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STATUS OF BETA— AND GAMMA-DECAY AND SPONTANEOUS-FISSION DATA FROM TRANSACTINIUM ISOTOPES

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C. W. Reich

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ABSTRACT

Several categories of β - and γ -related decay data for the transactinium isotopes are assessed in the light of their potential use in applied areas. The status as of August, 1975, of these data is summarized for 142 transactinium nuclides with $228 \leq A \leq 257$ by the listing of experimental values and errors where known. Several useful compilations of transactinium-isotope decay data are discussed. Recent developments related to the yields and energy distributions of prompt and delayed neutrons from spontaneous fission are briefly treated. Comments and observations about the interrelation of the important nuclear-data activities of measurement, compilation and evaluation and needs assessment are given. The applications-oriented file of decay data prepared at our laboratory for ENDF/B is discussed. Finally, a summary by G. Rudstam of the status of the OSIRIS work on delayed-neutron energy spectra of individual precursors is included.

FOREWORD

This report contains the text of an invited review paper, prepared for presentation at the IAEA Advisory Group Meeting on Transactinium Isotope Nuclear Data held in Karlsruhe, FRG on November 3-7, 1975.

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I. INTRODUCTION

In this paper, we review and summarize the current status of a broad range of categories of decay data for the transactinium nuclides ($Z \geq 90$). The selection of the specific types of decay data which are treated here was based on a consideration of their general importance for various applications of decay data. For each individual nuclide, measured values (and, where reported, their uncertainties) of these chosen decay parameters are listed. This compilation of measured values provides a convenient means of assessing the adequacy of the present data for use in specific applications. It should be emphasized that these values do not constitute a set of evaluated or "recommended" values.

The inclusion of decay data in the subject matter of this meeting, the first one of international scope on the subject of transactinium-isotope nuclear data, provides another illustration of the increasing recognition of the importance of radioactive-nuclide decay data as one category of "Nuclear Data". While data from radioactive-decay studies have contributed much to the basic concepts of nuclear physics, their relevance to a number of applied problems is now becoming more widely appreciated. For example, decay data for fission products constituted a major topic for discussion at the IAEA Panel Meeting on Fission-Product Nuclear Data⁽¹⁾. Also, the scope of the Evaluated Nuclear Data File (ENDF/B) has now been expanded to incorporate such data, partly in response to their obvious importance for the assessment of certain safety questions in nuclear reactors. The recently released Version IV is the first version of ENDF/B to contain a detailed set of decay data⁽²⁾. With the increasing interest in assessing the impact

of radioactivity on the environment, attention is being focused not only on the monitoring of radioactive effluents associated with the operation of nuclear power plants but also on all aspects of the nuclear fuel cycle, including the management of the waste products and the safeguarding of the reprocessed fuel material. Among the components of such an assessment are the identification of the important radioactive nuclides and the establishment of a commonly accepted and utilized base of relevant, evaluated decay data. In some cases, this evaluation may point out the need for a vigorous program of experimental measurements to provide such data where they are either nonexistent or not of the required accuracy. Through its subject matter and organization, the present meeting represents, for the transactinium nuclides, one step toward the effective use of nuclear decay data in the solution of important problems of both an applied and a basic character.

1. Applications

To provide a framework for the discussion of the decay data to be treated, it is appropriate to point out some of the applications of such data. Since detailed discussions of the applications of these data appear in a number of papers presented at this meeting we give here only a brief listing. In reactor-related applications, decay data are needed for the proper assessment of the impact of radioactivity on the environment from all components of the fuel cycle, from the mine through the reprocessing plant, and including the accounting for and safeguarding of the fissionable material. Important operational problems include not only monitoring of the effluents from the nuclear-power plants, but also the storage and handling of the spent fuel. In

long-term operation of fast reactors, there is a considerable build-up of transactinium isotopes, leading to the accumulation of a sizeable inventory of nuclides for which spontaneous fission is a significant decay mode; and the evaluation of the neutron source term in such systems following shutdown is an important problem.

Biomedical applications represent another area where decay data have an important impact. In calculations of the absorbed dose, for example, it is necessary to know not only the energy release in radioactive decay, but also the form in which this energy is emitted (e.g., conversion electrons, x-rays, β and γ radiation and α particles). To do this realistically requires a quite detailed knowledge of the decay scheme. In the quantitative assay of radioactivity to determine the amount of a given radioactive nuclide present, a knowledge of the nuclide half-life and the energies and absolute intensities of the radiations being measured in the analysis is necessary. Because of the widespread use of γ -ray spectroscopy employing Ge(Li) spectrometers to do such assays, the γ -ray absolute intensities represent a particularly important subset of decay data.

2. Special Features of Transactinium-Nuclide Decay Data

Experimentally, the study of the decay properties of the transactinium nuclides is in many ways little different from that of any other class of nuclei. However, the decay of the transactinium nuclei exhibits a much richer variety of phenomena than is the case for the nuclides commonly encountered in the region below (and slightly above) the $Z=82$ magic number. For example, in addition to β^- and electron-capture (and β^+) decay, α -particle emission and spontaneous fission--with prompt and delayed neutron emission--occur. Furthermore, these

nuclides frequently decay via two or three different, competing processes. The relative probabilities (branching ratios) of these decay modes are important.

Finally, internal conversion and its associated phenomena assume an important role in transactinium-nuclide decay data because of the large internal-conversion coefficients that result from the large Z -values and the generally lower energies of the γ -ray transitions. Consequently, the discrete electrons and the x-rays contain a significant fraction of the energy associated with the γ -decay process. Knowledge of the conversion-electron spectrum may be important in its own right or for the determination of absolute γ -ray intensities for some applications.

Taken together, this increased variety of modes of decay provides the measurer with valuable additional information for gaining insight into the make-up of these nuclides, but it greatly complicates the problems of data compilation and evaluation, particularly when data for various applications are desired.

3. The Role of Theory in Transactinium-Nuclide Decay Data

3.1 Nuclear models for strongly deformed nuclei

The transactinium nuclides are all included in the general category of "strongly deformed" nuclei, in that their equilibrium shapes are characterized by relatively large axially symmetric deformations. Because of this, the coupling scheme which describes their elementary modes of motion assumes a basic simplicity [see, e.g., (3)]. For example, their energy-level schemes exhibit a number of striking features such as the existence of a well-developed rotational-band structure. The spins (and parities) of these observed rotational

states can frequently be deduced from energy-spacing considerations alone. From such considerations and data on the within-band γ -ray intensities, one can extract multipolarity information concerning these transitions. Furthermore, the ordering and properties of the "single-particle" states in the strongly deformed nuclei can be calculated fairly simply⁽⁴⁾, and such calculations are found to give a good description of many of the properties of these states, particularly of those that lie at fairly low ($\lesssim 0.5$ MeV) excitation energies. For these deformed nuclei, nuclear physicists with experience in nuclear-structure studies can frequently use these various calculational tools and arguments based on "systematics" to make accurate state assignments and transition-probability estimates on the basis of rather fragmentary data. (These ideas and their application to the level structure of the strongly-deformed odd-A nuclei in the rare-earth region have been treated in detail elsewhere, e.g., in (5).) In the strongly-deformed doubly-odd nuclei, the coupling of the two odd nucleons, each in a definite "single-particle" state, gives rise to two nonrotational states. In one of these the two intrinsic spins are parallel and in one they are antiparallel, the former lying lower in energy (the so-called Gallagher-Moszkowski rule⁽⁶⁾). The ordering of isomer pairs in doubly-odd deformed nuclei appears to be quite well accounted for by this rule and it has been used to assign the relative positions of the two isomers observed in ^{236}Np and in ^{250}Es .

