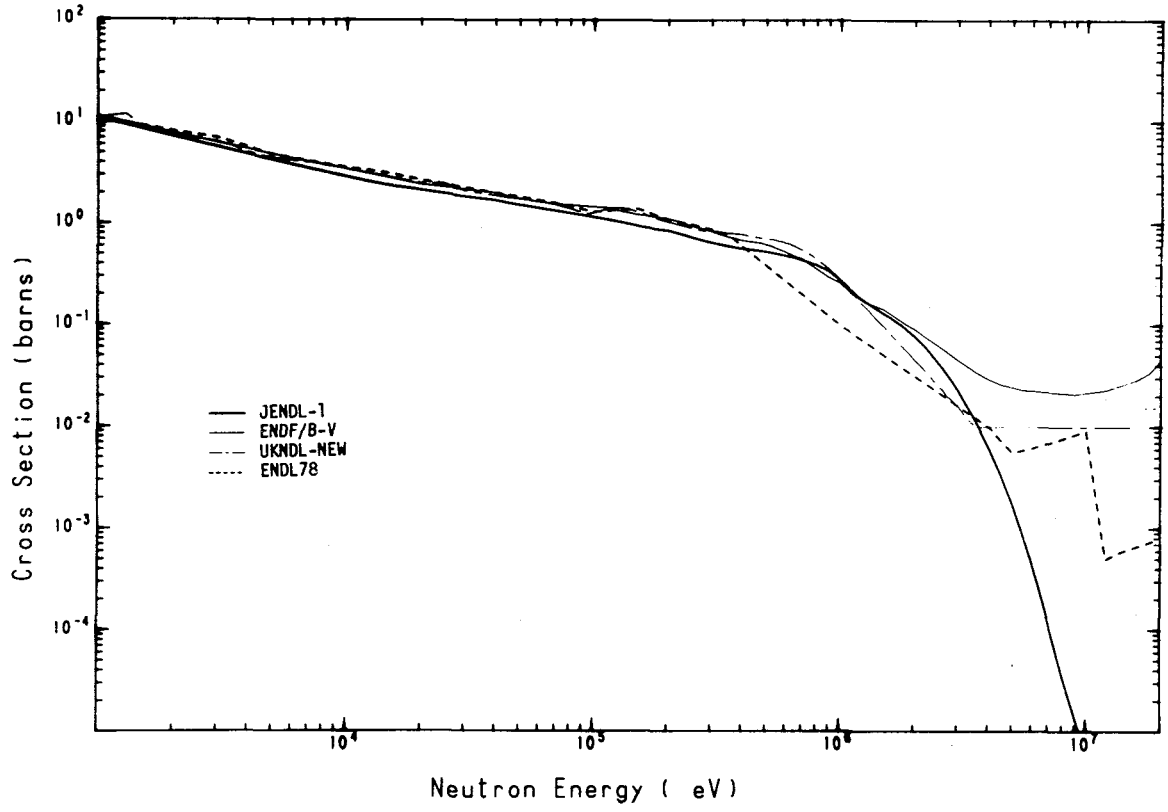


FIG. 21 Neutron Cross Section ^{241}Am CAPTURE ENERGY 0.01(eV) - 20.00(MeV)

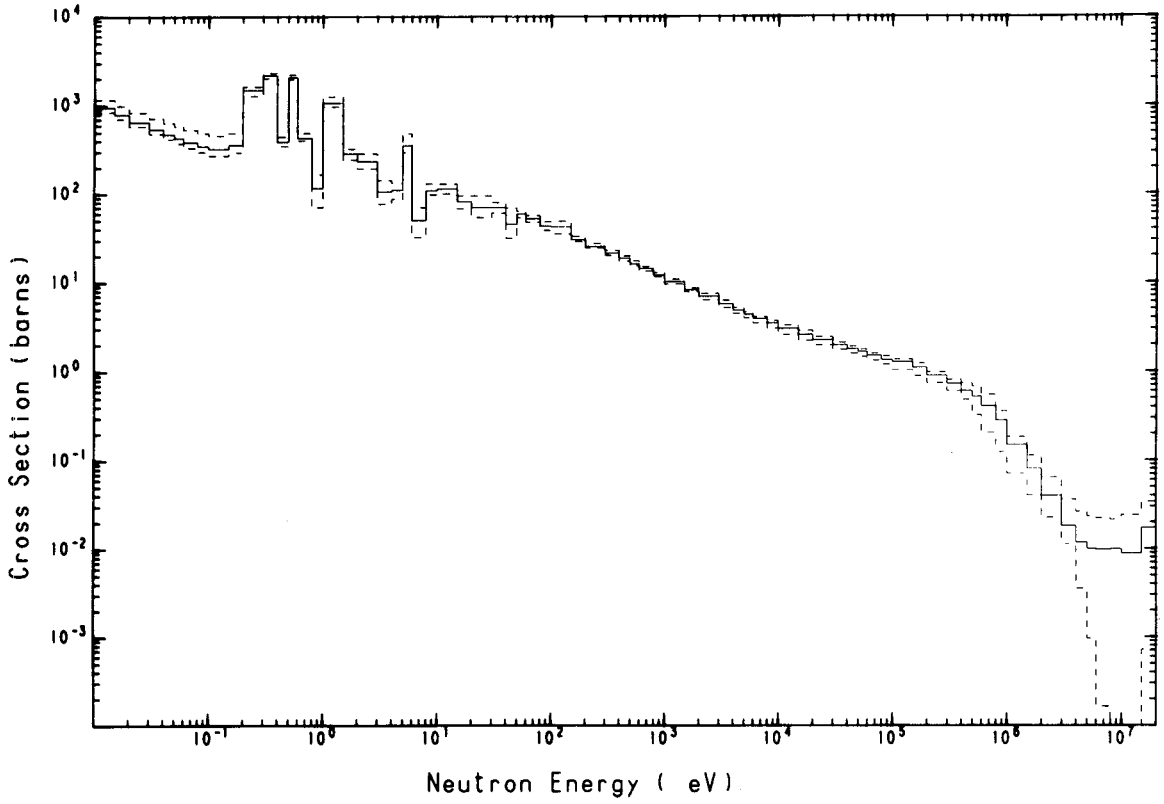


FIG. 22 Neutron Cross Section ^{241}Am FISSION ENERGY 0.01(eV) - 1.00(keV)

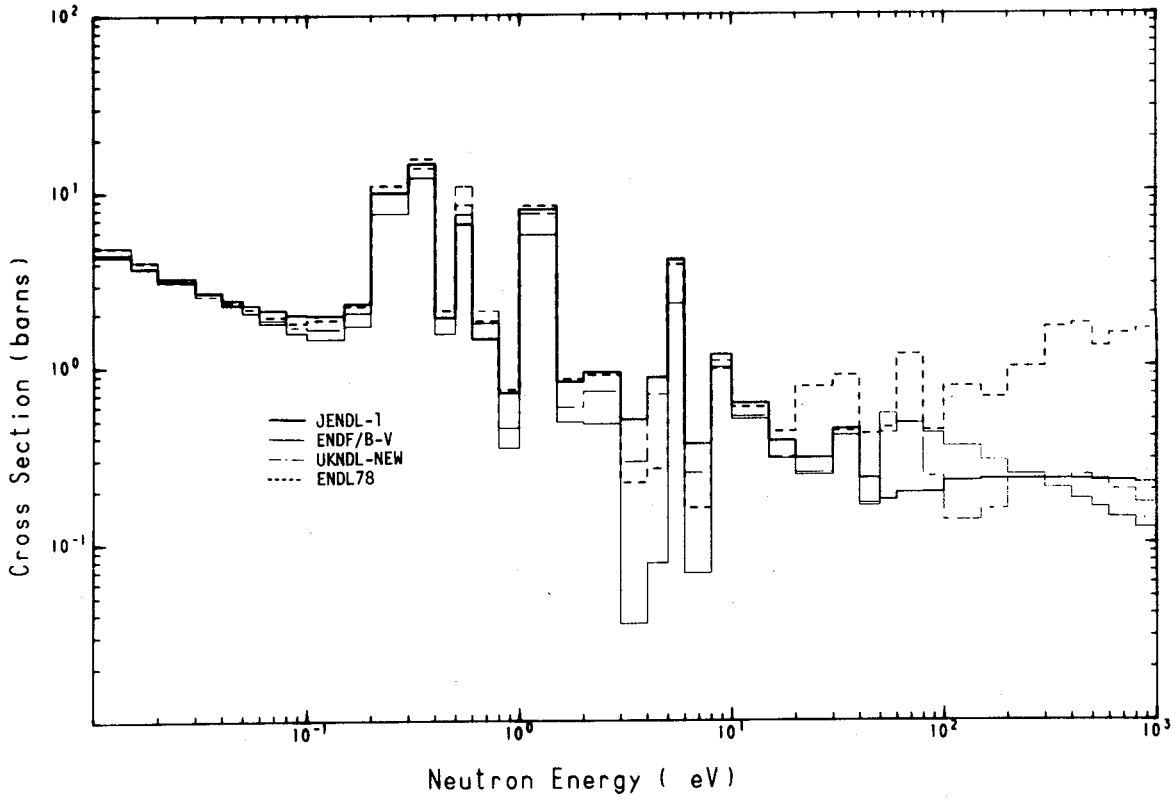


FIG. 23 Neutron Cross Section ^{241}Am FISSION ENERGY 1.00(keV) - 20.00(MeV)

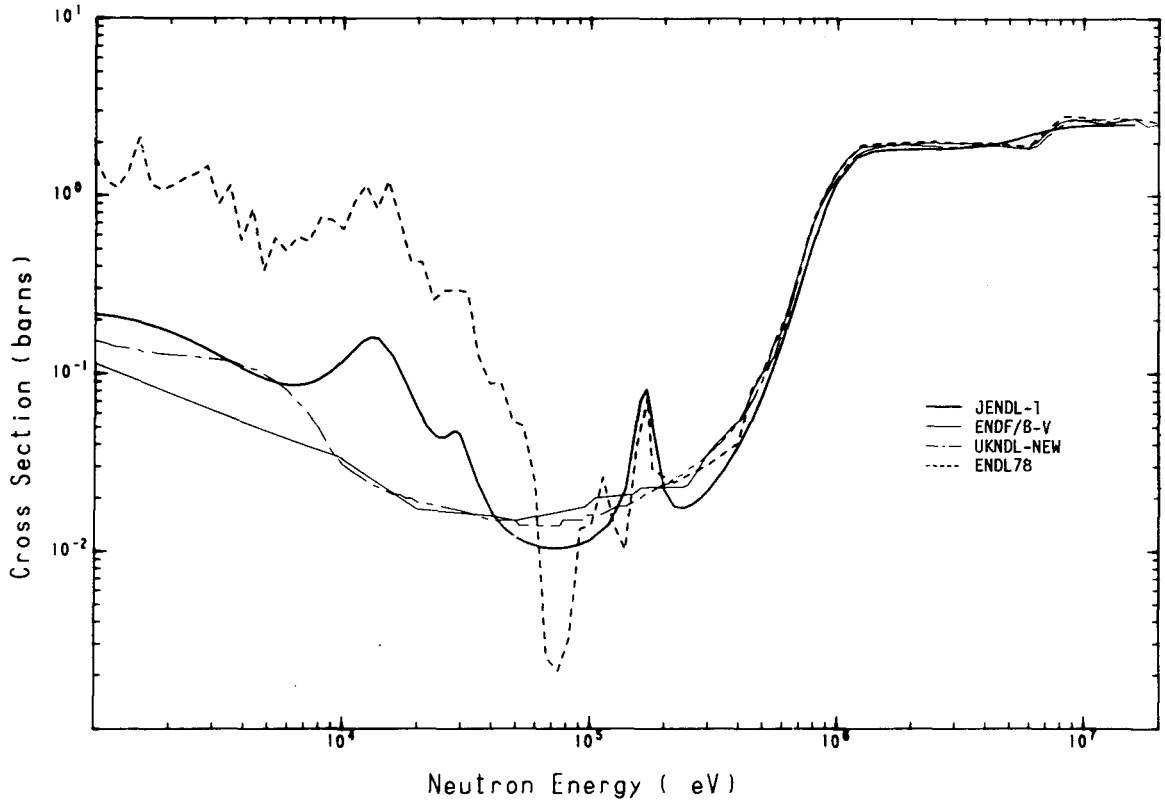


FIG. 24 Neutron Cross Section ^{241}Am FISSION ENERGY 0.01(eV) - 20.00(MeV)

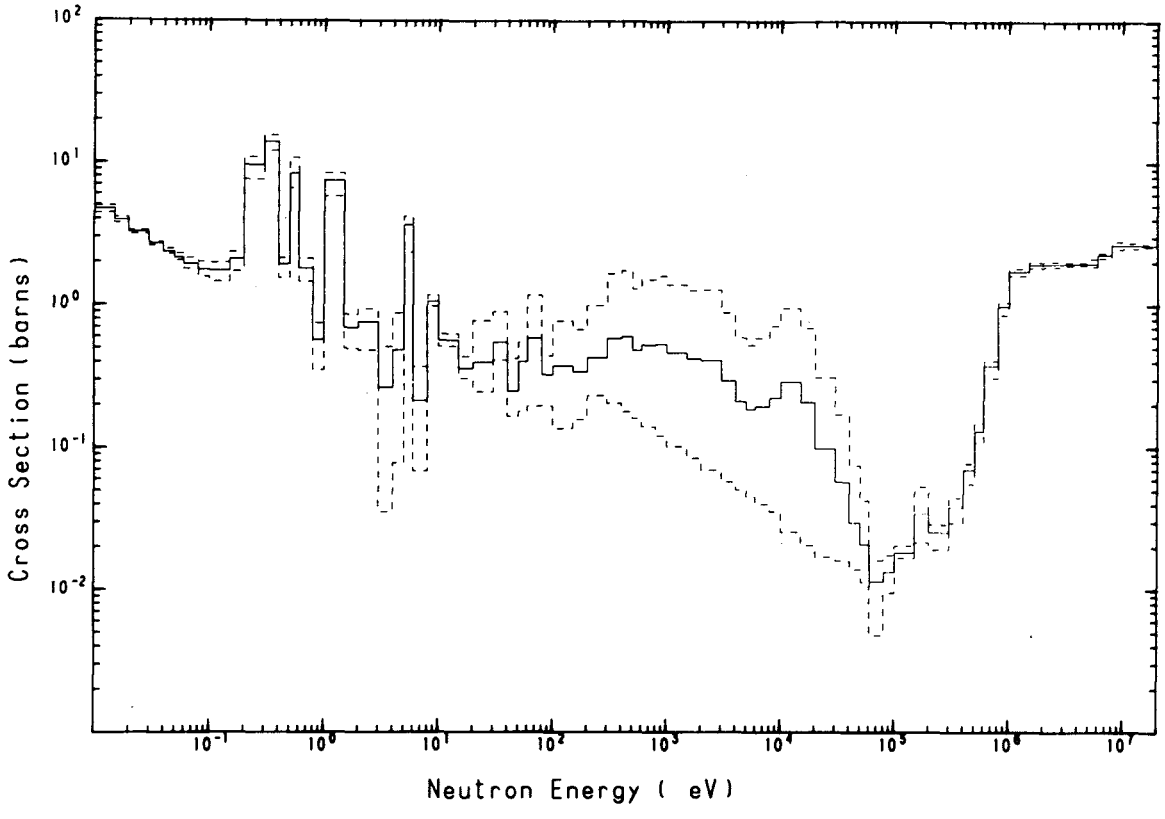


FIG. 25 Neutron Cross Section ^{243}Am CAPTURE ENERGY 0.01(eV) - 1.00(keV)