3.2 X-ray and discrete-electron spectra

The internal-conversion process is well understood theoretically, and the internal-conversion coefficients (ICC) can be calculated⁽⁷⁾ with high accuracy. (For some multipolarities, small systematic

differences between theory and experiment exist, but even here, these known differences can themselves be employed to provide reliable ICC values.) Consequently, the conversion-electron spectrum associated with a given γ ray can be accurately calculated from the γ -ray energy and multipolarity (the latter either measured or deduced as described in subsection 3.1 above).

The energies and relative intensities of the prominent components of the K x-ray spectrum produced in radioactive decay of a given nuclide can be predicted with sufficient accuracy to be useful for many applications, provided that the decay scheme is known. Recent relative K x-ray intensity data in the region $96 \leq Z \leq 99$ ⁽⁸⁾ and $81 \leq Z \leq 96$ ⁽⁹⁾ give generally good agreement with calculations for the stronger lines although they do indicate some disagreement ($\sim 7\%$ at $Z=96$) in the $K\beta/K\alpha$ intensity ratio. While the energies of the L x-ray series can be accurately obtained from the binding-energy data of Bearden and Burr⁽¹⁰⁾, the relative intensities of the L lines cannot presently be accurately calculated. Nonetheless, estimates of the L x-ray intensity which are generally adequate for many applications (e.g., energy-release and dose-estimate calculations) can be made⁽¹¹⁾. Similarly, realistic calculations of the Auger electron spectrum cannot be made but estimates adequate for many applications can be generated⁽¹¹⁾.

4. Topics to be Discussed in the Paper

In the remaining chapters of this review, we present the current status of selected categories of decay data for the transactinium nuclides. In Chapter 2, we discuss several important existing compilations (and some currently in preparation) of transactinium-

nuclide decay data. Chapter 3, the main thrust of this paper, contains a discussion of the reasons for the selection of the data to be listed and a tabular summary of the decay data themselves. Chapter 4 contains a brief discussion of the yields and energy distributions of prompt and delayed neutrons from spontaneous fission. Chapter 5 presents some general observations concerning the use of decay data in applied areas and the improving of conditions under which relevant data with the required accuracy can be identified and supplied in a timely manner.

In Appendix A, the data content and layout of the decay data for Version V of ENDF/B is discussed within the context of the ENDF/B Actinide File. Finally, a summary of delayed-neutron spectral measurements by Rudstam and co-workers at the OSIRIS Facility at Studsvik, Sweden is given in Appendix B.

II. REMARKS ON DECAY-DATA COMPILATIONS FOR THE TRANSACTINIUM NUCLIDES

While several compilations of decay data oriented specifically toward the fission-product nuclides exist (e.g., (12), (13), and the relevant portions of the ENDF/B-IV Fission-Product File), no equivalent such compilations presently exist solely oriented toward users of transactinium-nuclide decay data. Those compilations in which decay data for the transactinium nuclides do occur are generally oriented toward a much larger class of nuclides and/or a much broader (or restricted) category of data. Numerous compilations of a rather specialized data content (e.g., half-lives, γ -rays arranged according to energy, or nuclide, or nuclide half-life) exist in which transactinium nuclides are included. Some of these have been discussed in the review paper by Rudstam⁽¹⁴⁾ in the context of their fission-product decay-data content; and the reader is referred to that review for further information concerning them.

We now briefly discuss several compilations containing transactinium-nuclide decay data which are quite useful to workers in both basic and applied areas. They have also been utilized in the preparation of much of the work contained in this paper.

1. Nuclear Data Sheets (Academic Press, New York, continuing)

These are standard reference material for non-neutron nuclear data. The most recent issues of this series which are relevant to the transactinium-nuclide decay data are the following:

A=230, 234, 238, 242 - Y. A. Ellis, Vol. 4, No. 6 (1970)

A=232, 236, 240 - M. R. Schmorak, Vol. 4, No. 6 (1970)

A=229, 233 - Y. A. Ellis, Vol. 6, No. 3 (1971)

A=231, 235 - A. Artna-Cohen, Vol. 6, No. 3 (1971)

A=237, 241 - Y. A. Ellis, Vol. 6, No. 6 (1971)

A=239 - A. Artna-Cohen, Vol. 6, No. 6 (1971)

243≤A≤261 - Y. A. Ellis and A. H. Wapstra, Vol. 3, No. 2 (1969).

The Data Sheets for the even-A nuclides with A>243 are currently being revised⁽¹⁵⁾, and some of their contents have been used in the preparation of the data summary given in Chapter 3 of this review.

These data sets are quite useful, particularly for the basic nuclear physicist and the specialized evaluator, but the quite broad coverage of different types of nuclear data renders their use difficult for many applications-oriented people. Somewhat disconcerting for many applied users is the practice of listing on the level schemes the transition (i.e., photon + conversion-electron) intensities for the γ rays instead of simply the photon intensities. The relatively long cycle times between revisions of the A-chains also presents a problem for the applied users, although the issuing of the companion "Recent References" helps keep the nuclear physicist or evaluator aware of the fairly recent data. The files are presently being extensively computerized; and consideration is being given to various means of decreasing the cycle time.

2. C. M. Lederer, J. M. Hollander and I. Perlman, Table of Isotopes, Sixth Edition (John Wiley and Sons, New York, 1967)

This has been a standard reference work for radioactive-nuclide decay data and has been widely used, especially by the applied user. Its major difficulty is long cycle time between editions. Somewhat disconcerting is the practice of listing the γ -ray intensities on the level schemes in such a fashion that the sum of these intensities out

of each level is 100%, so that the actual γ -ray relative intensity data cannot easily be inferred by reference to the decay scheme. At present, this data file is extensively computerized, which should simplify editing and updating. A seventh edition is presently in preparation; and the data base for the nuclides with $A \geq 231$ for this edition, supplied by C. M. Lederer⁽¹⁶⁾, was extensively used in the work described in Chapter 3 below.

3. A. H. Wapstra and N. B. Gove, The 1971 Atomic Mass Evaluation, Nuclear Data Tables A, Vol. 9 No. 4-5 (1971)

This compilation contains Q values for all relevant decay processes, derived from careful consideration and adjustment of all experimental information relating to atomic-mass differences. Also important is a listing of the uncertainties in these adopted values. The Q values used in this review paper were taken from an unpublished revision of this compilation⁽¹⁷⁾.

4. R. Vaninbroux, Half-Lives of Some Long-Lived Actinides: a Compilation, Euratom Report EUR-5194e (1974)

This report contains an up-to-date collection of half-life data on a number of the longer-lived isotopes of U and Pu and of ^{241}Am and ^{252}Cf . Recommended half-life values are given; and generally these values are listed in the present paper.

5. F. Manero and V. A. Konshin, Status of the Energy-Dependent $\bar{\nu}$ -Values for the Heavy Elements ($Z > 90$) from Thermal to 15 MeV and of $\bar{\nu}$ -Values for Spontaneous Fission, Atomic Energy Review 10 (1972) 637

This excellent survey contains a complete compilation of the data published up to August, 1972. Of relevance for the present review is the tabulation of the prompt $\bar{\nu}$ values for the spontaneous fission of 21 transactinium isotopes ranging from ^{232}Th to ^{257}Fm .

6. E. K. Hyde, I. Perlman and G. T. Seaborg, The Nuclear Properties of the Heavy Elements, Vol. I-III, (Prentice-Hall, Englewood Cliffs, 1964)

Very comprehensive, these three volumes treat essentially all aspects of transactinium nuclear data. As such, they are quite valuable reference material for those interested in gaining a knowledge of most facets of this subject. However, since they have not been updated, most of their data content is not up-to-date and hence not particularly useful to users whose data needs require a current and evaluated set of data.

7. Actinide Data File for ENDF/B, Version V

Mention should be made of the fact that a file of Actinide Nuclear Data is currently being prepared under the auspices of CSEWG for issue in Version V of ENDF/B. One component of this Actinide File will be evaluated decay data for the included isotopes. Because of its relevance to this meeting, the content and organization of the decay data on this file will be discussed in Appendix A below.