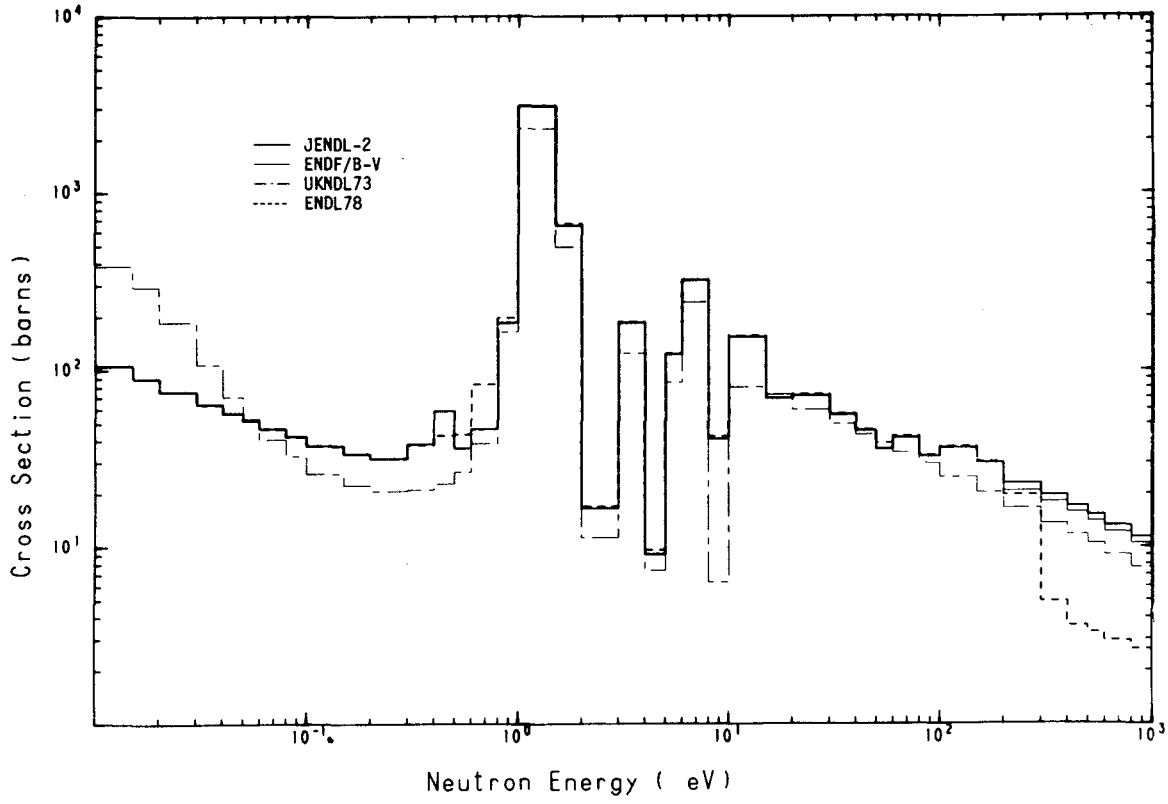


FIG. 26 Neutron Cross Section ^{243}Am CAPTURE ENERGY 1.00(keV) - 20.00(MeV)

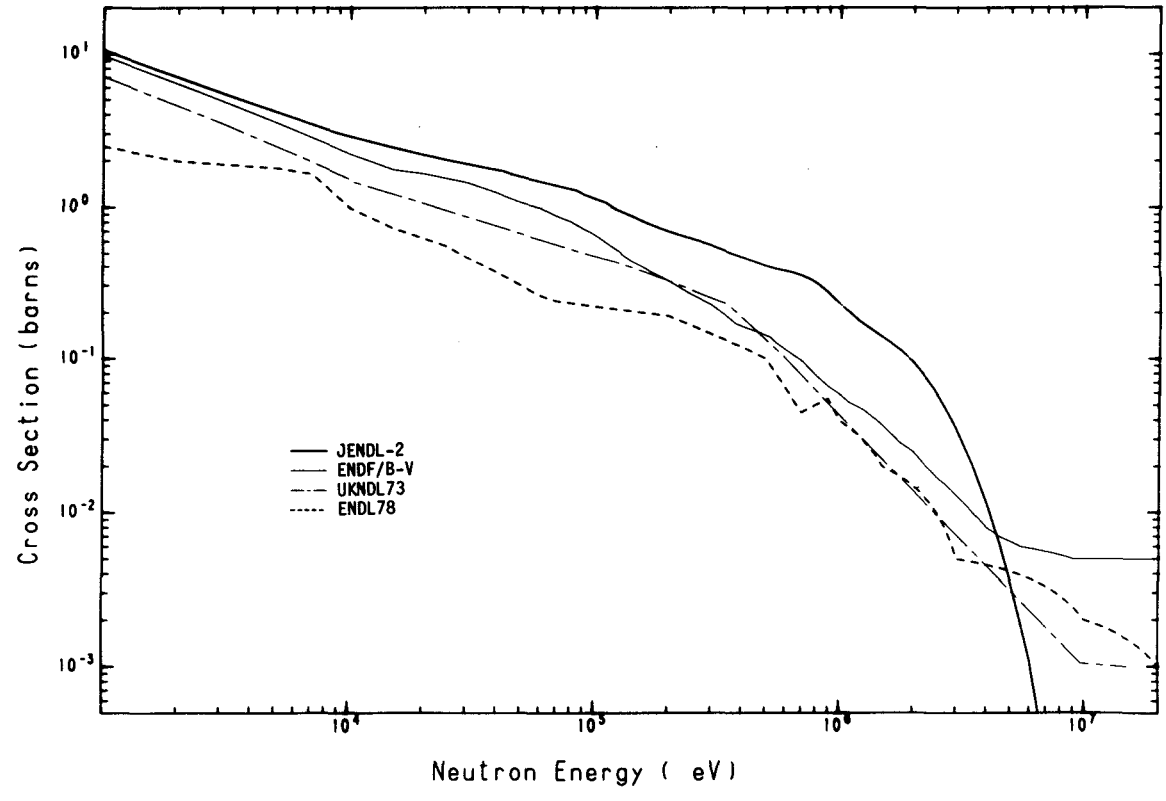


FIG. 27 Neutron Cross Section ^{243}Am CAPTURE ENERGY 0.01(eV) - 20.00(MeV)

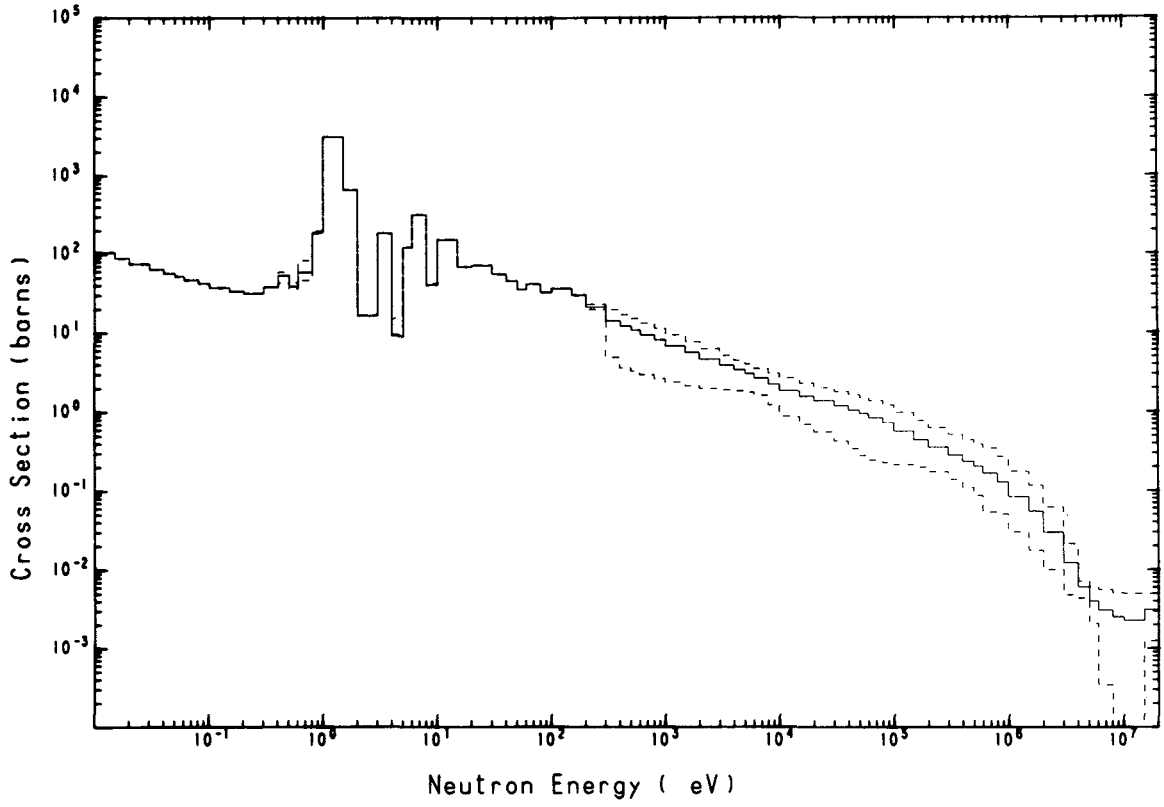


FIG. 28 Neutron Cross Section ^{243}Am FISSION ENERGY 0.01(eV) - 1.00(keV)

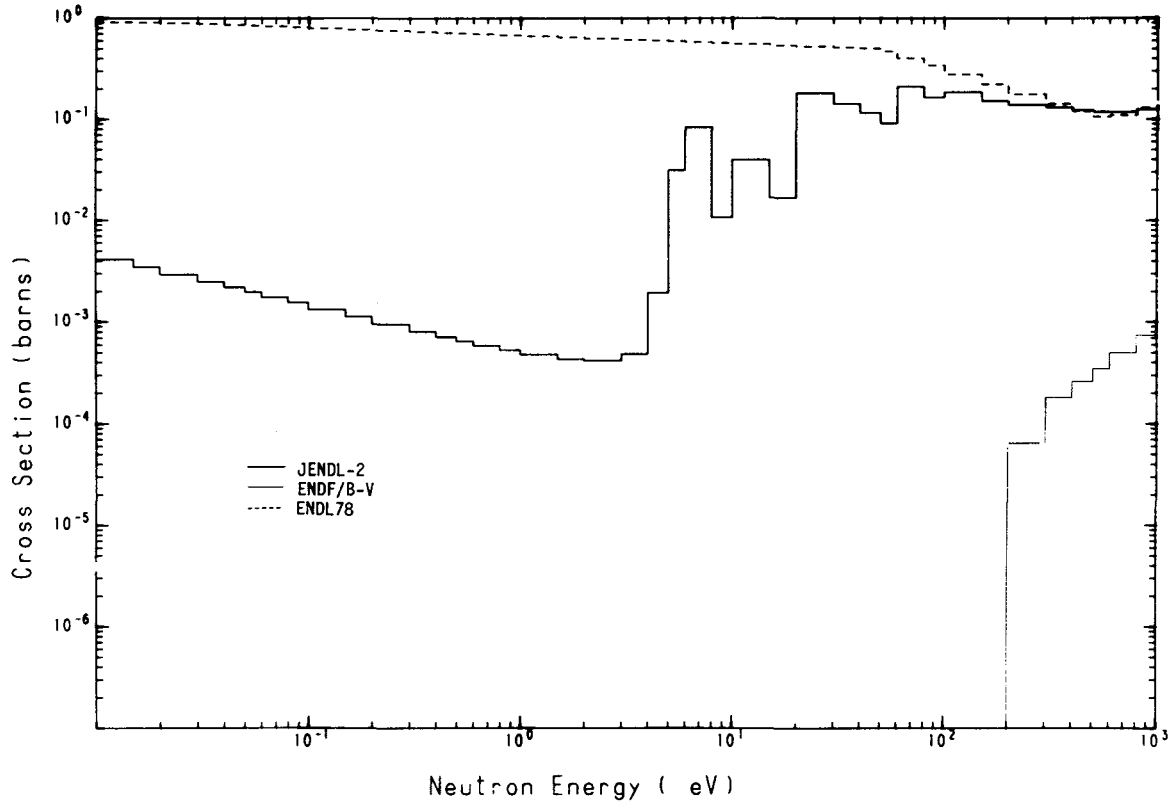


FIG. 29 Neutron Cross Section ^{243}Am FISSION ENERGY 1.00(keV) - 20.00(MeV)

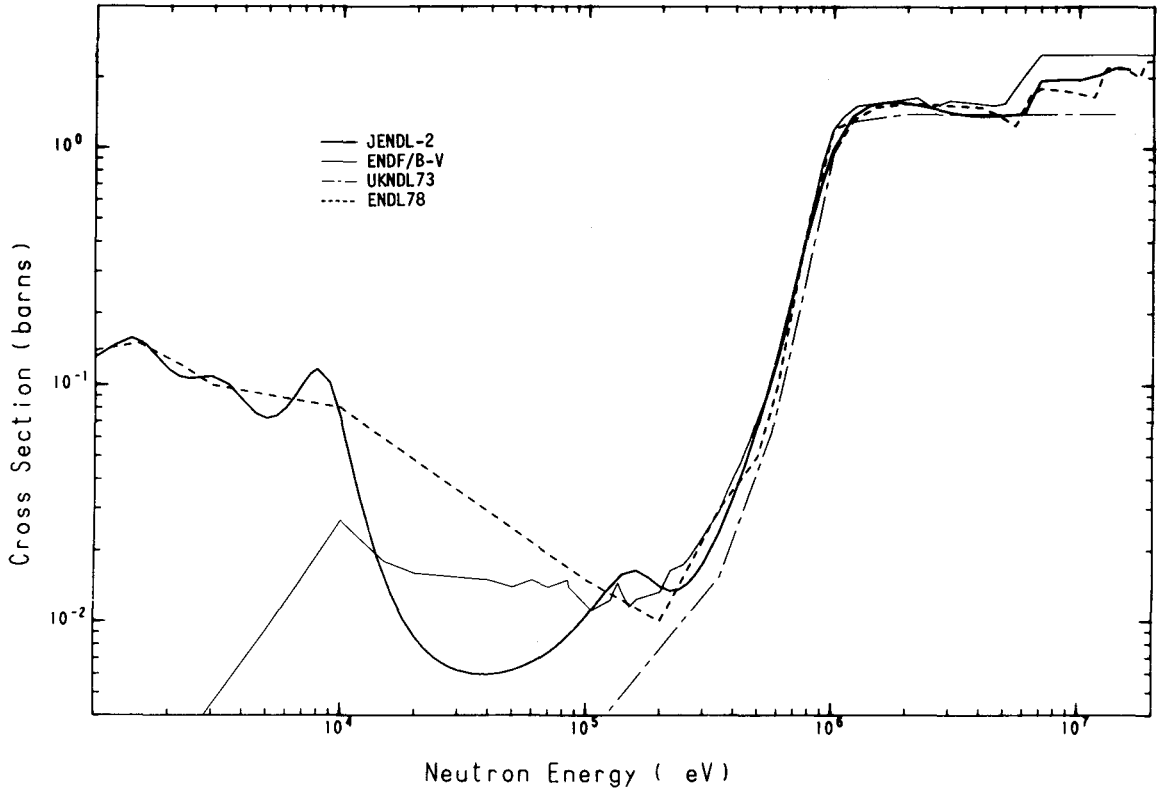


FIG. 30 Neutron Cross Section ^{243}Am FISSION ENERGY 0.01(eV) - 20.00(MeV)