III. STATUS OF SELECTED DECAY DATA FOR TRANSACTINIUM ISOTOPES

In Table I is summarized the current status of selected decay data on the transactinium isotopes in the mass region $228 < A < 257$. We first discuss the organization of the table and then briefly comment on some of the points to emerge from this assessment of the decay-data status.

1. Comments on the Content and Organization of the Table

Entries for 142 nuclides and isomeric states are contained in Table I. These constitute essentially all the nuclides in this mass region for which some decay data, other than simply a half-life, are available. In the table, we have listed numerical values and their uncertainties for the various quantities. To the extent that these uncertainties are correct, they indicate the "status" of a given quantity. It should be emphasized that these values are in no way intended to serve as a set of "recommended data".

In the table, some of the listed data refer to α transitions and α -decay-related half-lives. These are included to illustrate the various data categories and are not to be regarded as being in contradiction to the more extensive treatment of α -particle data in the review paper B6⁽¹⁸⁾ presented at this meeting.

For each nuclide, the observed decay modes and their branching ratios (in percent) are given. This is followed by the half-life data, which include the total nuclide half-life in all cases and the spontaneous-fission (s.-f.) half-life where it exists. In some cases, the s.-f. half-life is measured directly (and the s.-f. branching ratio is inferred) and in some cases the s.-f. branching ratio is measured directly (and the s.-f. half-life is inferred). The manner in which

TABLE I

Summary of selected decay data for the transactinium nuclides ($Z \geq 90$) with $228 \leq A \leq 257$. The quantities in parentheses represent the uncertainties in the last significant figure (or figures) of the associated value. For further discussion, see the text.

Nuclide	Decay Modes	Branching Ratios (%)	Half-life Data			Q (keV)	Intensity of ground-state transition ^[a] (%)	γ-ray transition data ^[b] E _γ (keV); I _γ (%)	Status of c.-e. data	Decay Scheme Status	References and Comments
			Value	Range	No. of Meas.						
²²⁸ Th	Decay chain terminating with ²⁰⁸ Pb		1.913(1)y	--	--	--	--	{2614.66(10); 35.93(6)} {583.14(3); 30.(2)}	--	--	[1]. I _γ values are equilibrium values for the decay chain.
²²⁹ Th	α	100.	7340.(160)y	--	--	5168.0(12)	0.01	193.63(6); 4.5	A(mag.)	B	[2]. I _γ value deduced from absolute c.e. intensities and theoretical ICC.
²²⁹ Pa	e.c. α	99.75 0.25	1.4(4)d --	-- --	-- --	306.(13) 5835.(5)	-- ≤0.5	-- --	-- --	C B	[2,3]
²²⁹ U	e.c. α	≈80. ≈20.	58.(3)m --	-- --	-- --	1318.(14) 6472.4(31)	-- 64.	-- --	-- --	C C	[2]
²³⁰ Th	α s.f.	100. ≤5×10 ⁻¹¹ [c]	7.7(2)×10 ⁴ y ≥1.5×10 ¹⁷ y	-- --	-- --	4767.2(15) --	76.3 --	67.73(3); 0.38 --	B(mag.) --	B --	[4,5]
²³⁰ Pa	e.c. β ⁻ α	85.6(5) 10.4(5) 0.0032	17.4(4)d -- --	-- -- --	-- -- --	1304.0(25) 560.(6) 5438.0(20)	0 0 23.(5)	951.99(5); 29.3 -- --	A(Si) -- --	A B C	[4,6-8]. I _γ value listed is average of 28.3(3)[6] and 30.3[8].
²³⁰ U	α	100.	20.8d	--	--	5991.4(20)	67.5(5)	72.13; 0.54	--	B	[4]
²³¹ Th	β ⁻	100.	25.52(1)h	--	--	387.(5)	0	84.17; 7(1)	A(mag.)	A	[2,9]
²³¹ Pa	α s.f.	~100. ~3×10 ⁻¹⁰ [c]	3.257(10)×10 ⁴ y 1.1×10 ¹⁶ y	{+0.014} {-0.023}	3 --	5147.3(10) --	11. --	283.56(6); 1.3 --	A(mag.) --	A --	[2,9]. I _γ value estimated to be uncertain by ~ 20%.

Table I (continued)

^{231}U	e.c. α	$\sim 100.$ 0.0055	4.2(1)d --	-- --	-- --	360.(50) 5550.(50)	-- --	84.18;-- --	B(mag.) --	B C	[2,9]. The value 7% is given for this absolute I_γ . It is unclear how this value was measured.
^{231}Np	e.c. α	<99. >1.	48.8(2) π --	-- --	-- --	1840.(80) 5400.(50)	-- --	370.3(3); -- --	-- --	B C	[9]
^{232}Th	α	100.	1.407(7) $\times 10^{13}\text{y}$	$\begin{Bmatrix} +0.043 \\ -0.017 \end{Bmatrix}$	5	4082.(4)	77.	59.(1);	B(emuls.)	B	[1,9]. γ not observed. Transition (i.e., γ +c.e.) intensity = 23.(2)%.
^{232}Pa	β^-	100.	1.31d	--	--	1337.(10)	0	150.(3);12.	A(mag., Si)	A	[4,9]. I_γ value from measured (β,γ) coincidences and conversion-electron intensities.
^{232}U	α s.f.	$\sim 100.$ $\sim 10^{-10}[\text{c}]$	72.6(7) y 8.(6) $\times 10^{13}\text{y}$	$\begin{Bmatrix} +1.0 \\ -0.9 \end{Bmatrix}$ --	2 --	5413.92(25) --	68.6(6) --	129.0(2);0.082 --	B(emuls.) --	B --	[4,9]. I_γ value from relative-intensity data [4,11] and $I_\gamma=0.21\%$ for the 57.6-keV γ . From α -intensity and c.e. data, however, I_γ is expected to be ~ 0.058 .
^{232}Np	e.c.	100.	14.7(3) m	--	--	2700(SYST.)	<1	327.3(3);52.	--	B	[4,9]
^{232}Pu	e.c. α	>80. <20.	34.1(7) m --	-- --	-- --	1060(SYST.) 6700.(50)	-- 62.	-- --	C C	C C	[9]
^{233}Th	β^-	100.	22.29(5) m	$\begin{Bmatrix} +1.311 \\ -0.17 \end{Bmatrix}$	4	1245.1(24)	85.	66.50(5);2.6(4)	A(mag.)	A	[2,9]. Sum of β^- intensities to ground and first excited state (6.7 keV).
^{233}Pa	β^-	100.	27.0(1) c	--	--	572.3(25)	3.	311.89(1);36.	A(mag.)	A	[2,9]
^{233}U	α s.f.	$\sim 100.$ $1.3 \times 10^{-10}[\text{c}]$	1.592(3) $\times 10^5\text{y}$ 1.2(3) $\times 10^{17}\text{y}$	$\begin{Bmatrix} +0.034 \\ -0.039 \end{Bmatrix}$ --	11 --	4908.5(12) --	84.4 --	317.15(2);0.008(1) --	A(mag.) --	A --	[2,9,12]. $T_{1/2}$ from [10]. This I_γ value is a factor of ~ 2 smaller than is obtained from the absolute γ -intensity normalization used in [2,9].
^{233}Np	e.c. α	$\sim 100.$ ~ 0.001	36.2(1) m --	-- --	-- --	1100.(SYST) 5700.(SYST)	$\sim 96.$ --	312.1(3); 0.75 ? --	-- --	B C	[9]. Sum of e.c. transition intensities to first three members of ground-state band.