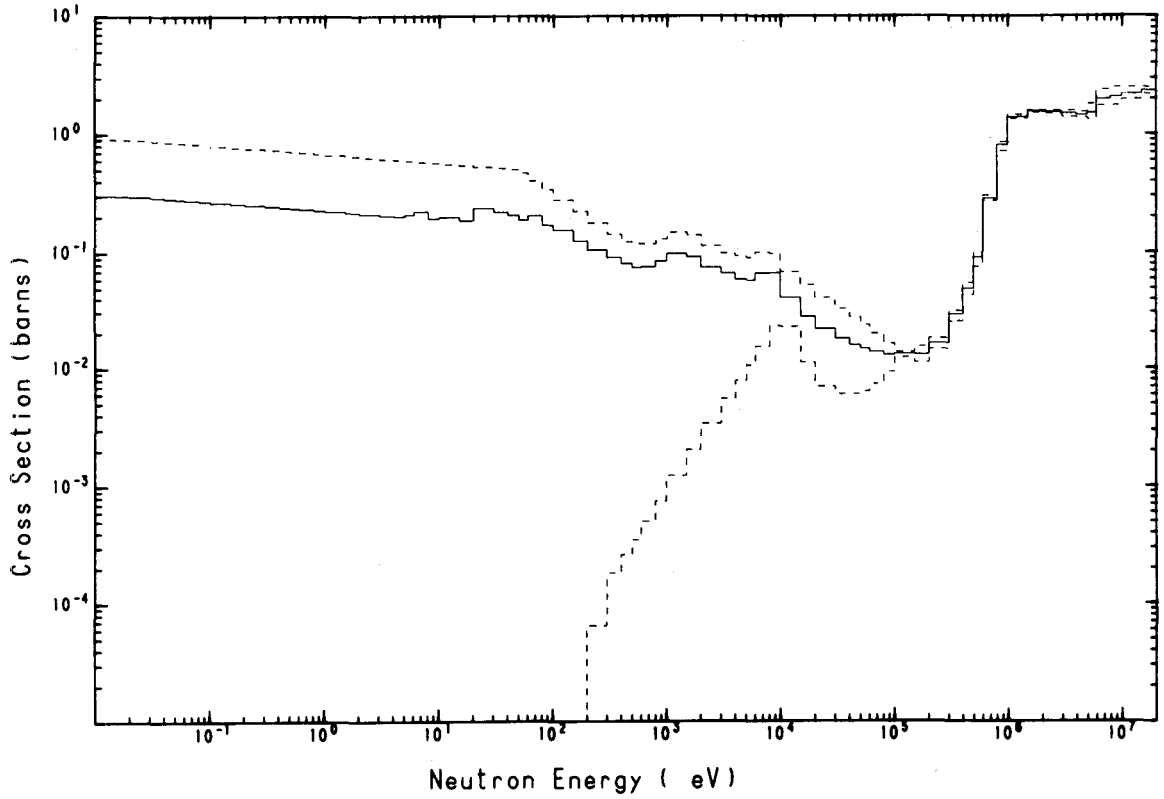


FIG. 31 Neutron Cross Section ^{244}Cm CAPTURE ENERGY 0.01(eV) - 1.00(keV)

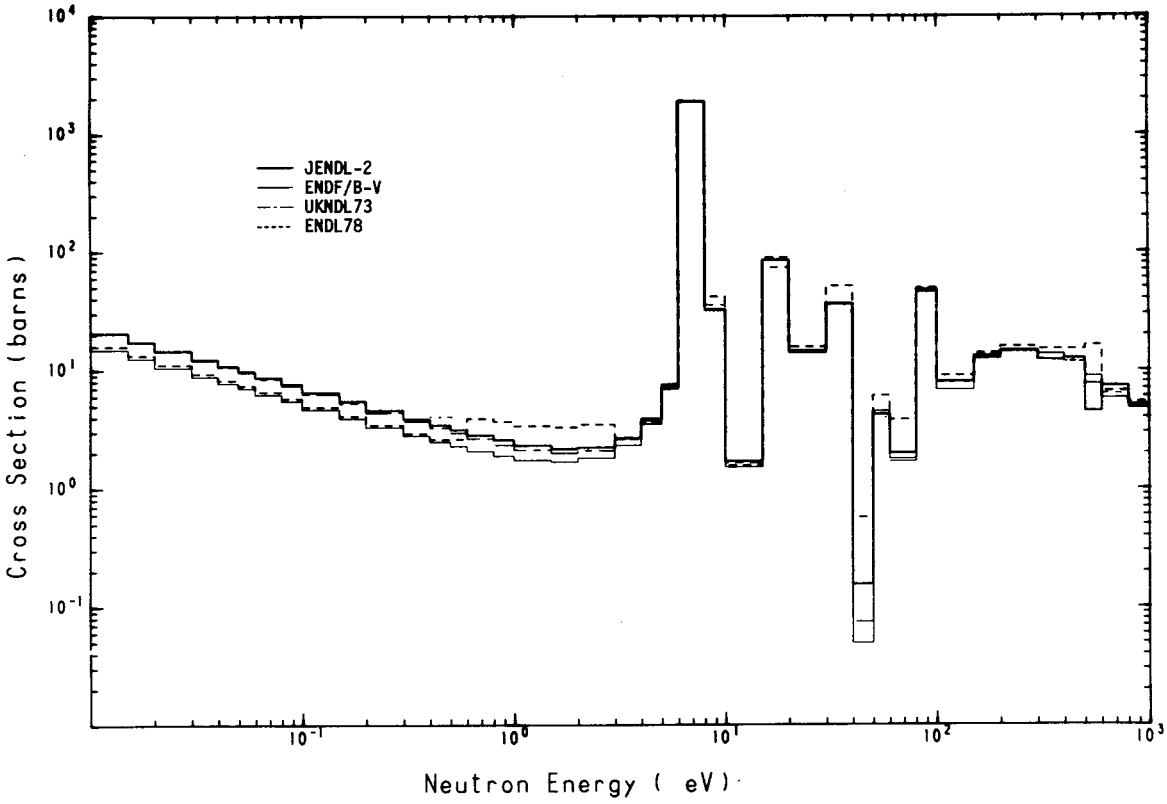


FIG. 32 Neutron Cross Section ^{244}Cm CAPTURE ENERGY 1.00(keV) - 20.00(MeV)

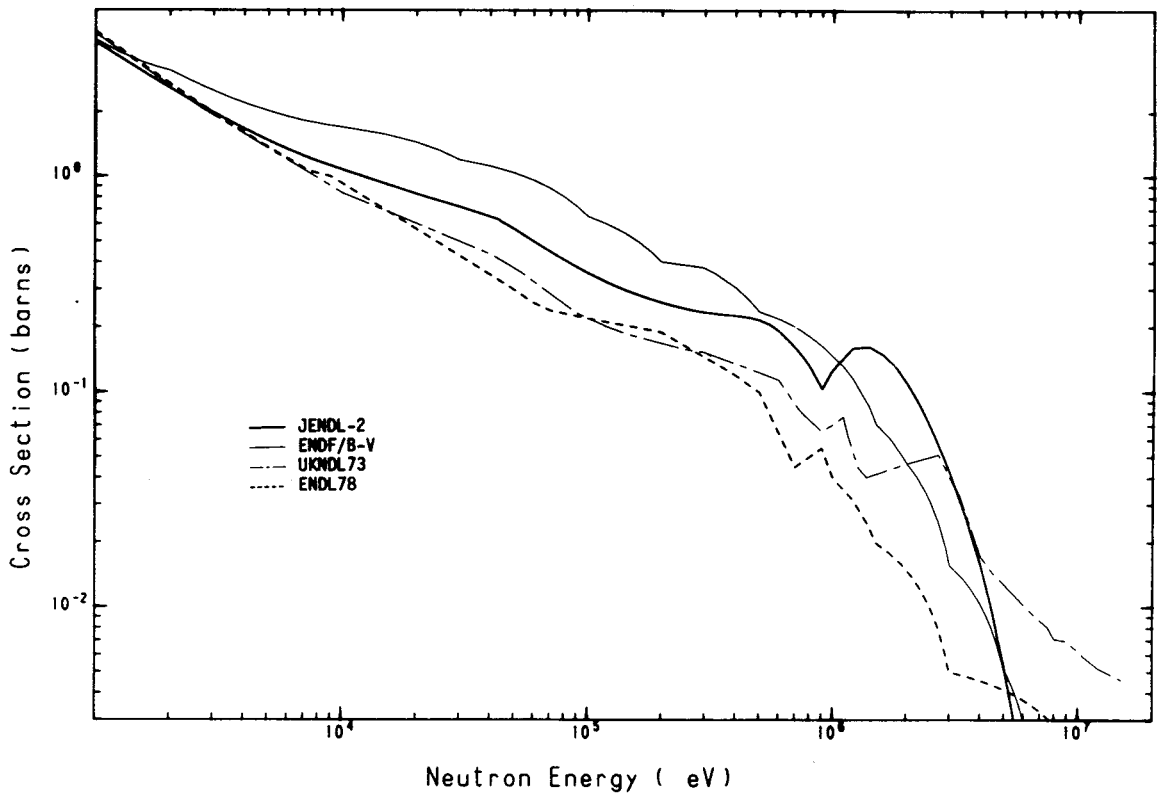


FIG. 33 Neutron Cross Section ^{244}Cm CAPTURE ENERGY 0.01(eV) - 20.00(MeV)

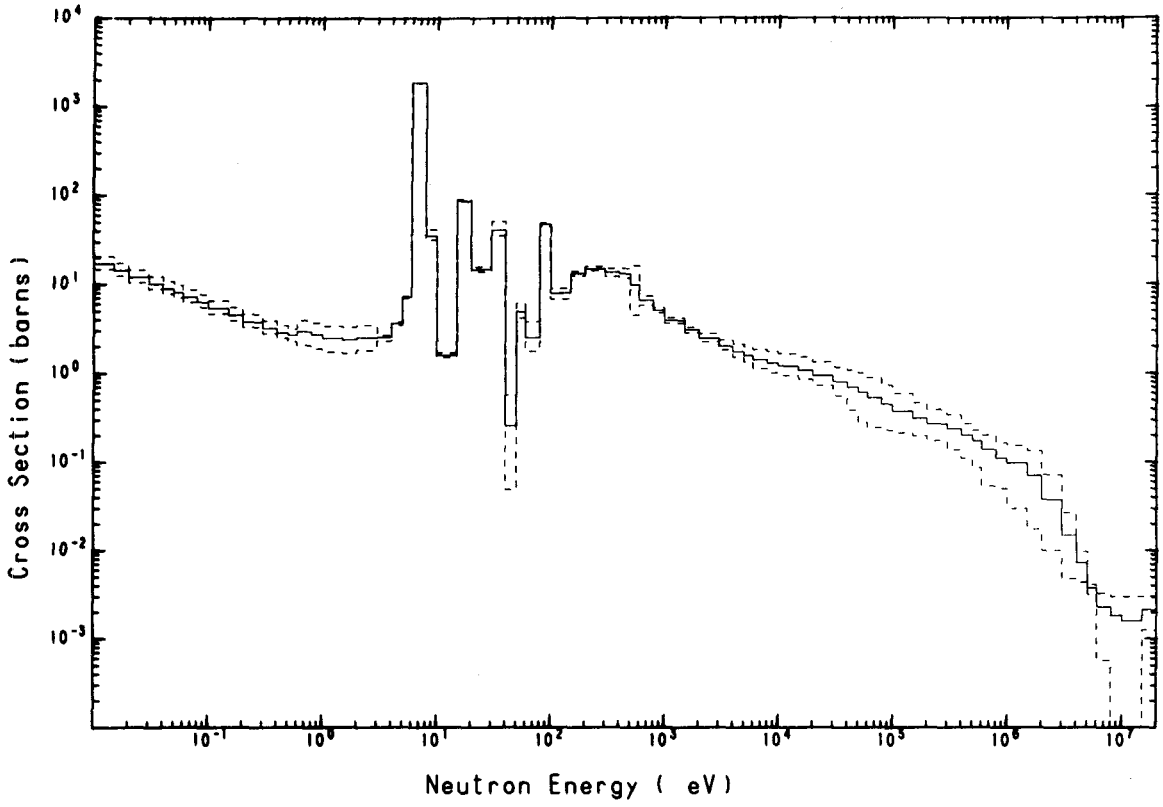


FIG. 34 Neutron Cross Section ^{244}Cm FISSION ENERGY 0.01(eV) - 1.00(keV)

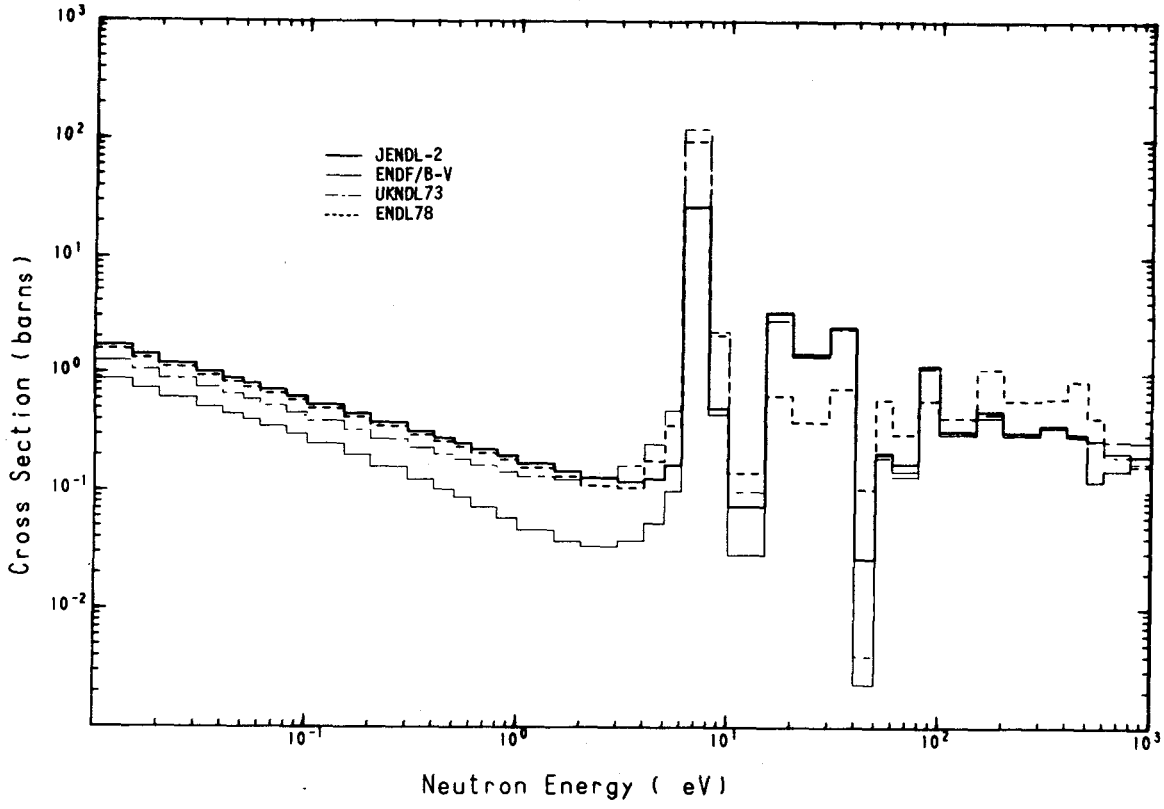


FIG. 35 Neutron Cross Section ^{244}Cm FISSION ENERGY 1.00(keV) - 20.00(MeV)

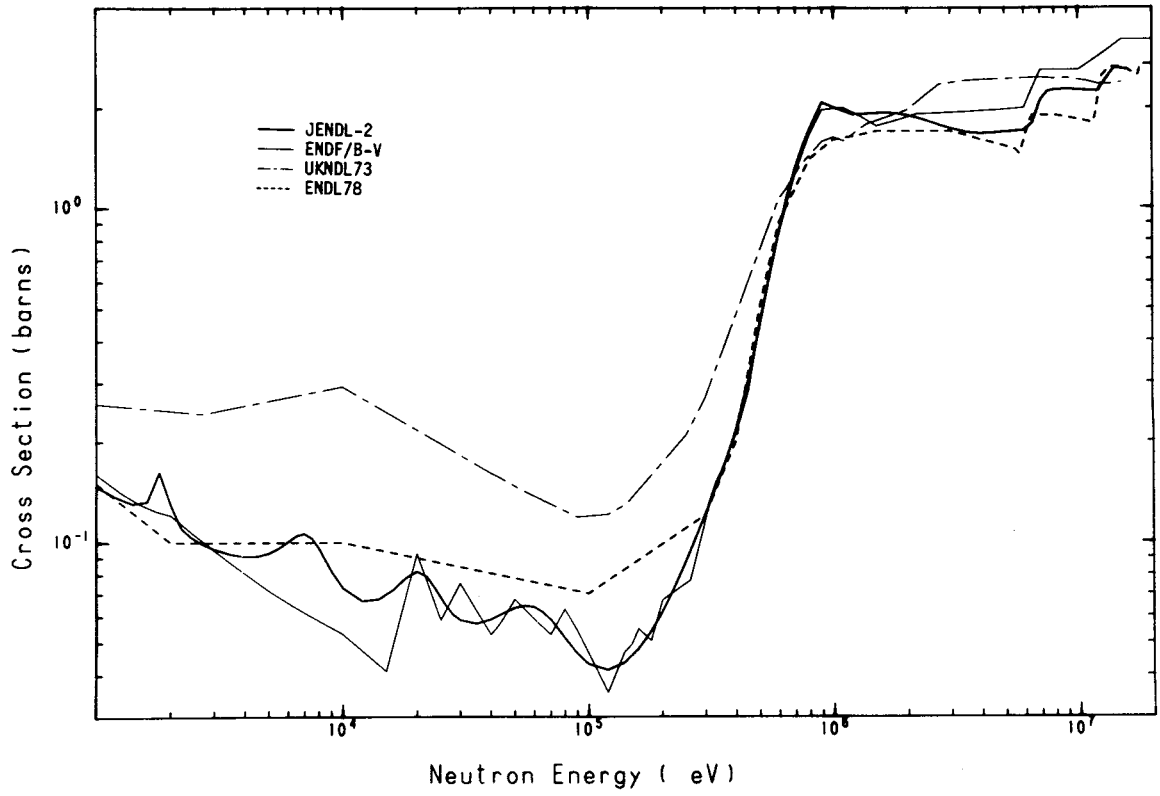


FIG. 36 Neutron Cross Section ^{244}Cm FISSION ENERGY 0.01(eV) - 20.00(MeV)

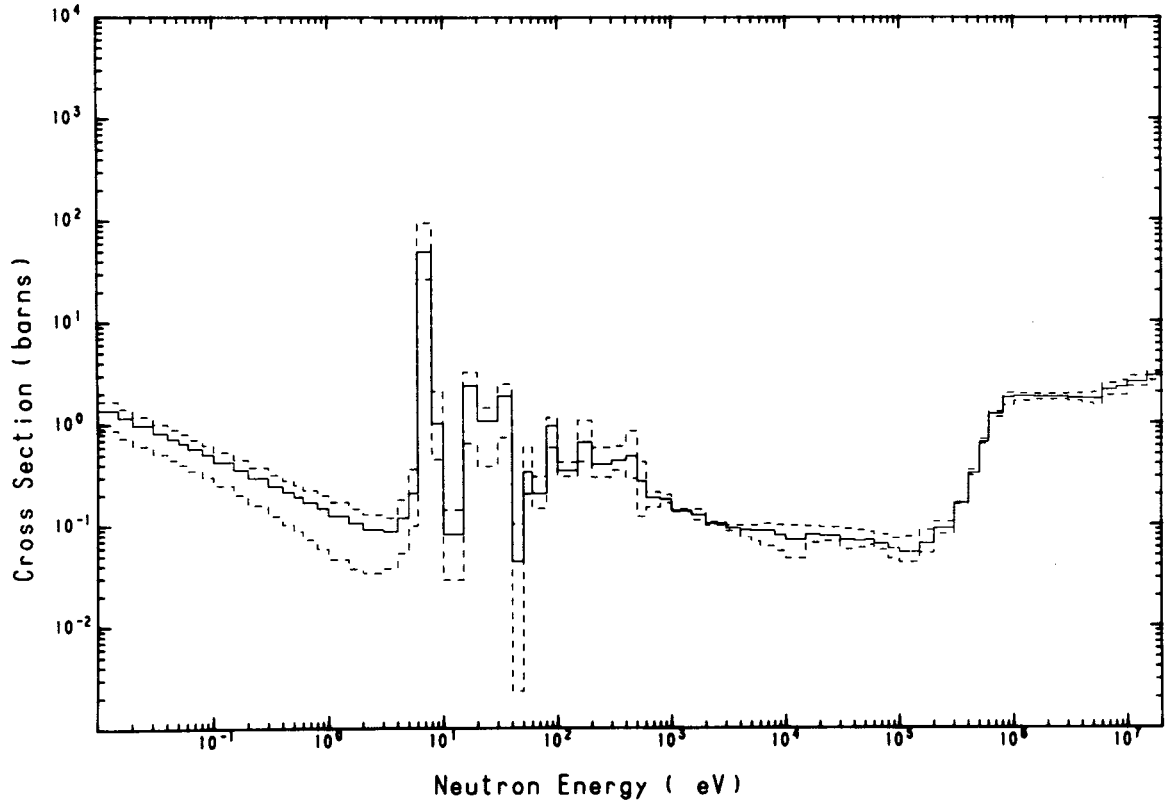


FIG. 37 Neutron Cross Section ^{245}Cm CAPTURE ENERGY 0.01(eV) - 1.00(keV)

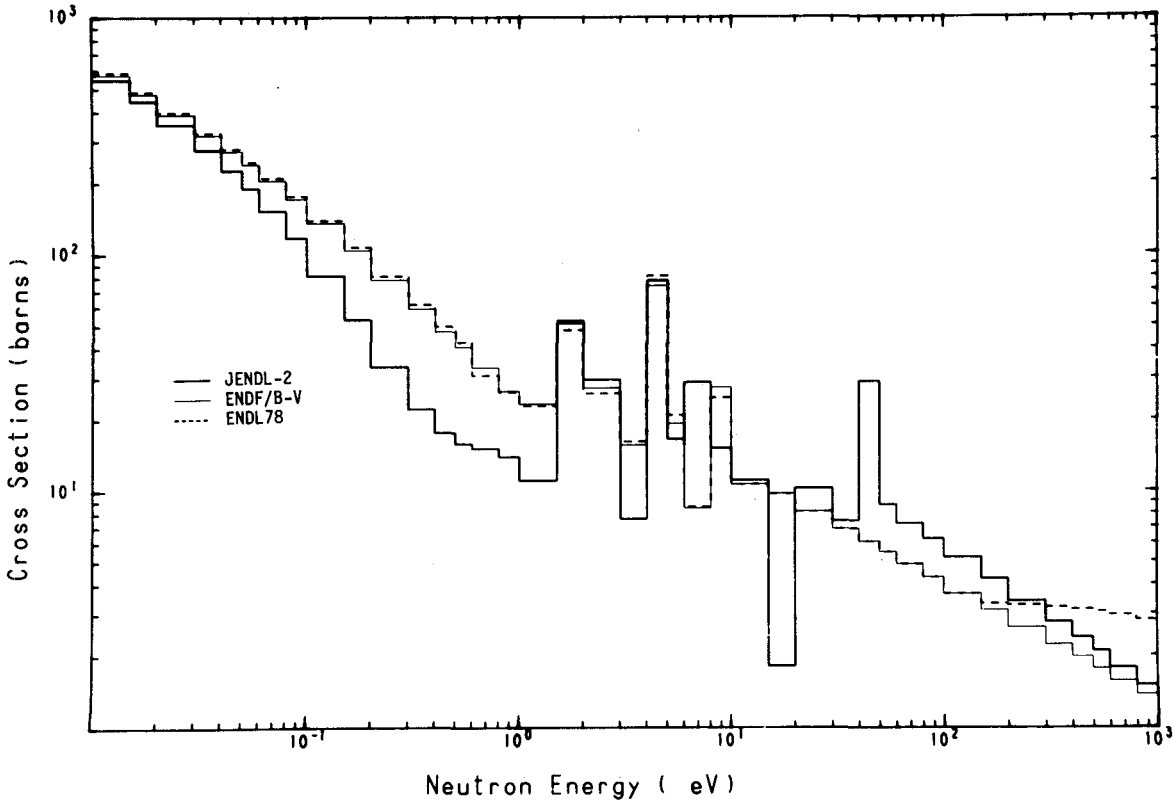


FIG. 38 Neutron Cross Section ^{245}Cm CAPTURE ENERGY 1.00(keV) - 20.00(MeV)

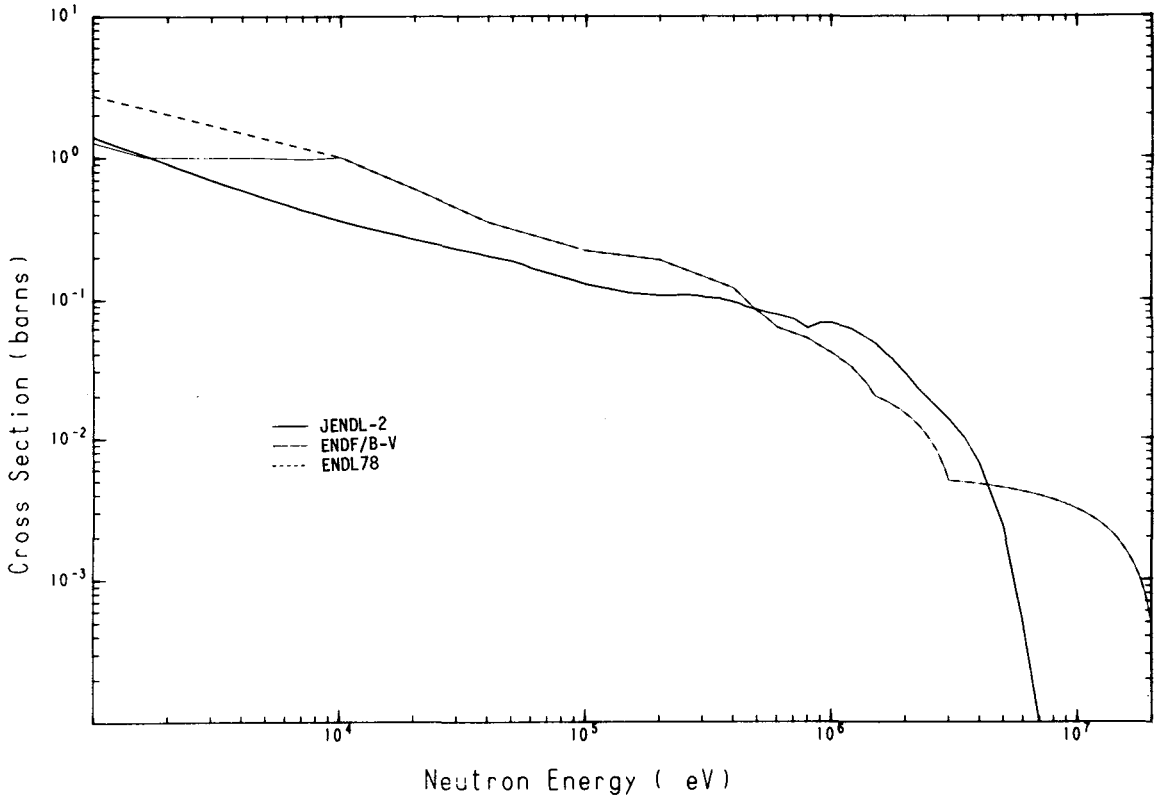


FIG. 39 Neutron Cross Section ^{245}Cm CAPTURE ENERGY 0.01(eV) - 20.00(MeV)

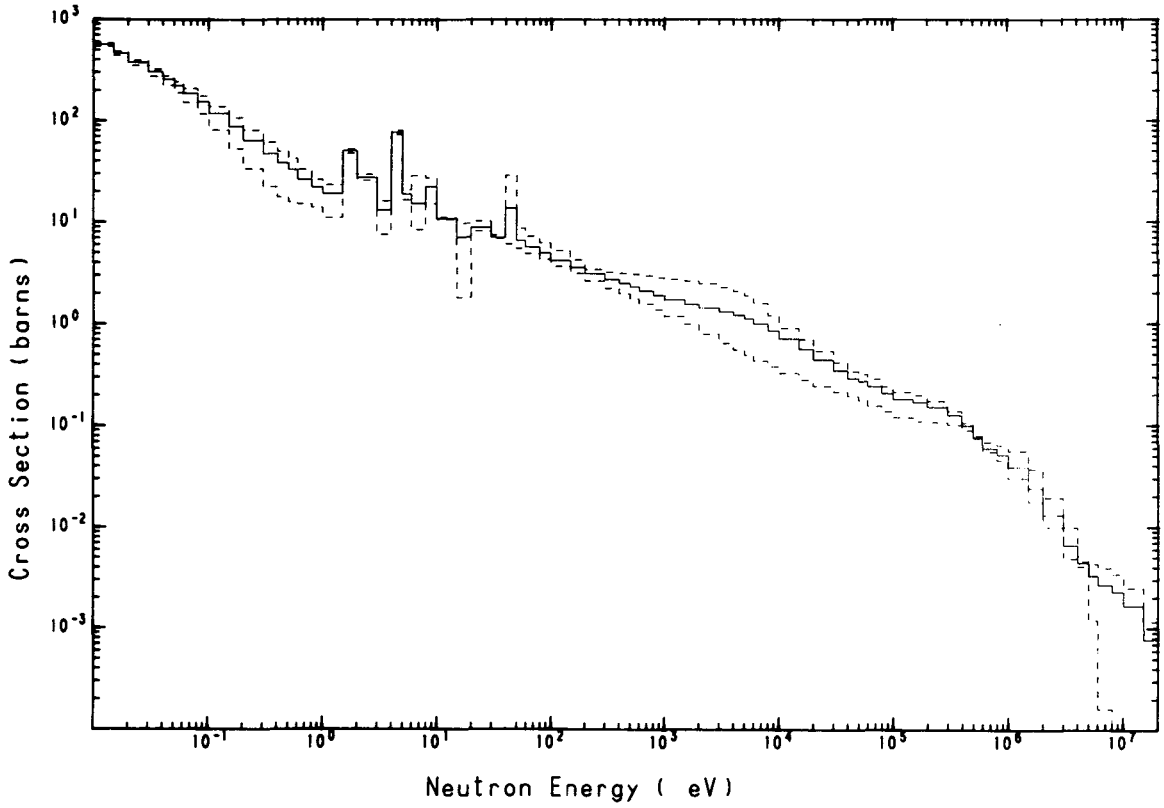


FIG. 40 Neutron Cross Section ^{245}Cm FISSION ENERGY 0.01(eV) - 1.00(keV)

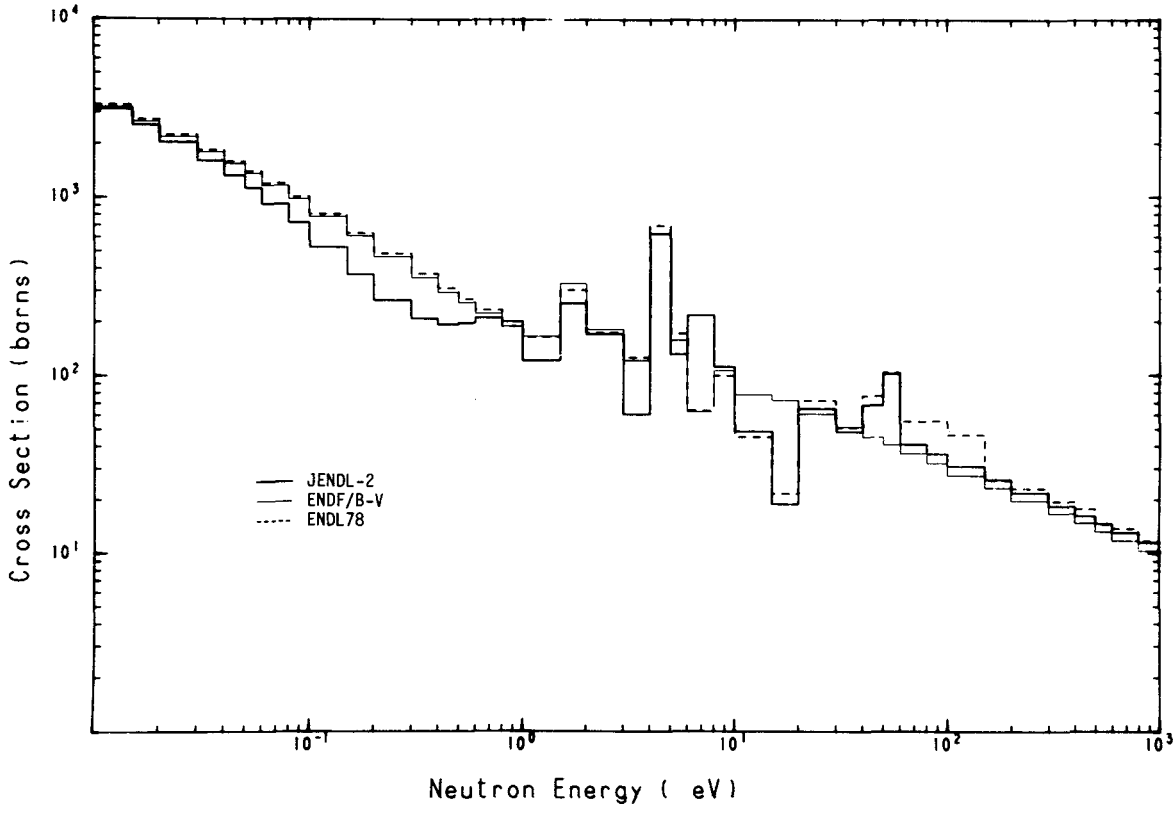


FIG. 41 Neutron Cross Section ^{245}Cm FISSION ENERGY 1.00(keV) - 20.00(MeV)