Table I (Continued)

^{233}Pu	e.c. α	99.88 0.12(5)	20.9(4)m --	-- --	-- --	2030.(SYST) 6416.(20)	-- --	235.4(3); --	-- --	B C	[9]
^{234}Th	β^-	100.	24.101(25)d	--	--	262.5(25)	0	112.81(5);0.24(1)	A(mag.)	A	[4,9]
^{234}Pa	β^-	100.	6.68(1)h	{ ± 0.05 }	2	2208(5)	0	883.237(33);12.	A(mag.)	A	[4,9]
$^{234\text{m}}\text{Pa}$	β^- I.T.	99.87 0.13(3)	1.170(4)m --	{ $+0.08$ } { -0.03 }	4	2292.	98.	1001.025(22);0.59	A(mag.)	A	[4,9]. Energy of isomeric state not precisely known. A value of ~ 84 keV is used in [9].
^{234}U	α s.f.	~ 100 $\sim 1 \times 10^{-9}[\text{c}]$	$2.446(7) \times 10^5 \text{y}$ $2(1) \times 10^{16} \text{y}$	{ $+0.074$ } { -0.007 }	7	4856.4(19)	72.5(30)	{ 53.222(19);0.15 } { 120.905(12);0.050 }	-- --	B --	[4,9]. $T_{1/2}$ from [10]. Quoted $I_\gamma(120)$ values range from $\sim 0.04\%$ [4] to 0.23% [11].
^{234}Np	e.c.+ β^+	100.	4.40(5)d	--	--	1808.(9)	26.	1558.7(6);18.	A(mag.)	A	[4,9]
^{234}Pu	e.c.	94. 6.	8.8(1)h --	-- --	-- --	390.(12) 6310.(5)	-- 68.	{no γ 's observed}	C C	C C	[4,9]
^{235}Th	β^-	100.	6.9(2)m	--	--	--	0.	--	--	C	[2,9]
^{235}Pa	β^-	100.	24.0(2)m	{ $+0.2$ } { -0.3 }	2	1400.(100)	--	--	--	C	[2,9]
^{235}U	α s.f.	~ 100 $2.6 \times 10^{-7}[\text{c}]$	$7.038(20) \times 10^8 \text{y}$ $2.7(10) \times 10^{17} \text{y}$	{ $+0.092$ } { -0.098 }	8 2	4678.8(25) --	4.6 --	185.712(10);54. --	-- --	A --	[2,9]. $T_{1/2}$ from [10].
^{235}Np	e.c. α	~ 100 0.0014	396.(1)d --	-- --	-- --	123.(1) 5188.(4)	~ 100 1.5(2)	-- 84.2(1); 1.1×10^{-4}	-- --	C B	[2,9]. I_γ from measured γ/α intensity and α -decay branching ratio.
^{235}Pu	e.c. α	~ 100 0.0030(6)	25.0(1)m --	{ ± 0.7 }	2	1130.(60) 5958.(31)	~ 56 100.	49.3(3);1.84 --	-- --	B C	[2,9]
^{236}Th	β^-	100.	37.5(15)m	--	--	--	46.	110.7(5);5.	--	B	[9]. I_β and I_γ values inferred from γ -ray intensities from sources containing both parent and daughter activities.
^{236}Pa	β^-	100.	9.1(2)m	--	--	3100.(200)	--	642.0; --	--	C	[4,9]

Table I (Continued)

^{236}U	α s.f.	$\sim 100.$ $1.2 \times 10^{-7}[\text{c}]$	$2.34(2) \times 10^7 \text{y}$ $2. \times 10^{16} \text{y}$	$\begin{Bmatrix} +0.12 \\ +0.0015 \end{Bmatrix}$ --	3 --	4569.2(24) --	74. --	112.750(16); 0.019 --	B(emuls.) --	B --	[4,9]. $T_{1/2}$ from [10].
^{236}Np	β^-	100.	$1.29(6) \times 10^6 \text{y}$	--	--	986.(10)	--	--	--	C	[4,9]
$^{236\text{m}}\text{Np}$	β^-	48.(1)	$22.5(4) \text{h}$	--	--	537.(8)	$38.(7)^{[\text{d}]}$	$44.63(10); --$	A(mag., Si) A(Si)	A	[4,9]
	e.c.	52.(1)	--	--	--	986.(10)	$40.^{[\text{d}]}$	$642.42(10); 1.0(2)$	--	A	
^{236}Pu	α s.f.	$\sim 100.$ $8 \times 10^{-8}[\text{c}]$	$2.851(8) \text{y}$ $3.5(1) \times 10^9 \text{y}$	-- --	-- --	$5866.7(20)$ --	$68.9(5)$ --	$109.0; 0.012$ --	-- --	B --	[4,9]
^{237}Pa	β^-	100.	$8.7(2) \text{n}$	--	--	2250.(10)	19.4	$853.7(2); 34.1(34)$	--	B	[9,13,14]. Q_β from [13]. I_β is total β intensity to first 3 members of ground-state band. I_γ value from absolute β and γ measurements.
^{237}U	β^-	100.	$6.75(1) \text{d}$	--	--	519.3(11)	0.	$208.005(23); 23.3$	A(mag.)	A	[9,14]. A 4π β - γ measurement (see [2]) gives $I_\gamma(208)=20.2\%$.
^{237}Np	α	100.	$2.14(1) \times 10^6 \text{y}$	--	--	4957.2(14)	2.6	$86.49(10); 12.5(13)$	A(mag., Si)	A	[9,14]
^{237}Pu	e.c.	$\sim 100.$	$45.63(20) \text{d}$	--	--	224.(5)	60.	$59.54(1); --$	--	B	[9,14]. Value given for α branch is sum of intensities to ground and first excited states.
	α	0.0033(3)	--	--	--	5754.(5)	$21.(4)$	--	--	C	
^{237}Am	e.c.	$>99.$	$73.0(10) \text{m}$	--	--	1540(SYST)	$\approx 5.$	$280.230(20); 47.3(20)$	A(mag., Si)	A	[9,15]
	α	0.025(3)	--	--	--	6200(SYST)	--	--	--	C	
^{238}Pa	β^-	100.	$2.3(1) \text{n}$	--	--	3960(300)	0.	--	--	B	[4,9]
^{238}U	α	$\sim 100.$	$4.468(.0) \times 10^8 \text{y}$	$\begin{Bmatrix} +0.092 \\ +0.0003 \end{Bmatrix}$	4	4270.6(39)	77.	$49.55(6); --$	--	B	[4,9]. $T_{1/2}$ from [10].
	s.f.	$5.1 \times 10^{-5}[\text{c}]$	$8.81(7) \times 10^3 \text{y}$	$\begin{Bmatrix} +1.29 \\ -0.81 \end{Bmatrix}$	7	--	--	--	--	--	
^{238}Np	β^-	100.	$2.117(2) \text{d}$	--	--	1292.5(32)	0.	$984.45(2); 24.$	A(mag.)	A	[4,9]

Table I (Continued)