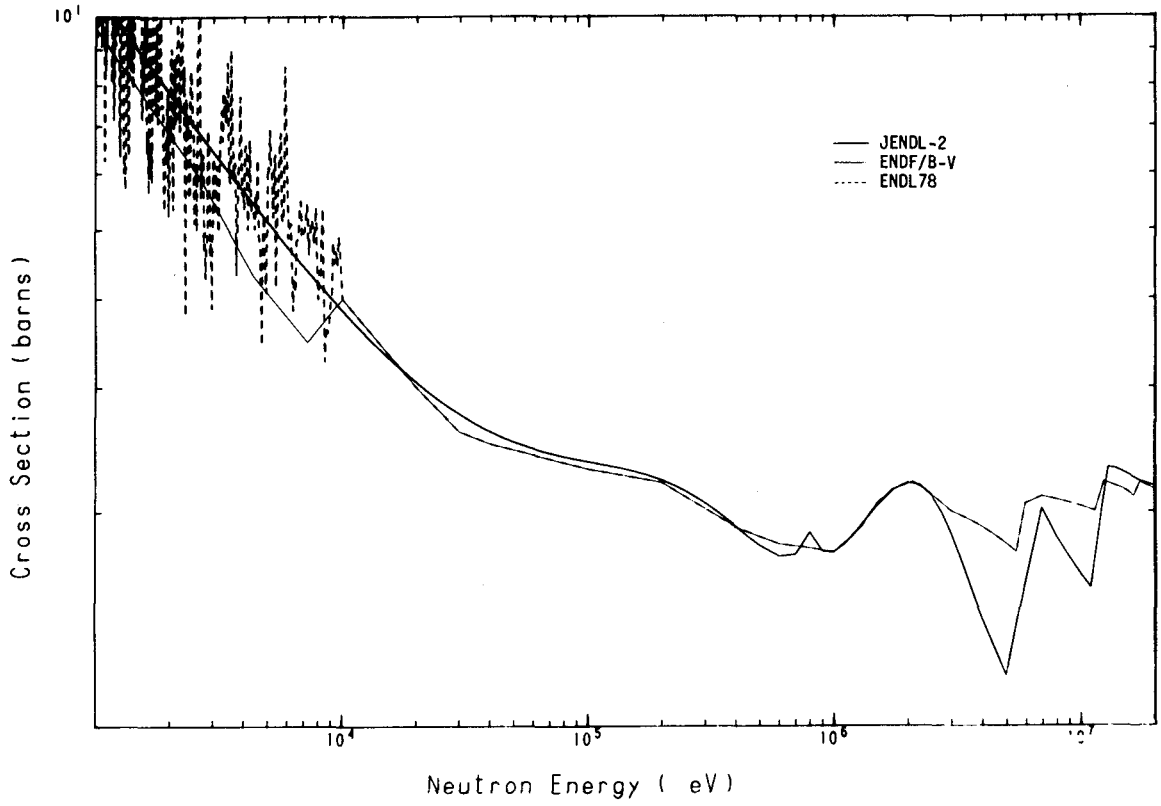
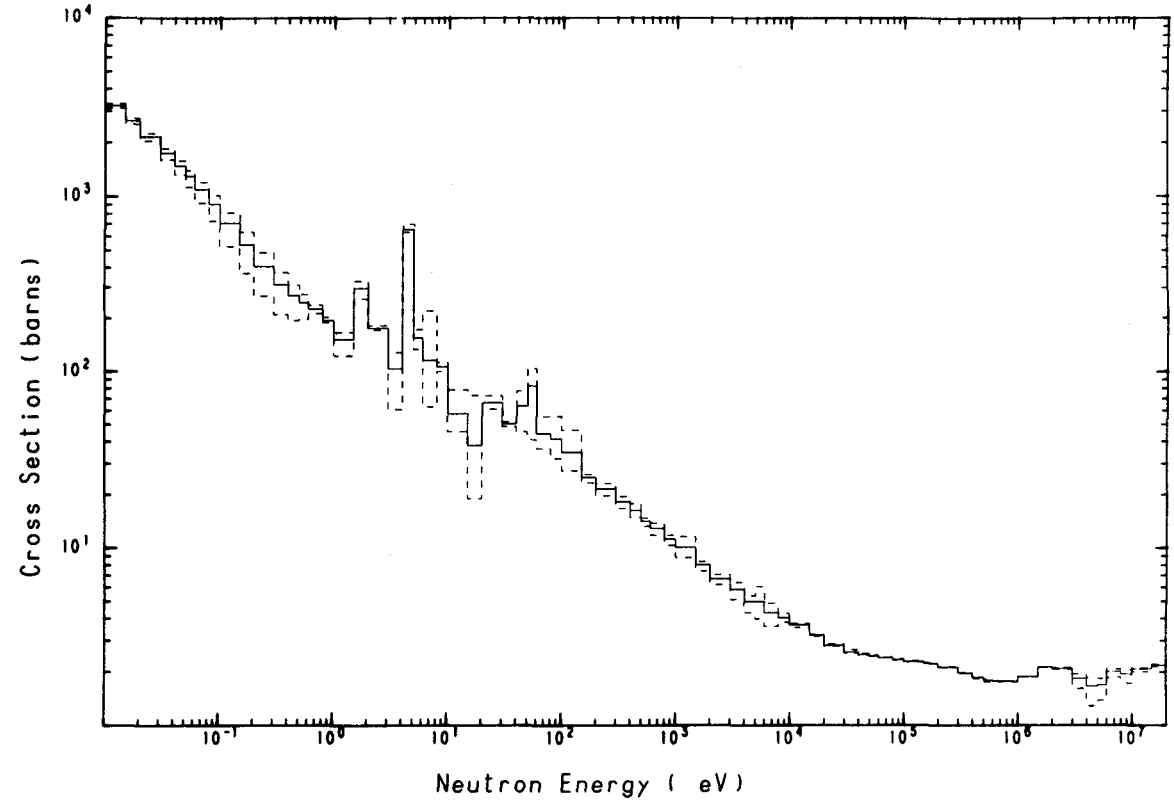


FIG. 42 Neutron Cross Section ^{245}Cm FISSION ENERGY 0.01(eV) - 20.00(MeV)



EVALUATION AND CALCULATION OF NEUTRON TRANSACTINIDE CROSS-SECTIONS

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Abstract

This paper reviews the state of the art of nuclear theory and its application to the evaluation and calculation of neutron reaction cross sections of transactinium isotopes. In particular, the paper describes the current evaluation of the total files of neutron reaction data for ^{240}Pu and ^{241}Pu in the energy range between 10^{-5} eV and 15 MeV based on a thorough analysis of available experimental data and on the use of modern theoretical concepts, and the work in progress on the evaluation of the total neutron reaction data file for ^{242}Pu and ^{241}Am.

At the Heat and Mass Transfer Institute during the last years the efforts of researchers have been made to develop the methods for evaluating nuclear constants of heavy fissile nuclei and to obtain self-consistent systems of nuclear transactinide data (total files). Based on a thorough analysis of the available experimental data and on the use of modern theoretical concepts, the total files of nuclear data are recently elaborated in the energy range between 10^{-5}eV and 15 MeV for ^{240}Pu and ^{241}Pu. Now the total file of ^{242}Pu is in the process of completion and the one for ^{241}Am is being developed.

As it is impossible to evaluate nuclear data for transactinides because of the lack of reliable experimental data, theoretical models are to be used and developed.

The modern state of the art of nuclear theory, when specially developed models with thoroughly tested parameters are employed, makes it possible to predict neutron integral-nature cross sections for heavy fissile nuclei with no experimental data, within the accuracy from 5 to 30 %, depending on the type of cross sections, energy ranges and the availability of indirect experimental information. The theory of nuclear reactions in this case should be considered as a means to obtain different parameters that would allow analysis of various experimental data as a whole. Determination of reliable parameters, based on a systematic analysis of a great deal of the existing experimental data, should be considered at present as a main trend in evaluating nuclear data.

In the resolved resonance energy range, for example, when σ_t and σ_f are experimentally known, the parametrization of neutron cross sections of fissile nuclei permits calculation of radiative capture cross sections that cannot be easily measured. Our computer programs realizing the Reich-Moore, Adler-Adler and Breit-Wigner formalisms may be employed to make a single- and multilevel analysis of the neutron cross sections and to determine resonance parameters based on the available experimental data. However, in virtue of scanty experimental data and the absence of the measured spins for the nuclei heavier than ^{239}Pu, it is early to speak about a detailed multilevel analysis of these nuclei. It is therefore advisable to adopt the Breit-Wigner formalism for transactinides.

The most important information that should be obtained from the resonance range is associated with $\langle\Gamma_\gamma\rangle$ and $\langle D \rangle$, since determination of their absolute values, within an accuracy of 10%, using the theoretical models or nuclear systematics /1-2/ still remains to be a problem.

Our analysis of the experimental data for resolved resonance energy ranges (0.25-100.0 eV) for ^{241}Pu has led to the following average parameters: $\langle D \rangle = 1.34 \pm 10$ eV, $\langle\Gamma_\gamma\rangle = 43.0 \pm 5.0$ MeV, $\langle\Gamma_f\rangle = 352.9 \pm 35.0$ MeV, $S_o = (1.16 \pm 0.19).10^{-4}$ $(eV)^{-1/2}$ for ^{242}Pu (in the range of 2.67 eV - 1.0 keV): $\langle D \rangle = 14.233 \pm 0.536$ eV, $\langle\Gamma_\gamma\rangle = 22.61 \pm 0.65$ MeV, $S_o = (0.91 \pm 0.1o).10^{-4}$ $(eV)^{-1/2}$.

Our calculations of the neutron cross sections in the energy range of the unresolved resonances have shown that for odd nuclei targets (^{235}U, ^{239}Pu, ^{241}Pu) in the unresolved resonance range (up to 100 keV), it is possible to consider a contribution of the s- and p-waves alone not only to σ_t but also to partial cross sections. For even nuclei-targets (^{240}Pu, ^{242}Pu) in the unresolved resonance range (150-200 keV), the s-, p- and d-waves should be taken into account to make a more correct calculation of average cross sections.

For all heavy fissile nuclei in this energy range, the energy dependence of the level space distance should be allowed for since, despite $E << B_n$, it does exists and achieves ~ 15% at 100 keV. So, for ^{241}Pu at 100 keV, the neglect of the energy dependence of $< D >_j^{\pi}$ gives a 1.1% increase in $< \sigma_f >$, a 2.1% increase in $< \sigma_{nn'} >$, a 15% decrease in $< \sigma_{n\gamma} >$ and a 16% decrease in $< \alpha >$.

The presence of inelastic neutron scattering reactions in the unresolved resonance range should be considered to obtain average resonance parameters. So, for ^{235}U the effect of inelastic neutron scattering is ~ 10% of σ_f at 100 keV. For ^{241}Pu (reaction threshold (n,n') is ~ 40 keV), the effect of the (n,n') reaction competition on the cross sections of other processes, although smaller than for nuclei ^{235}U and ^{239}Pu, is still substantial. For σ_f it is ~ 4% at 100 keV, for σ_γ, ~ 10% and for α, ~ 6%.

The Fermi-gas model was employed to determine the level space distances, $< D >_j$, and the main level density parameter a was calculated from the observed $< D >_{obs}$. As the unresolved resonance energy range is small and lies near the normalization region to $< D >_{obs}$, the energy dependence of the parameter a as well as a contribution of rotational and vibrational modes to the level density may be neglected. Neither the use of the various values of the spin-off parameter σ^2 in the Fermi-gas equation affect the predicted values of $< D >_r (E)$.

Figures 1 through 4 show the calculation of σ_t, $\sigma_{n\gamma}$, σ_f and $\sigma_{nn'}$ for ^{242}Pu.

We have studied the effect of partial width distributions on average cross sections for the case of several channels for fissile nuclei. Strictly speaking, definition of ν as the number of channels is correct only in the case of equal relative contributions of channels to the average widths. The generalized distribution /3/ should be used in the general case of non-equal relative contributions of the channels. We have ob-

tained simple generalized Porter-Tomas distributions for the mostly encountered cases of two and three fission channels. The experimental width distributions can be related to the structure of transient fissile nuclear states in terms of the generalized distribution. So, this distribution as applied to analyze the fissile widths of ^{239}Pu of 51 $0^{\pm}$ - resonances improves an agreement with experiment against the situation when ν in the Porter-Tomas distribution coincides with the number of channels equal to 2 (Fig. 5). In this case the values of channel contributions α_1=0.77 and α_2=0.23, obtained from the width distribution dispersion, agree with the transient state scheme proposed by Lynn /4/.

The evaluation of the effect of the generalized distribution, Γ_f, and the Porter-Tomas distribution with $\nu_{fr}=\nu_{eff\ fr}$ on the width fluctuation factors $S_{n\alpha r}$ and, hence, on the average cross sections $\langle\sigma_{nn}\rangle_r$, $\langle\sigma_{nn}\rangle_r$ and $\langle\sigma_{nf}\rangle_r$ for ^{239}Pu shows that at 0.1 keV, the difference in S^{o+}_{nn} and $S^{+o}_{n\gamma}$ is ~ 18% and in S^{o+}_{nf}, ~ 5% at $|\alpha_1 - \alpha_2| = 0.7 - 0.9$. With increasing energy, this difference decreases and at 100 keV, it is about 6~9% for S^{o+}_{nn} and $S^{o+}_{n\gamma}$, and about 3% for S^{o+}_{nf} (figs. 6 and 7).

Hence, in calculations of the average cross sections for fissile nuclei in the unresolved resonance region, the generalized Porter-Tomas distribution rather than the traditional one should be adopted to analyze fissile width fluctuations with a small number of channels.

The use of the Porter-Tomas distribution involving $\nu_{eff\ fr}$ for analyzing fluctuations of Γ_{fr} is valid only for very weakly or very strongly differing relative contributions of the channels when it is also reasonable to apply the integer values of ν.

The fissile width fluctuation factor, S_{nf}, for even-even nuclei-targets of ^{240}Pu, ^{242}Pu-type should be calculated with regard for a fissile width distribution in the sub-barrier region /5/. The value of $\left\langle \frac{\Gamma_{nr}\Gamma_{\alpha r}}{\Gamma_r} \right\rangle$ in this case cannot be calculated analytically. Therefore, one of the ways to determine this value

when calculating the average cross sections for even-even nuclei targets is the averaging of $\frac{\Gamma_{nr}\Gamma_{xr}}{\Gamma_r}$ obtained by the Monte Carlo method that was implemented in our approach. This approach was adopted to calculate σ_{nf} of ^{240}Pu and ^{242}Pu with good accuracy (fig. 3).

Consider the problem of the accuracy of neutron cross section predictions in the unresolved resonance energy range (up to 200 keV). The model applied for $\langle\sigma_{nn}\rangle$, $\langle\sigma_{nn'}\rangle$, $\langle\sigma_{n\gamma}\rangle$, $\langle\sigma_t\rangle$ calculations in this range cannot be a source of essential errors. This is attributed to the reasonable use of the narrow resonance approximation in this energy range and adopted partial width distributions, as well as to $E \ll B_n$, normalization with respect to $\langle D\rangle_{obs}$ and $\langle\Gamma_\gamma\rangle_{obs}$. We shall evaluate the uncertainties associated with errors of the parameters used in calculations of ^{242}Pu cross sections. The analysis has shown that consideration of the errors of a s-wave contribution to the potential scattering cross section and those of s- and p-wave contributions to $\sigma_{compound}$ due to uncertainties in σ_p, S_o and S_1 is fairly sufficient for evaluating the error of the calculated total cross section $\langle\sigma_t\rangle$. The error in the calculated total cross section, $\langle\sigma_t\rangle$, has proved to be 5-7%.