^{238}Pu	α	$\sim 100.$	87.8(8)y	$\begin{Bmatrix} +0. \\ -1.4 \end{Bmatrix}$	4	5593.30(21)	71.1(12)	99.871(10); 0.0074(1)	B(mag., Si)	A	[4,9]. $T_{1/2}$ from [10]. I_Y measured [15]. A value of 0.080% is also reported [11] for $I_Y(99.8)$.
	s.f.	$1.84(5) \times 10^{-7}$	$4.77(14) \times 10^{10} \text{y} [e]$	--	--	--	--	--	--	--	
^{238}Am	e.c.	$\sim 100.$	1.63(5)h	--	--	2257.(32)	$\sim 6.$	962.8(1); 29.(2)	A(Si)	A	[4,9]
	α	$1.0(4) \times 10^{-4}$	--	--	--	6042.(31)	--	--	--	C	
^{239}U	β^-	100.	23.54(5)m	--	--	1267.4(29)	20.	74.66(2); 59.3 ?	B(mag.)	B	[9,14]. I_B value represents sum of β intensity to ground and first excited states.
^{239}Np	β^-	100.	2.354(2)d	$\begin{Bmatrix} +0.012 \\ -0.008 \end{Bmatrix}$	4	721.5(19)	0.	$\{228.19(1); 11.3(2)\}$ $\{277.60(3); 14.3(2)\}$	A(mag.)	A	[9,14]. I_Y values from [17].
^{239}Pu	α	$\sim 100.$	$2.430(25) \times 10^4 \text{y}$	$\begin{Bmatrix} +0.011 \\ -0.0235 \end{Bmatrix}$	10	5243.6(8)	73.	$\{129.28; 0.0062(1)\}$ $\{413.69; 0.00151(2)\}$	A(mag., Si)	A	[9,14]. $T_{1/2}$ from [10].
	s.f.	$4.4 \times 10^{-13} [c]$	$5.5 \times 10^{15} \text{y}$	--	1	--	--	--	--	--	Listed α -branch intensity is actually that feeding the 0.073-keV, 26.1-m isomeric state in ^{235}U . I_Y values are from [16]. Values of 0.0056% and 0.0013%, respectively, are reported for $I_Y(129)$ and $I_Y(413)$ in [11].
^{239}Am	e.c.	> 95.9	11.9(1)h	--	--	803.8(24)	$\sim 56.$	277.604(16); 15.(3)	A(mag., Si)	A	[9]
	α	0.01(1)	--	--	--	5924.4(20)	0.33(2)	48.3(15); 0.005(2)	--	B	
^{240}U	β^-	100.	14.1(2)h	--	--	500.(60)	0.	44.10(7); 1.69(20)	B(mag.)	B	[4,9]. I_Y measured using equilibrium ^{244}Pu source.
^{240}Np	β^-	100.	65.(3)m	--	--	2090.(60)	0.	566.4(2); $\sim 29.$	--	B	[4,9]
^{240}mNp	β^-	99.9	7.50(6)m	--	--	2090.(60)	41.(5)	597.40(7); 12.5(6)	B(mag., emuls.)	A	[4,9]. This isomer probably lies above 65-m ^{240}Np , but the precise energy difference is unknown. The Q_B value listed is that of the ^{240}Np ground state. I_Y value measured using equilibrium ^{244}Pu source.
	I.T.	~ 0.1	--	--	--	--	--	--	--	--	

Table I (Continued)

^{240}Pu	α	$\sim 100.$	$6.55(7) \times 10^3 \text{y}$	$\begin{Bmatrix} +0.21 \\ -0.31 \end{Bmatrix}$	7	5256.16(25)	76.	$\begin{Bmatrix} 45.235(20); 0.045(-) \\ 104.233(10); 0.0070(1) \\ 642.30; 1.45(5); \times 10^{-5} \end{Bmatrix}$	A(mag., Si)	A	[4,9]. $T_{1/2}$ from [10]. I_γ measured using assayed sources [16]. Values of 0.045%, 0.01% and $4.1 \times 10^{-5}\%$, respectively, are given for these 3 γ rays in [11].
	s.f.	$5.0 \times 10^{-6} [\text{c}]$	$1.313(1) \times 10^{11} \text{y}$	$\begin{Bmatrix} +0.137 \\ -0.143 \end{Bmatrix}$	5	--	--	--	--	--	
^{240}Am	e.c.	> 99.7	$50.8(3) \text{h}$	--	--	1346.(20)	0.	987.79(6); 73.3(25)	B(Si)	B	[4,9]. $Q_{\text{e.c.}}$ value reported by [18], from K to total capture ratio.
	α	1.9×10^{-4}	--	--	--	5670.(SYST)	--	--	--	C	
^{240}Cm	α	$\sim 100.$	28.d	--	--	6397.0(6)	71.1	--	--	C	[4,9]
	s.f.	$4.0 \times 10^{-6} [\text{c}]$	$1.9(4) \times 10^6 \text{y}$	--	--	--	--	--	--	--	
^{241}Np	β^-	100.	16.0(2)m	--	--	1360.(100)	--	--	--	C	[9,14]
^{241}Pu	β^-	$\sim 100.$	14.89(9)y	$\begin{Bmatrix} +0.27 \\ -0.29 \end{Bmatrix}$	5	20.81(20)	100.	--	--	A	[9,14]. I_γ value from measured γ/α ratio and α branching ratio. An I_γ value of $2.2(2) \times 10^{-4}$ is deduced from the data of [19].
	α	0.00245(8)	--	--	--	5139.4(11)	0.35	148.60(4); $1.50(2) \times 10^{-4}$	--	B	
^{241}Am	α	$\sim 100.$	432.(4)y	$\begin{Bmatrix} +26.1 \\ -5.7 \end{Bmatrix}$	6	5637.93(14)	0.35	59.537(1); 35.9(3)	A(mag.)	A	[9,14]. $T_{1/2}$ from [10].
	s.f.	$4.1 \times 10^{-10} [\text{c}]$	$1.05(2) \times 10^{14} \text{y}$	$\begin{Bmatrix} +0.093 \\ -0.247 \end{Bmatrix}$	2	--	--	--	--	--	
^{241}Cm	e.c.	99.0	32.8(2)d	--	--	771.(5)	<4.	471.305(20); 72.(3)	A(mag.)	A	[9,15]
	α	1.0(1)	--	--	--	6184.8(15)	0.15	145.536(9); --	--	C	
^{242}Pu	α	$\sim 100.$	$3.87(5) \times 10^5 \text{y}$	$\begin{Bmatrix} +0.01 \\ -0.22 \end{Bmatrix}$	5	4981.7(12)	78.9	44.915(13); 0.042	--	B	[4,9]. $T_{1/2}$ from [10]. Four of the $T_{1/2}$ values are measured relative to half-lives of other Pu isotopes.
	s.f.	$5.55 \times 10^{-4} [\text{c}]$	$6.97(8) \times 10^{10} \text{y}$	$\begin{Bmatrix} +0.48 \\ -0.51 \end{Bmatrix}$	3	--	--	--	--	--	
^{242}Am	β^-	82.7	16.01(2)h	--	--	665.(5)	37. ^[d]	42.12; --	B(mag.)	B	[4,9]
	e.c.	17.3(3)	--	--	--	752.(5)	6. ^[d]	44.54; --	B(mag.)	B	
$^{242\text{m}}\text{Am}$	I.T.	$99.5^{+0}_{-0.2}$	152.(7)y	--	--	48.63	--	48.63; --	A(mag.)	A	[4,9]. $Q_{\text{I.T.}}$ value is the energy of the isomeric state. Q_α value is that of ground state + E(I.T.). $I_\gamma(49.3)$ is obtained from α -branching intensity and measured γ/α value.
	α	0.476(14)	--	--	--	5637.5(38)	0.	49.3; 0.20	--	B	
	s.f.	$1.6 \times 10^{-8} [\text{c}]$	$9.5(35) \times 10^{11} \text{y}$	--	1	--	--	--	--	--	

Table I (Continued)

^{242}Cm	α	$\sim 100.$	162.9(1)d	$\begin{Bmatrix} +1.5 \\ -0.44 \end{Bmatrix}$	4	6215.96(14)	74.0(5)	$\begin{Bmatrix} 44.08(5); 0.030(5) \\ 157.6(3); 0.20(5) \end{Bmatrix}$	B(mag.)	A	[4,9]
	s.f.	$6.8 \times 10^{-6} [c]$	$6.6(1) \times 10^6 \text{y}$	$\begin{Bmatrix} +0.6 \\ -0.5 \end{Bmatrix}$	2	--	--	--	--	--	
^{243}Pu	β^-	100.	4.957(2)h	--	--	583.2(39)	58.	84.0(2); 23.(2)	A(Si)	A	[9]. I_γ value from measurements of ^{243}Pu γ 's in equilibrium with ^{247}Cm . An $I_\gamma(84)$ value of 27.6% is also reported.
^{243}Am	α	$\sim 100.$	7370(40)y	--	--	5438.1(10)	0.16	74.67; 66.(3)	A(Si)	A	[9]. I_γ value from determination of absolute γ -ray emission rates from calibrated source [20].
	s.f.	$1.8 \times 10^{-8} [c]$	$4.2(4) \times 10^{13} \text{y}$	$\begin{Bmatrix} +15.8 \\ -0.9 \end{Bmatrix}$	2	--	--	--	--	--	
^{243}Cm	α	99.7	30y	$\begin{Bmatrix} +2. \\ -1.5 \end{Bmatrix}$	2	6168.3(10)	1.5	228.2; 10.6(3)	B(mag.)	A	[9]. I_γ value from absolute γ -ray emission rates from calibrated source [20].
	e.c.	0.25	--	--	--	8.7(24)	100.	277.6; 14.0(4)	--	A	
^{243}Bk	e.c.	>99.	4.6(2)h	--	--	1507.(6)	--	87.4(1); --	C(Si)	C	[9,21]. I_γ value from measured γ/α ratio and α -decay branching.
	α	0.15	--	--	--	6871.(5)	15.4(10)	187.1(5); 0.06	--	B	
^{244}Pu	α	$\sim 100.$	$8.2(1) \times 10^7 \text{y}$	$\begin{Bmatrix} +0.08 \\ -0.7 \end{Bmatrix}$	4	4663.7(10)	80.6(8)	--	--	C	[9,21,22]. $T_{1/2}$ from [10].
	s.f.	$0.12 [c]$	$6.55(32) \times 10^{10} \text{y}$	--	--	--	--	--	--	--	
^{244}Am	β^-	100.	10.1(1)h	--	--	1429.0(20)	0.	744.1; 61.	B(mag.)	B	[9,21,22]
^{244m}Am	β^-	$\sim 100.$	26.m	--	--	1498.(10)	$\sim 80.$	42.9; --	C(mag.)	B	[9,21,22]. Q_β value taken from measured energy of ground-state β^- transition.
	e.c.	0.039(3)	--	--	--	72.(7)	--	--	--	C	
^{244}Cm	α	$\sim 100.$	18.11(1)y	$\begin{Bmatrix} +0.01 \\ -0.011 \end{Bmatrix}$	2	5901.70(11)	76.4(2)	42.824(8); 0.026	B(mag.)	B	[9,21,22]
	s.f.	$1.346(2) \times 10^{-4}$	$1.345(3) \times 10^7 \text{y}$ [e.]	$\begin{Bmatrix} +0.115 \\ -0.093 \end{Bmatrix}$	5	--	--	--	--	--	
^{244}Bk	e.c.	>99.	4.35(15)h	--	--	2280(SYST)	--	217.6(3);	--	C	[9,21]
	α	0.006	--	--	--	6777.(10)	$\sim 50.$	--	--	C	

Table I (Continued)

^{245}Pu	β^-	100.	10.56(2)h	$\begin{Bmatrix} +0.03 \\ -0.08 \end{Bmatrix}$	2	1260.(30)	$\sim 10.$	327.2(5);23.3	B(Si)	B	[9,21]. I_{β^-} value is sum of β^- branch intensities to the lowest 7 states.
^{245}Am	β^-	100.	2.05(1)h	--	--	898.3(25)	78.	252.3(7);6.1(6)	B(Si, mag.)	B	[9,21]. I_{γ} value is from measured γ/β ratio.
^{245}Cm	α	100.	8475.(58)y	$\begin{Bmatrix} +62. \\ -210. \end{Bmatrix}$	2	5623.5(19)	0.5	173.;14.	--	C	[9,21]. I_{γ} value from γ/α ratio. $T_{1/2}$ values measured relative to $T_{1/2}(^{244}\text{Cm})$.
^{245}Bk	e.c. α	99.9 0.105	4.98(2)d --	-- --	-- --	819.(5) 6464.(5)	0. 15.5(5)	252.7(3);30. 474.5(15);0.022	B(mag.,Si) --	C C	[9,21]. Value of $I_{\gamma}(474)$ from γ/α ratio.
^{245}Cf	e.c. α	~ 70 ~ 30	43.6(8)m --	-- --	-- --	1563.(7) 7255.8(20)	-- --	-- --	-- --	C C	[9,21]
^{246}Pu	β^-	100.	10.85(2)d	--	--	374.(10)	0.	223.75(2);23(2)	C(mag.)	B	[9,21,22]
^{246}Am	β^-	100.	39.(3)m	--	--	2300.(50)	0.	679.(1);53.	--	B	[9,21,22]
^{246}mAm	β^-	100.	25.0(2)m	--	--	2300.(50)	$\sim 0.$	798.80(4);26.	B(Si)	A	[9,21-23]. Q_{β} assumed same as for ground state.
^{246}Cm	α	$\sim 100.$	4748.(14)y	$\begin{Bmatrix} +77. \\ -94. \end{Bmatrix}$	3	5476.1(26)	79.(1)	44.545(9);	--	C	[9,21,22]. $T_{1/2}$ values generally given relative to $T_{1/2}(^{244}\text{Cm})$.
	s.f.	0.0261(1)	$1.82(1) \times 10^7 \gamma [e]$	$\begin{Bmatrix} +0.03 \\ -0.02 \end{Bmatrix}$	2	--	--	--	--	--	
^{246}Bk	e.c.	100.	1.83(15)d	--	--	1600.(SYST)	see comment	800.0(5);70	B(Si)	B	[9,21,22]. Feeding of ground-state band <20%. Intensity of ground-state branch assumed to be zero. I_{γ} value from [22]. [9] gives 56% for this value.
^{246}Cf	α	$\sim 100.$	35.7(5)h	--	--	5476.1(26)	77.9(2)	147(4);0.003E(2)	--	C	[9,21,22]. I_{γ} from $\alpha\gamma$ coincidence measurements.
	s.f.	$2.3 \times 10^{-4} [c]$	$1.74(12) \times 10^3 \gamma$	$\begin{Bmatrix} +0.36 \\ -0.4 \end{Bmatrix}$	3	--	----	--	--	--	
^{246}Es	e.c.	90.	7.7(5)m	--	--	3830(SYST)	--	--	--	C	[9,21,22]
	α	10(2)	--	--	--	7700(SYST)	--	--	--	C	

Table I (Continued)