When analyzing the sources of the uncertainties of $\langle\sigma_{n\gamma}\rangle$ for ^{242}Pu, it has appeared that a minimum contribution to the error of $\langle\sigma_{n\gamma}\rangle$ is attributed to the uncertainty in $\langle\Gamma_\gamma\rangle$, while a maximum contribution to that in $\langle\Gamma_n\rangle_r$, which, in its turn, is due to uncertainties in S_o, S_1 and $\langle D\rangle_r$. So, the error of the calculated $\langle\sigma_{n\gamma}\rangle$ in the range between 1 and 200 keV amounts to 8%, for $\langle\sigma_{nn}\rangle$, it is 6-8%, for $\langle\sigma_{nn'}\rangle$, it is 13% at 100 keV and 9% at 200 keV.

Thus, in the unresolved resonance range at 100 keV for odd nuclei targets and at 150-200 keV for even nuclei, a self-consistent calculation has been made of the average neutron cross sections (σ_t, σ_f, $\sigma_{nn'}$, $\sigma_{n\gamma}$) and their errors

for ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu. If the average resonance parameters are accurately found, then the accuracy of the prediction of ,e.g. $\sigma_{n\gamma}$, by this method in this energy range is 5-10%. The minimum required experimental information involves a knowledge of the averaged parameters taken from the resolved resonance region and the data for σ_t and σ_f, at least, in the limited keV energy range.

To calculate and evaluate neutron cross sections in the energy range from 1 keV to 5 MeV, we have developed the method and its relevant computer programs which allow simultaneous calculation of neutron cross sections of all types of compound processes within the framework of the optical and statistical approaches, with the competition of fission and radiation channels being taken into account. Fission transmission coefficients were calculated using the fission channel theory when discrete and continuous spectra of the transient states of a fissile nucleus were taken into consideration. For fissile nuclei with a negative fission threshold, a $(n,\gamma f)$ process should be allowed for. It is especially important when calculating $\sigma_{n\gamma}$ since this process gives a more strong spin and energy dependence of radiative widths. A stronger dependence of the calculated widths $\langle \Gamma_{\gamma f} \rangle_{j^\pi}$ on the form of the spectral factor $f(E,\varepsilon_\gamma)$, as compared to $\langle \Gamma_\gamma \rangle_{j^\pi}$ on $f(E,\varepsilon_\gamma)$ makes it possible to conclude that within the accuracy of the available experimental data on $\Gamma_{\gamma f}$ for ^{239}Pu and ^{241}Pu, the spectral factor in terms of the Weisskopf form generally gives a worse agreement with the experimental data than the Lorentz form while the latter ensures a satisfactory agreement with the experimental data for $\Gamma_{\gamma f}$.

Figures 8 and 9 show a comparison of the predicted and experimental data for σ_γ (^{239}Pu) having an error of 6-25% in the energy range from 1 keV to 1 MeV. An agreement between the experimental and evaluated data is better than 10% in the whole energy range between 1 keV and 0.8 MeV where experimental data are available.

In the energy range below 100 keV, the most reliable are the calculations based on the average energy range parameters that permit an account of the structure in the cross sections. Figure 8 gives a comparison of both approaches to calculation of $\sigma_{n\gamma}$ (^{239}Pu) below 100 keV, namely, a statistical approach (solid curve) and that based on the unresolved resonance energy range parameters (dashed curve). Above 20 keV both curves coincide and below 20 keV a maximum difference between these curves is about 8%. In the energy range between 1 and 100 keV, the calculated curves give the best agreement with the experimental data of Gwin et al; and Weston and Todd.

In the energy range between 0.1 and 1.0 MeV for as strong fissile nuclei as ^{239}Pu, the calculation of $\sigma_{n\gamma}$ is mainly affected by the correct regard for the fission competition, and the difference between two forms of the spectral factors (Weisskopf and Lorentz) proves to be insignificant.

The use of the approximation of Tepel et al. /6/ for calculating average cross sections requires a specific combination of decay channels and their transmission coefficient ratios to be taken into account. Tepel's approach can be applied either in the case of slightly differing transmission coefficients for channels or when several weak and several strong channels exist provided that their total number is ~ 10. The greatest difference is observed in the average cross sections predicted by the formalisms of Tepel et al. and of Hauser-Feschbach (with a correction for width fluctuation), when calculating weak cross sections , for example, $\sigma_{n\gamma}$ and σ_{nn} for fissile nuclei (Fig. 10). Therefore, if the number of channels as well as the number of their freedom degrees is small and if there is a strong competitive channel, then Tepel's approach can give incorrect results. In the case of a large number of open channels, Tepel's expression coincides with Hauser-Feschbach's formula.

Figures 11 and 12 present the data on $\sigma_{n\gamma}$ and σ_{nn} for ^{239}Pu calculated by these two approaches. It is seen that

the fission cross section, σ_{nf}, (^{239}Pu), calculated by the approach of Tepel et al. is 15% higher and the capture cross section is 15% lower in the whole energy range between 1 keV and 1 MeV against the results obtained by the statistical Hauser-Feschbach method, the latter exhibiting a better agreement with the experimental data for σ_{nf} and, probably, for $\sigma_{n\gamma}$.

The above data allow a conclusion that the approximation of Tepel and et al. can be hardly used to calculate neutron cross sections of fissile nuclei in the energy range up to 1 MeV ; that is attributed to the small number of decay channels and to the presence of a strong competitive fission channel with small ν_f.

The Fermi-gas equation neglecting the collective effects of rotational and vibrational modes on level densities is used to calculate the neutron cross sections. The semi-microscopic method for calculating the level density recently developed by Soloviev et al. /7-8/ makes it possible to allow for a contribution of vibrational and rotational modes; however, this method appears to be highly tedious, especially in the high energy range, that limits its applicability for evaluating nuclear data.

Therefore, the statistical method for averaged characteristics of excited nuclei developed by Ignatyuk et al. /9/ has been employed to elucidate a contribution of the collective effects on the level density in calculations of neutron cross sections of heavy nuclei.

Figure 13 shows an energy dependence of the level density for a ^{240}Pu compound nucleus which was calculated by the generally accepted Fermi-gas model, the Fermi-gas model involving the collective effects of rotational and vibrational modes and the superfluid nucleus model. Figures 14 and 15 give a comparison of the experimental and predicted data for $\sigma_{n\gamma}$ (^{242}Pu) and $\sigma_{n\gamma}$ (^{238}U) in the energy range between 0.1 and 3.0 MeV.

These figures illustrate an important role of the collective effects on the nucleus level density when applied to $\sigma_{n\gamma}$ calculations. For even-even nuclei, when the fission competition is not high, the best calculation results for $\sigma_{n\gamma}$ were obtained using the spectral factor in the Lorentz form, taking into account the collective effects on the level density and employing the deformed potential.

Thus, based on the statistical approach with the neutron transmission coefficients obtained from the optical model (spherical or non-spherical), it is possible to make simultaneous calculation of the compound reaction cross sections for fissile nuclei with accuracies about 5% in σ_t and σ_{nx}, about 10% in σ_f, about 10-15% in $\sigma_{n\gamma}$ and about 20-30% in $\sigma_{nn'}$. With no experimental data for $\sigma_{n\gamma}$ and $\sigma_{nn'}$ for fissile nuclei these can be calculated using the developed method with the above accuracies. Minimum information necessary for such calculations of $\sigma_{nn'}$ and $\sigma_{n\gamma}$ incorporates the experimental data on σ_f, at least at several energy points, average parameters $\langle \Gamma_\gamma \rangle$ and $\langle D \rangle$, and a nucleus decay scheme.

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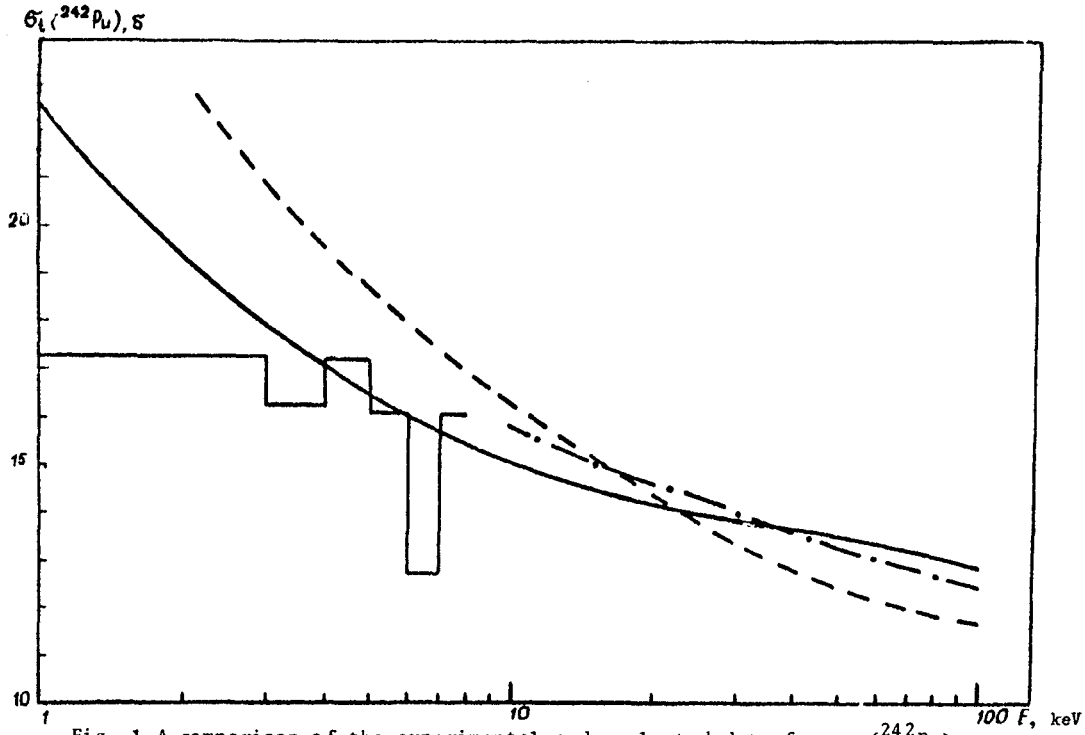

Fig. 1 A comparison of the experimental and evaluated data for σ_t (^{242}Pu) below 100 keV (⎍⎍ - experimental data of Young and Reeder /10/, ---- evaluation of Caner and Yiftah /11/, —·—·—·— calculation of Lagrange and Jary /12/, _____ present work).

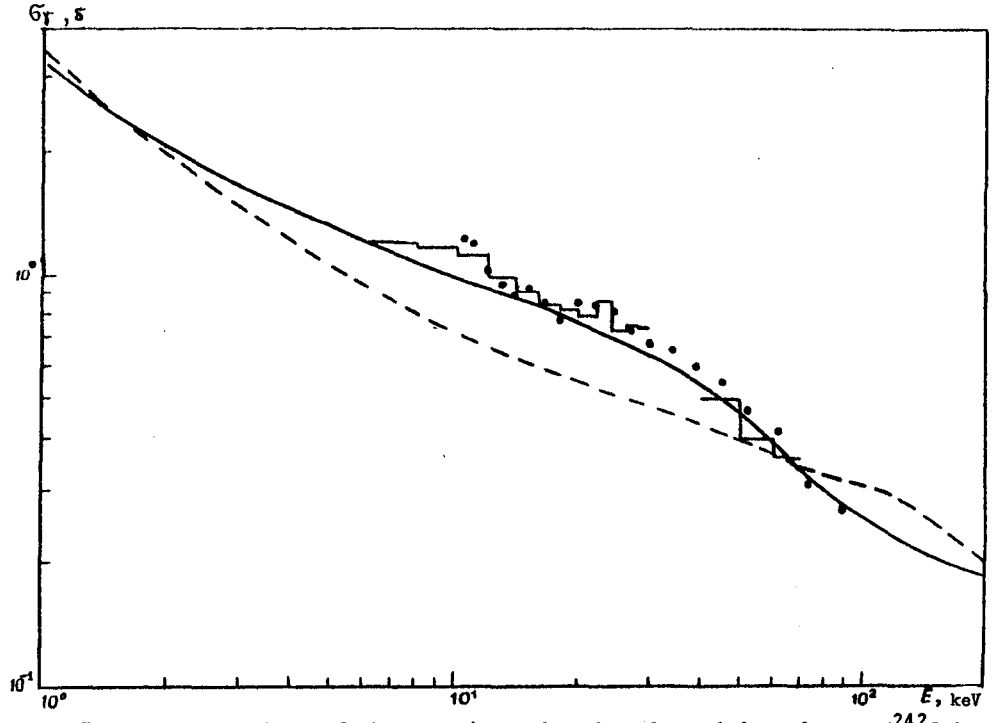

Fig. 2 A comparison of the experimental and evaluated data for σ_γ (^{242}Pu) (⎍⎍ experimental data of Hockenbury et al. /13/, • data of Wisshak and Käppeler /14/, ----- evaluation of Caner and Yiftah /11/, _____, present work).

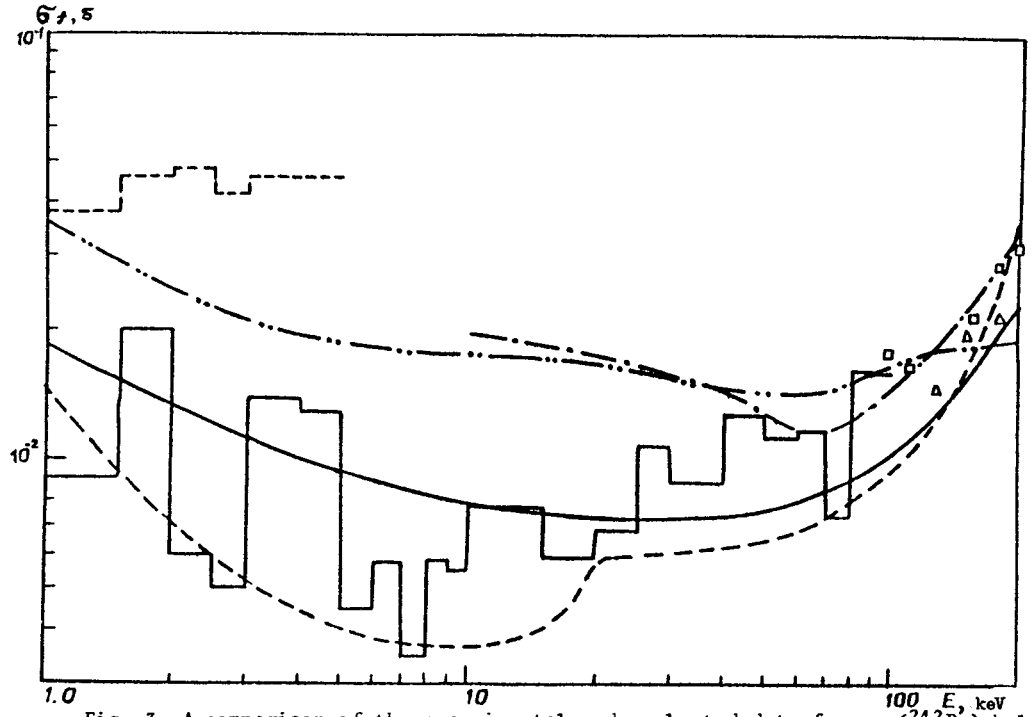

Fig. 3 A comparison of the experimental and evaluated data for σ_f (^{242}Pu) below 200 kev (-□□- data of Bergen and Fullwood /15/, ⎍⎍ - data of Auchampaugh et al. /16/,---- evaluation of Caner and Yiftah /11/,-.-.-.- calculation of Lagrange and Jary /12/,-..- present calculation using Lynn's parameters /17/, _____ present calculation with parameters E_A = 5.94 MeV, $\hbar\omega_A$ = 0.8 MeV; E_B = 5.64 MeV, $\hbar\omega_B$ = 0.52 MeV).