^{247}Am	β^-	100.	22(2)m	--	--	--	--	285.(2);--	C(Si)	C	[9,21]
^{247}Cm	α	100.	$1.56(5)\times 10^7\text{y}$	--	--	5352.1(35)	13.8(7)	402.4(5);72.(6)	--	B	[9,21]. I_γ value determined from relative α - and γ -emission rates.
^{247}Bk	α	100.	$1.38(25)\times 10^5\text{y}$	--	--	5889.(5)	5.5(5)	265.(10);~30.	--	C	[9,21]
^{247}Cf	e.c.	100.	2.45(15)h	--	--	6600.(SYST)	0. ?	295.(5); --	--	C	[9,21]
^{247}Es	e.c.	93.	4.8(2)m	---	--	2350.(SYST)	--	--	--	C	[9,21]
	α	7.	--	--	--	7441.(30)	--	--	--	C	
^{248}Cm	α	91.67	$3.50(4)\times 10^5\text{y}$	$\begin{Bmatrix} +0.11 \\ -0.103 \end{Bmatrix}$	3	5161.(5)	81.9(13)	--	--	C	[9,21,22]. $T_{1/2}$ and $T_{1/2}(\text{s.f.})$ values from averaged $T_{1/2}(\alpha)$ and $\alpha/\text{s.f.}$ values. $T_{1/2}(\alpha)$ generally obtained relative to $T_{1/2}(^{244}\text{Cm})$.
	s.f.	8.33(7)	$4.20(4)\times 10^5\text{y}$	$\begin{Bmatrix} +0. \\ -0.085 \end{Bmatrix}$	2	--	--	--	--	--	
^{248}Bk	β^-	--	>9y	--	--	750.(SYST)	--	--	--	C	[9,21,22]
	e.c.	--	--	--	--	600.(SYST)	--	--	--	C	
$^{248\text{m}}\text{Bk}$	β^-	70.	19(3)h	$\begin{Bmatrix} +4. \\ -3. \end{Bmatrix}$	2	750.(SYST)	--	--	--	C	[9,21,22]. Q values assumed the same as those for the ground state.
	e.c.	30.	--	--	--	600.(SYST)	--	--	--	C	
^{248}Cf	α	~100.	335.3(33)d	$\begin{Bmatrix} +9.7 \\ -1.8 \end{Bmatrix}$	2	6369.(30)	83.0(5)	--	--	C	[9,21,22]
	s.f.	$0.0026^{[c]}$	$3.5(2)\times 10^4\text{y}$	$\begin{Bmatrix} +0.5 \\ -0.3 \end{Bmatrix}$	2	--	--	--	--	--	
^{248}Es	e.c.	>99.	26.(4)m	$\begin{Bmatrix} +2. \\ -1. \end{Bmatrix}$	2	3060.(SYST)	--	--	--	C	[9,21,22]
	α	~0.25	--	--	--	7150.(SYST)	--	--	--	C	
^{248}Fm	α	99.9	37.(4)s	--	--	8001.(20)	80.	--	--	C	[9,21,22]
	s.f.	0.1	10.(5)h	--	--	--	--	--	--	--	
^{248}Md	e.c.	80.(10)	7.(3)s	--	--	5110.(SYST)	--	--	--	C	[9,22]
	α	20.	--	--	--	6800.(SYST)	25.	--	--	C	
^{249}Cm	β^-	100.	64.(3)m	--	--	903.(9)	--	--	---	C	[9,21]

Table I (Continued)

^{249}Bk	β^-	$\sim 100.$	$314.(8)\text{d}$	--	--	$126.1(13)$	$100.$	--	--	A	[9,21]
	α	$0.00145(8)$	--	--	--	$5523.3(13)$	6.7	$327.2(5); --$	--	B	
	s.f.	$4.6 \times 10^{-8} [\text{c}]$	$1.87(9) \times 10^9 \text{y}$	--	--	--	--	--	--	--	
^{249}Cf	α	$\sim 100.$	$350.4(24)\text{y}$	$\begin{Bmatrix} +1.6 \\ -5.4 \end{Bmatrix}$	3	$6295.6(7)$	$2.4(1)$	$388.1(1); 66(2)$	$3(\text{Si})$	A	[9,21]. I_γ value from measured γ -ray emission rate.
	s.f.	$5.0(1) \times 10^{-7}$	$6.98(15) \times 10^{13} \text{y}$	$\begin{Bmatrix} -0.11 \\ -0.84 \end{Bmatrix}$	2	--	--	--	--	--	
^{249}Es	e.c.	99.5	$1.7(1)\text{h}$	--	--	$1405.(7)$	$\sim 46.$	$379.4(5); \sim 46.$	$3(\text{Si})$	B	[9]. $I_{\text{e.c.}}$ value is sum of feeding to lowest 2 states.
	α	$0.5(1)$	--	--	--	$6381.(5)$	--	--	--	C	
^{249}Fm	α	$100.$	$2.6(7)\text{m}$	--	--	$7700.(\text{SYST})$	--	--	--	C	[9,21]
^{249}Md	e.c.	$\sim 80.$	$24.(4)\text{s}$	--	--	$3760.(\text{SYST})$	--	--	--	C	[9]
	α	$\sim 20.$	--	--	--	$8460.(\text{SYST})$	--	--	--	C	
^{250}Cm	s.f.	$100.$	$1.13(5) \times 10^4 \text{y}$	--	--	--	--	--	--	--	[9,21]
^{250}Bk	β^-	$100.$	$3.222(5)\text{h}$	--	--	$1775.(8)$	$5.$	$988.96(15); 45.$	$3(\text{mag.})$	B	[9,21,22]
^{250}Cf	α	$\sim 100.$	$13.08(3)\text{y}$	--	--	$6129.2(6)$	$83.5(12)$	$42.852(5); --$	$3(\text{mag.})$	B	[9,21,22]
	s.f.	$0.077(2)$	$1.69(4) \times 10^4 \text{y}$	$\begin{Bmatrix} +0.04 \\ -0.03 \end{Bmatrix}$	2	--	--	--	--	--	
$^{250}\text{Es}^{[f]}$	e.c.	$100.$	$8.3(2)\text{h}$	--	--	$2000.(\text{SYST})$	--	--	$3(\text{Si})$	C	[9,22]
$^{250m}\text{Es}^{[f]}$	e.c.	100	$2.1(2)\text{h}$	--	--	$2000.(\text{SYST})$	--	--	--	C	[9,22]. Q value listed is the same as that for the ground state.
^{250}Fm	α	$>90.$	$31.(3)\text{m}$	--	--	$7548.(30)$	--	--	--	C	[9]
	s.f.	--	$\sim 10.\text{y}$	--	--	--	--	--	--	--	
^{250m}Fm	I.T.	--	$1.8(1)\text{s}$	--	--	--	--	--	--	C	[9]
^{250}Md	e.c.	$94.(3)$	$52.(6)\text{s}$	--	--	$4530.(\text{SYST})$	--	--	--	C	[9]
	α	$6.$	--	--	--	$8250.(\text{SYST})$	--	--	--	C	
^{251}Bk	β^-	$100.$	$57.0(17)\text{m}$	--	--	$1130.(\text{SYST})$	$0.$	--	--	C	[9,21]. Intensity of ground-state β^- branch deduced from probable difference in ground-state spins and parities ($\Delta I=3, \Delta \pi=\text{no.}$).

Table I (Continued)

^{251}Cf	α	100.	897.(45)y	$\begin{Bmatrix} +3. \\ -5. \end{Bmatrix}$	2	6171.8(14)	2.7(3)	176.6(1);17.(1)	B(Si)	B	[24]. $T_{1/2}$ from data in [21]. I_{γ}^2 value from $\alpha\gamma$ -coincidence measurements
^{251}Es	e.c. α	>99. 0.52	33.(1)h --	-- --	-- --	375.(9) 6593.(5)	~ 65 . ~ 80 .	177.6(3); 5. --	-- --	C C	[9,21]. Value given for ground-state e.c. branch is total feeding of first 3 members of ground-state band.
^{251}Fm	e.c. α	98.1 1.9(2)	5.30(8)h --	-- --	-- --	1490.(SYST) 7366.(15)	-- 1.5(1)	425.4(1);0.97(13)	B(Si)	C A	[9]. I_{γ} (425) determined from measured γ and α intensities together with α /e.c. branching.
^{251}Md	e.c. α	~ 90 . --	4.0(5)m --	-- --	-- --	3030.(SYST) 8050.(SYST)	-- --	-- --	-- --	C C	[9]
^{252}Cf	α s.f.	96.90 3.10(2)	2.640(3)y 85.3(5)y ^[e]	$\{\pm 0.019\}$	4	6217.0(5)	84.2(3)	$\{43.399(25);0.0148(9)\}$ $\{160.(15);0.0020(6)\}$	--	B --	[9,22]. I_{γ} values from $\alpha\gamma$ -coincidence measurements.
^{252}Es	α e.c.	78.(6) 22.(2)	350.(50)d --	-- --	-- --	6746.(5) 1130.(SYST)	80.2(9) 0.	$\{399.7(3);0.23(3)\}$ $\{418.5(3);0.23(3)\}$ 785.1(1);15.(2)	-- B(Si)	A A	[9,22]. I_{γ} (399,418) values determined from $\alpha\gamma$ -coincidence measurement and listed α -branching ratio. I_{γ} (785) deduced from intensity-balance considerations and e.c.-branching ratio.
^{252}Fm	α s.f.	~ 100 . 0.002 ^[c]	22.8(6)h 115.(60)y	$\begin{Bmatrix} +0.2 \\ -0.1 \end{Bmatrix}$ --	2 1	7154.(20) --	~ 85 . --	-- --	-- --	C --	[9,21,22]
^{252}Md	e.c.	--	2.3(8)m	--	--	3750.(SYST)	--	--	--	C	[9]
^{252}No	α s.f.	~ 70 . ~ 30 .	2.4(2)s ~ 7 .s	-- --	-- --	8546.(15) --	-- --	-- --	-- --	C --	[9]
^{253}Cf	β^- α	99.69 0.31(4)	17.82(9)d --	-- --	-- --	299.(10) 6136.(5)	~ 100 . 0.	{no γ 's reported}	-- --	C C	[9,21]
^{253}Es	α s.f.	~ 100 . $8.7(2)\times 10^{-6}$	20.47(2)d $6.4(2)\times 10^5\text{y}^{[e]}$	-- --	-- --	6739.58(23) --	89.8(2) --	389.18(4);0.026 --	A(mag.) --	A --	[9,21,25]