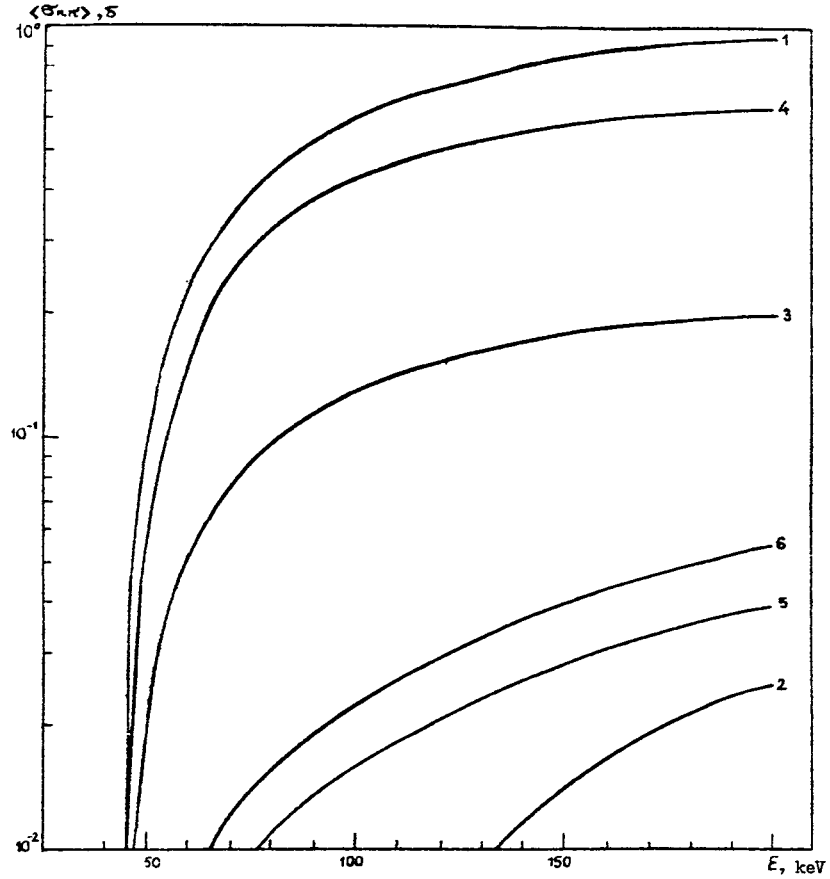

Fig. 4 Total (1) and partial (2-6) inelastic scattering cross sections for ^{242}Pu for the channels 1/2+, 1/2-, 3/2-, 3/2+ and 5/2+, respectively.

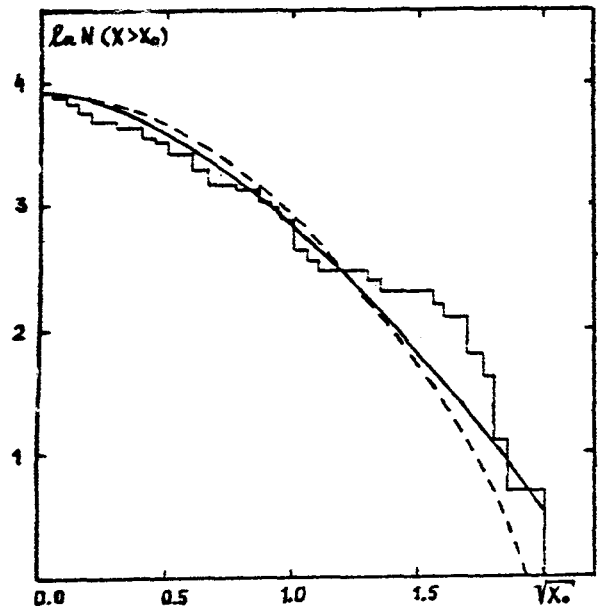

Fig. 5

Integral distribution of fissile widths of ^{239}Pu resonance as a function of $\sqrt{x}_o = \frac{\Gamma_{\lambda c}}{\Lambda < \Gamma_c >}$ (histogram - experimental data,----- integral Porter-Tomas distribution with $\nu=2$, _____ integral generalized distribution with $\alpha_1=0.77$, $\alpha_2=0.23$).

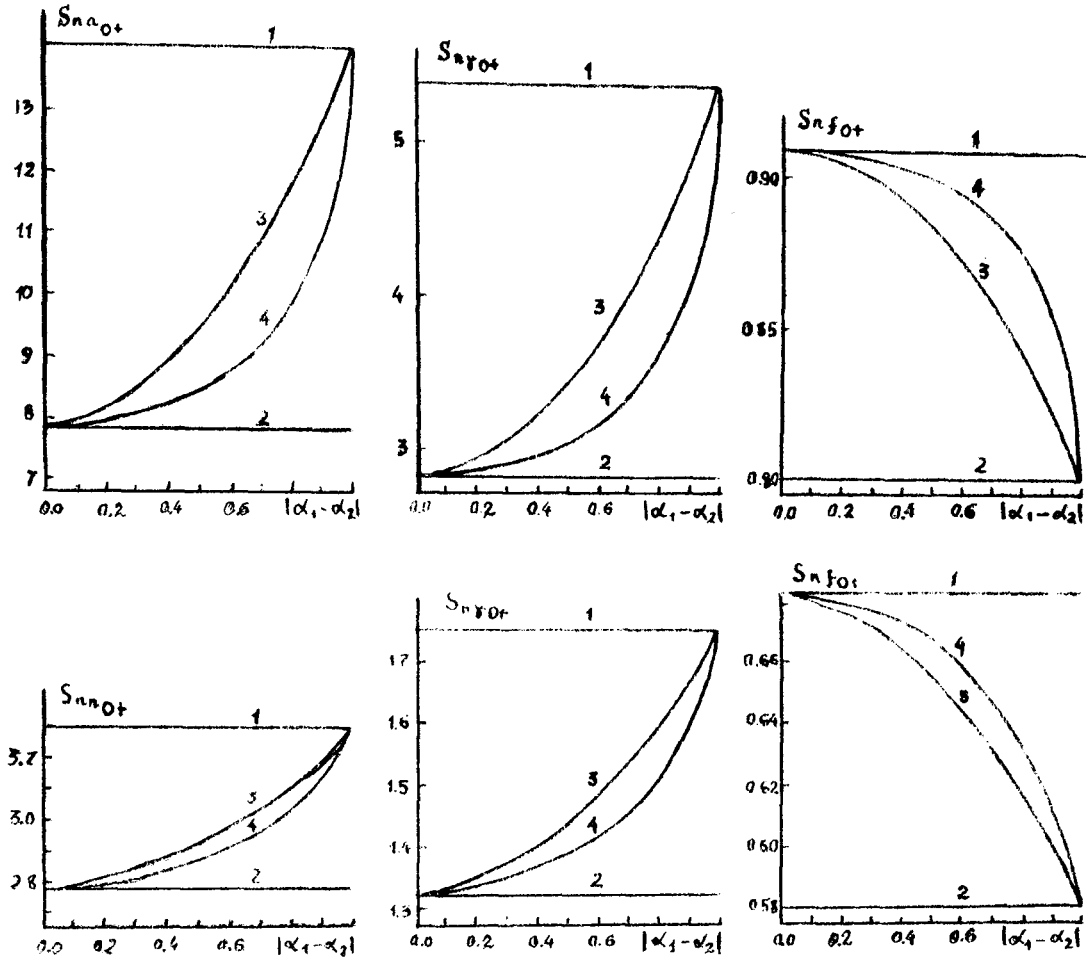

Fig. 6

S_{nn}^{0+}, $S_{n\gamma}^{0+}$ and S_{nf}^{0+} factors as a function of relative contributions of two fission channels for ^{239}Pu at E_n=0.1 keV (three upper figures) and E_n=100 keV (three lower figures) (curves 1,2,3 correspond to Porter-Tomas distribution with $\nu=2$, $\nu=1$, $\nu=\nu_{eff}$, curve 4 shows generalized distribution).

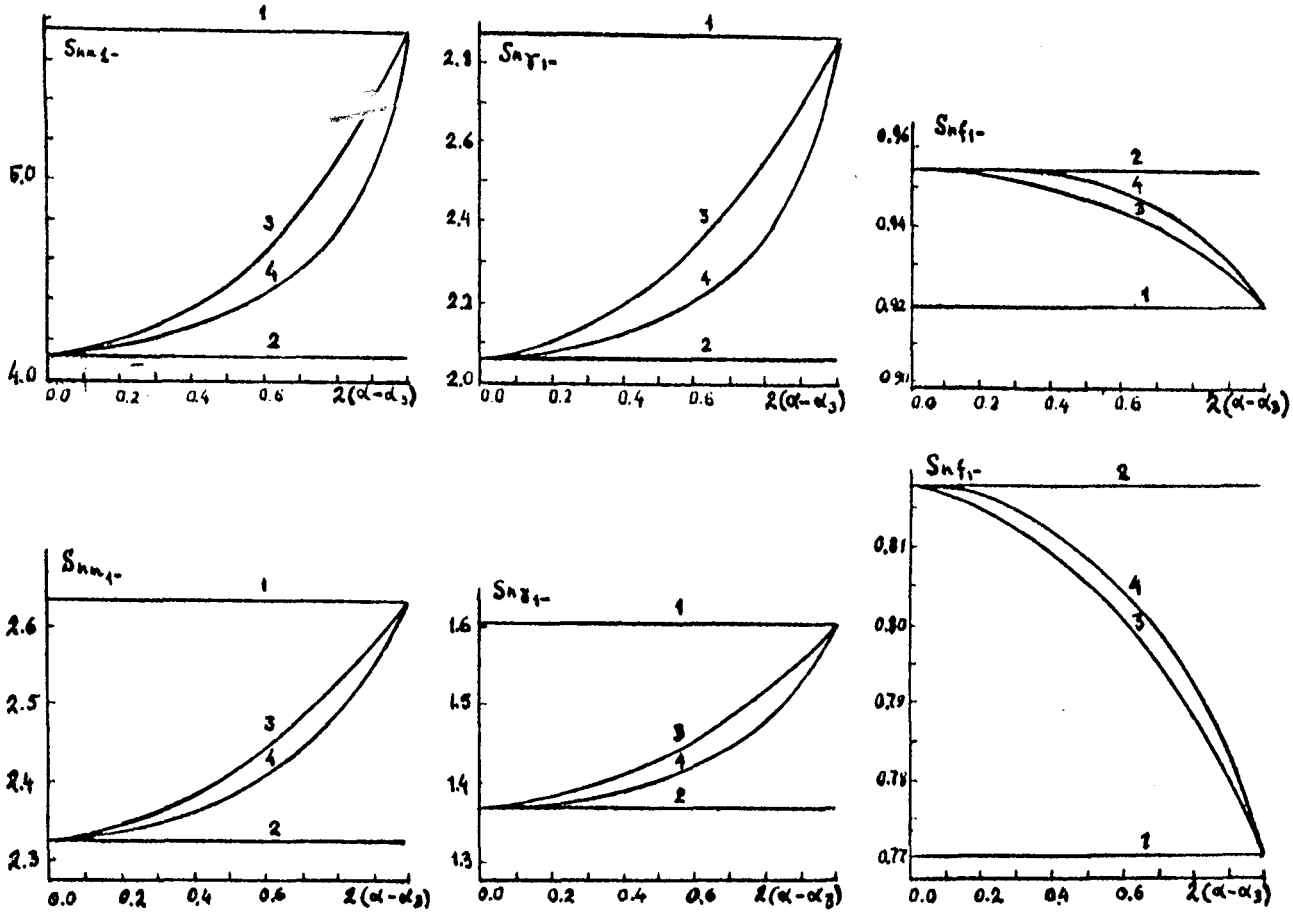

Fig. 7 S_{nn}^{1-}, $S_{n\gamma}^{1-}$, S_{nf}^{1-} factors as a function of relative contributions of three fission channels for ^{239}Pu at E_n = 0.1 kev (three figures) and E_n=100 keV (three lower figures). (curves 1,2,3 correspond to Porter-Tomas distribution with ν=2, ν=1, $\nu=\nu_{eff}$, curve 4 shows generalized distribution).

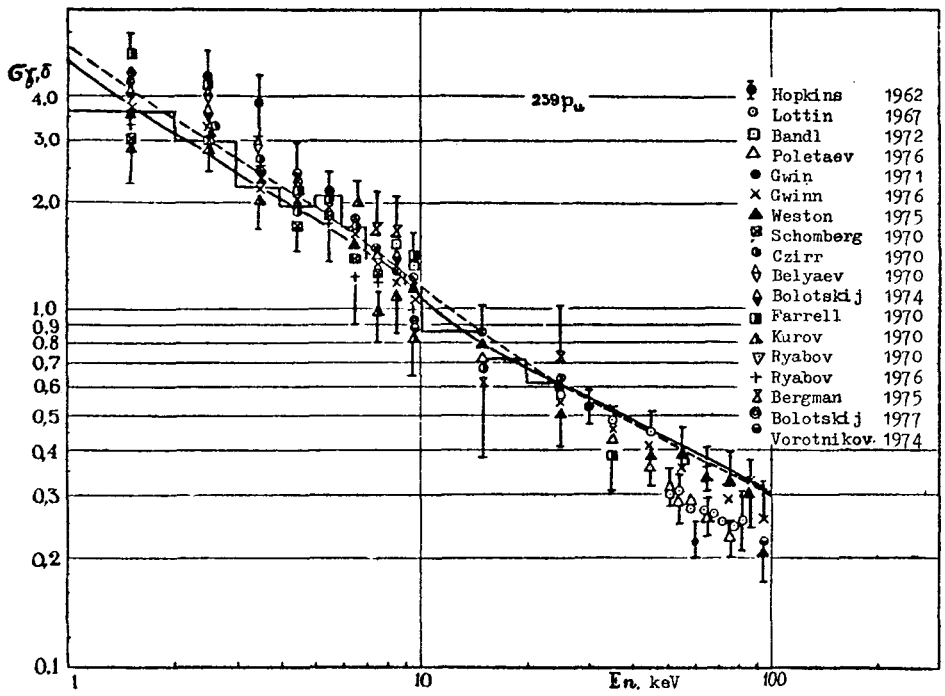

Fig. 8 A comparison of the experimental data for $\sigma_\gamma(^{239}Pu)$ and those predcited by the statistical model (solid curve, spectral factor expressed in the Lorentz form) and by average resonance parameters (dashed curve, energy-independent parameters; histogram, energy-dependent parameters $\langle \Gamma_n^0 \rangle$ and $\langle \Gamma_f \rangle_{j=1}^{\ell=0}$) with regard for the (n,γf)-reaction competition.

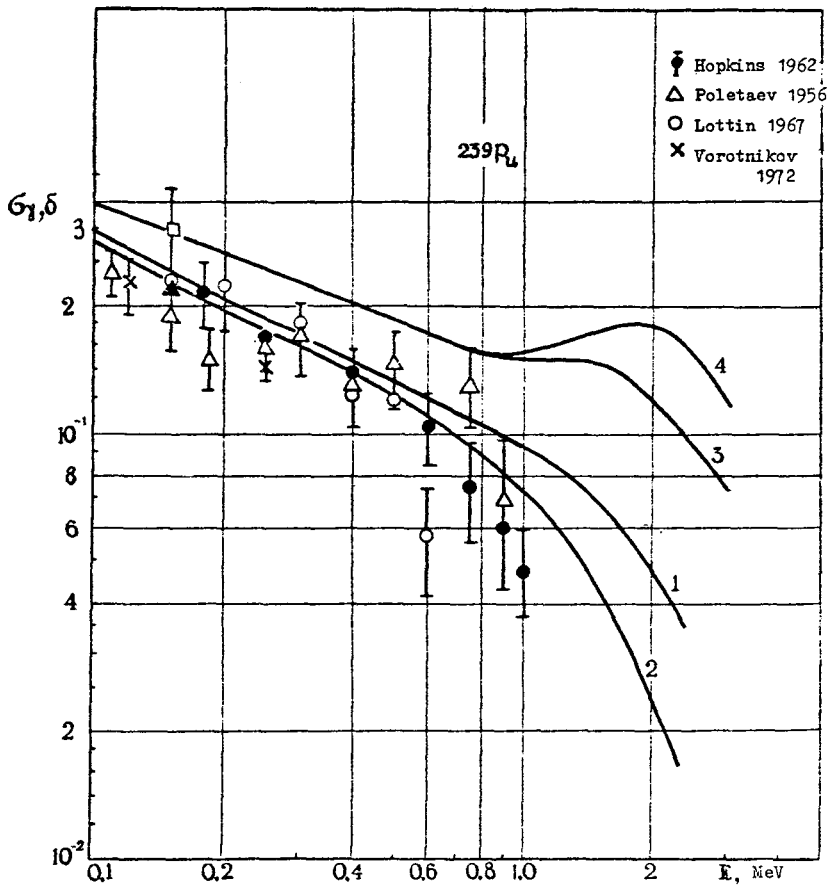

Fig. 9 A comparison of the experimental and predicted data for radiative capture cross section for ^{239}Pu (1, calculation with regard for (n,γf) and (n,γn'), spectral factor in the form of two Lorentz lines; 2, with regard for (n,γf) and (n,γn'), spectral factor in the Weisskopf form; 3, with regard only for (n,γn'), spectral factor in the Lorentz form; 4, with no regard for (n,γf) and (n,γn'), spectral factor in the Lorentz form).

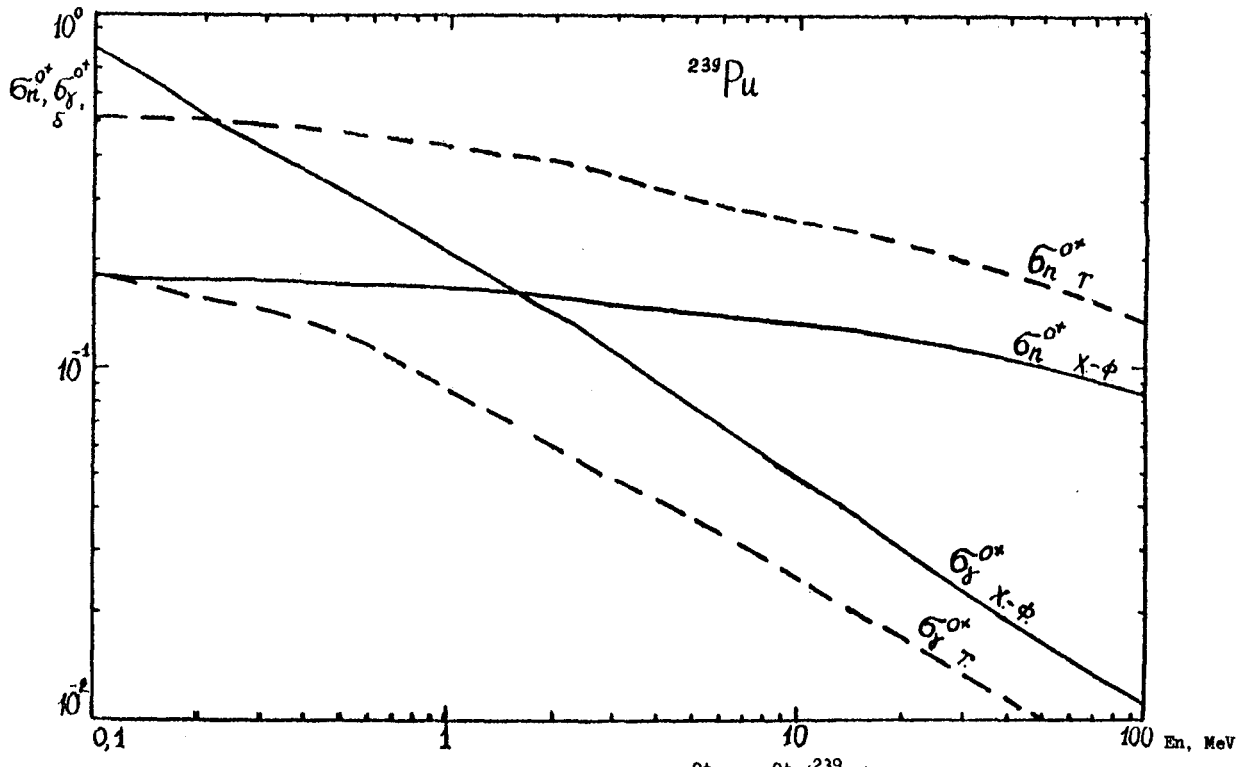

Fig. 10 A comparison of average cross sections σ_{nn}^{0+} and $\sigma_{n\gamma}^{0+}$ (^{239}Pu) calculated by the formalisms of Hauser-Feschbach (solid line) and Tepel et al. (dashed line).

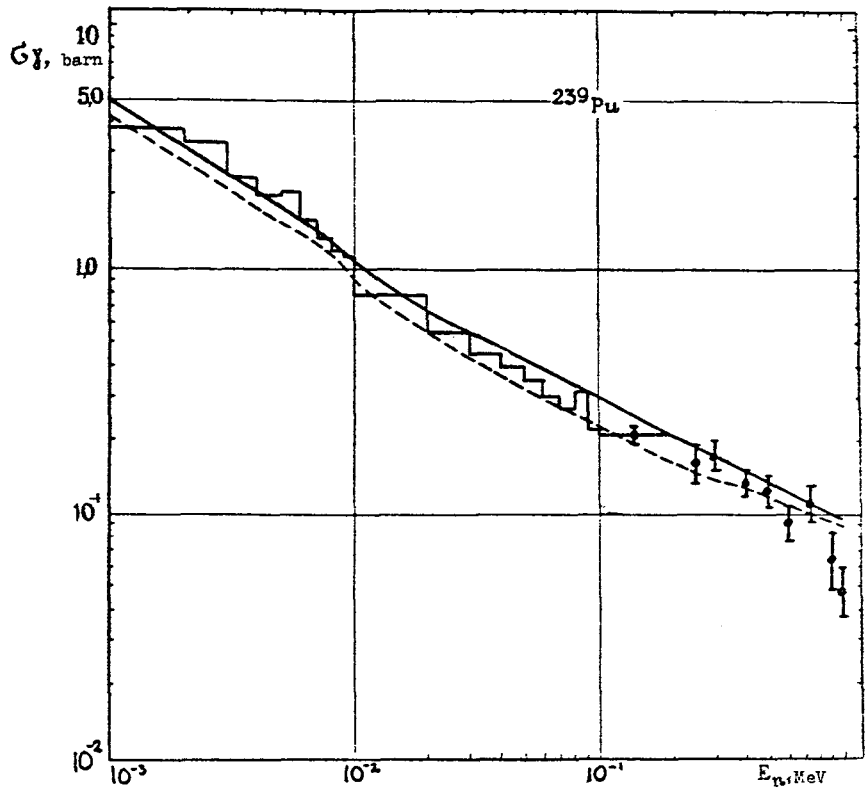

Fig. 11 A comparison of the predicted and experimental data for σ_γ (^{239}Pu) (_____ calculation from the present work, ----- calculation by the formalism of Tepel et al., ⎍⎍ evaluated data).

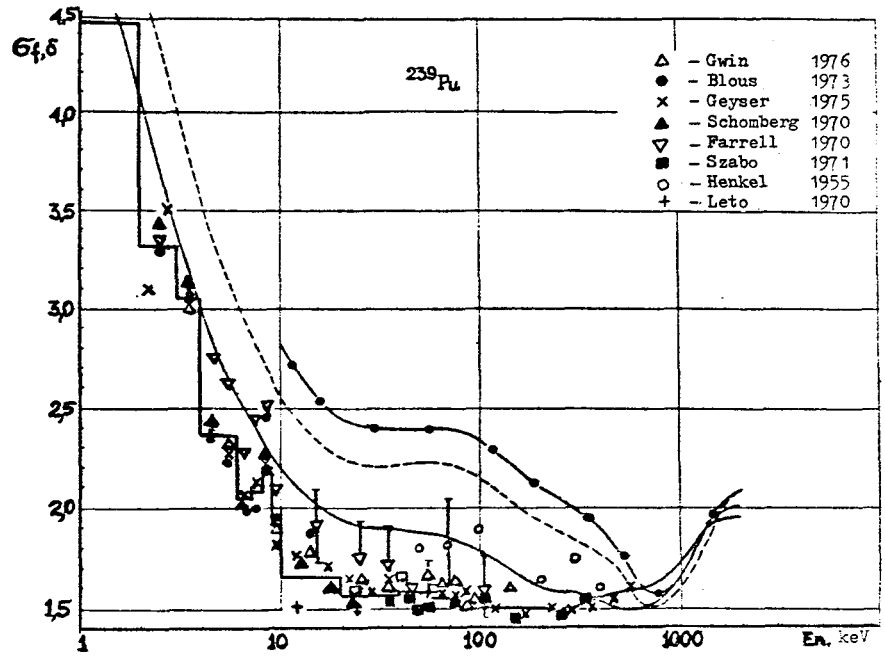

Fig. 12 A comparison of the predicted and experimental data for σ_f (^{239}Pu) (_____ present calculation, ------- calculation by the formalism of Tepel et al., -.-.-.-. calculation by the formalism of Hauser-Feschbach with no regard for the S-factor, ⎍⎍ evaluated data).

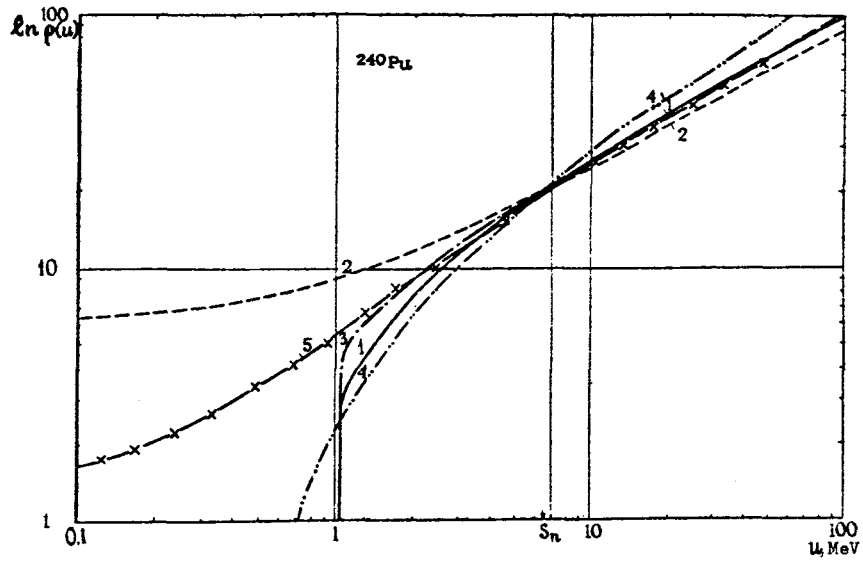

Fig. 13 Energy dependence of the logarithm of the total level density for ^{240}Pu (_____ 1, Fermi-gas model with no regard for collective effects of modes, Δ=1.04 MeV, ----- 2, Fermi-gas model with no regard for the collective effects of modes involving inverse shear with respect to pairing energy, Δ=-0.75 keV, -.-.-. 3, Fermi-gas model with regard for the collective effects of modes, Δ=1.04MeV, _··¯ .. -.. 4, superfluid-nucleus model with no regard for collective effects of modes, Δ_0= 0.801 MeV, - x - x 5, superfluid-nucleus model with regard for collective effects of modes, Δ_0 = 0.801 MeV).

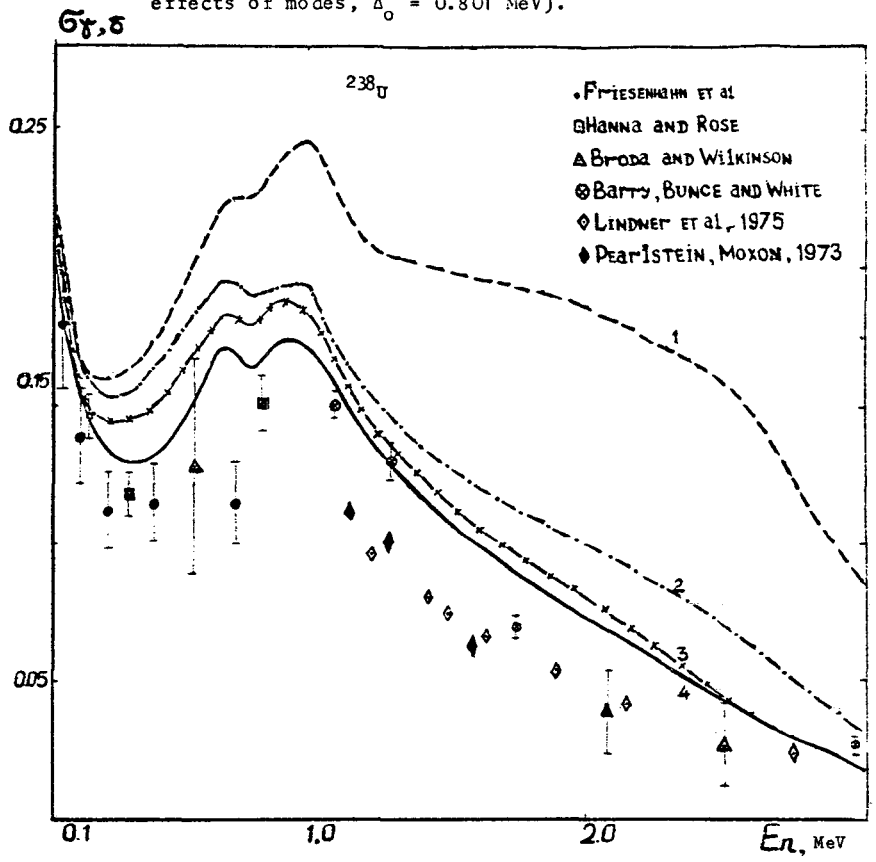

Fig. 14. A comparison of the predicted and experimental data for $\sigma_{n\gamma}$ (^{238}U) in the range of 0.1-3.0 Mev (curve 1, level density in the form of the Fermi gas; spectral factor in the Lorentz form; curve 2, Fermi gas and Weisskopf dependence; 3, level density with regard for collective modes, Lorentz dependence; curve 4, level density with regard for collective modes, spectral factor in the Lorentz form and use of the non-spherical optical potential).

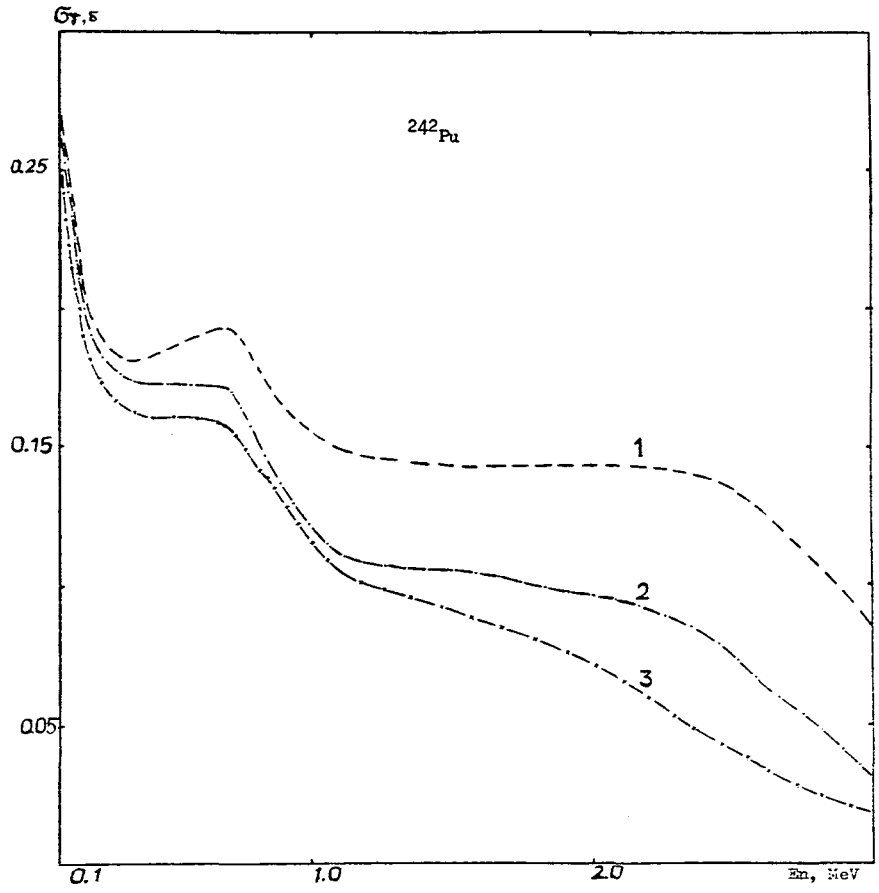

Fig. 15. Predicted data for $\sigma_{n\gamma}$ (^{242}Pu) in the range of 0.1-3.0 MeV (Curve 1, level density in the form of the Fermi gas, spectral factor in the Lorentz form; curve 2, Fermi gas and Weisskopf dependence; curve 3, level density with regard for collective modes, Lorentz dependence).