Table I (Continued)

^{253}Fm	e.c. α	88. 12.(1)	3.00(13)d --	-- --	-- --	341.(4) 7206.(4)	-- 1.3(2)	-- 271.8(4);2.6(4)	-- 3(Si)	C B	[9,21]. I_γ value from $\alpha\gamma$ -coincidence measurements and α -branching ratio.
^{254}Cf	α s.f.	0.310(16) 99.690	60.5(2)d 60.7(2)d	-- --	-- --	5931.4 --	83.(2) --	-- --	-- --	C --	[9,21,22]. $T_{1/2}$ (s.f.) calculated from $\alpha/(\alpha+s.f.)$ ratio and listed $T_{1/2}$ value.
^{254}Es	α	100.	276.d	--	--	6626.(5)	~ 0.005	{ 63.(2);2.0(3) 150.(2);0.020(3) }	3(emuls.)	B	[9,21,22]. I_γ (63) value from $\alpha\gamma$ -coincidence and γ -emission rate measurements.
^{254m}Es	β^- α e.c.	99.6 0.33(1) 0.078(6)	39.3(2)h -- --	-- -- --	-- -- --	1164.(11) 6704.(5) 668.(SYST)	$\sim 16.$ 4.0(5) 100.	693.67(7);24.7(17) 211.8(1);0.10(1)	B(mag.) B(Si)	A A C	[9,21,22]. I_γ values from measured γ -emission rate relative to α -rate from ^{254}Fm in equilibrium. Q values calculated from those for the ground state assuming an isomeric-state energy of 78(1) keV.
^{254}Fm	α s.f.	99.941 0.0590(3)	3.24(1)h 229.(1)d[e]	-- --	-- --	7315.(5) --	85.(1) --	151.(5);0.0010(3) --	-- --	C --	[9,21,22]
^{254}Md (1)[g]	e.c.	--	10.(3)m	--	--	2490.(SYST)	--	--	--	C	[9]. $Q_{e.c.}$ value is that for the ground-state decay.
^{254}Md (2)[g]	e.c.	--	28.(8)m	--	--	2490.(SYST)	--	--	--	C	[9]. $Q_{e.c.}$ value is that for the ground-state decay.
^{254}No	α	100.	55(5)s	--	--	8235.(15)	$\sim 85.$	--	--	C	[9,21,22]
^{254m}No	I.T.	--	0.28(4)s	--	--	--	--	--	--	C	[9]
^{255}Es	β^- α s.f.	92.0 8.0(4) 0.0041(2)	39.8(12)d -- 2.63(15) $\times 10^3$ y	-- -- --	-- -- --	290.(SYST) 6400.2(15) --	-- 87.7 --	-- -- --	-- -- --	C C --	[9,21]. $T_{1/2}$ (s.f.) derived from $\beta^-/s.f.$ ratio and $T_{1/2}$.
^{255}Fm	α s.f.	$\sim 100.$ 2.4(10) $\times 10^{-5}$	20.04(8)h ($9.6^{+5.7}_{-3.0}$) $\times 10^3$ y[e]	($+0.03$) (-0.14)	2	7242.(4) --	0.070(7) --	204.1(2);0.024(2) --	A(mag., Si)	A --	[9,21,25]. I_γ value from γ - and α -emission-rate measurements.

Table I (Continued)

^{255}Md	e.c. α	90. 10.(1)	27.(2)m --	-- --	-- --	1080.(SYST) 7950.(SYST)	-- --	-- 430.(40); --	-- --	C C	[9]. A value for e.c./ α of 93/7(1) is also reported.
^{255}No	α	100.	3.16(12)m	$\left\{ \begin{smallmatrix} +0.17 \\ -0.16 \end{smallmatrix} \right\}$	3	8445.(9)	3.(1)	--	--	C	[9,21]
^{256}Fm	α s.f.	8.1(3) 91.9	157.(2)m 2.85(4)h	-- --	-- --	7034.(5) --	-- --	-- --	-- --	C	[9,22]. $T_{1/2}$ (s.f.) calculated from measured $\alpha/(\alpha+\text{s.f.})$ ratio and listed $T_{1/2}$ value.
^{256}Md	e.c. α	90.6 9.4(4)	76.(3)m --	$\{\pm 1.\}$ --	2 --	1940.(SYST) 7843.(20)	-- 4.(1)	-- 400.(20); --	-- --	C C	[9,22]. E.c. and α branch intensities are an average of 2 reported values, 90.1/9.9(5) and 91.5/8.5(8), for $\alpha/(\text{e.c.}+\alpha)$.
^{257}Fm	α s.f.	99.79 0.210(5)	100.5(2)d 131.(3)y ^[e]	-- --	-- --	6866.2(31)	0.4(2)	241.2(7); 10.(1)	B(Si)	B	[9,21]. I_γ values from $\alpha\gamma$ -coincidence measurements.
^{257}Md	e.c. α	90. 10.(3)	5.2(3)h --	$\{\pm 0.2\}$ --	2 --	430.(SYST) 7600.(SYST)	-- --	-- --	-- --	C C	[9,21]
^{257}No	α	100.	24.5(14)s	$\{\pm 1.5\}$	2	8452.(30)	--	--	--	C	[9,21]

- [a]. Unless otherwise indicated, these intensity values give the percent of a given decay mode which directly populates the ground state of the respective daughter nucleus. Consequently, in those cases where more than one decay mode of a nucleus has an appreciable intensity, they must not be interpreted as being expressed as % of decays of the parent nucleus.
- [b]. Unless otherwise noted, the listed absolute I_γ values are derived from intensity-balance considerations within the decay scheme. They are always given in %/decay (i.e., photons/100 decays) of the parent nuclides.
- [c]. Spontaneous-fission branching ratio calculated from the listed values of $T_{1/2}$ (s.f.) and $T_{1/2}$.
- [d]. (^{236}mNp , ^{242}Am). These values represent intensities in % of decays of the parent nuclide rather than in % of decays via the respective decay mode.
- [e]. $T_{1/2}$ (s.f.) value derived from the $\alpha/\text{s.f.}$ ratio and the listed value of $T_{1/2}$.
- [f]. (^{250}Es , $^{250\text{m}}\text{Es}$). The relative ordering of the ground and isomeric states is not experimentally established. The ordering given here is based on the expectation that the coupling of the odd neutron and the odd proton will produce a high-spin ground state and a low-spin isomeric state. The short-lived activity is observed to feed low-spin states in the daughter nucleus, while the longer-lived activity does not. This indicates that the short-lived activity has a low spin and thus strongly suggests that it is the isomeric state.

Table I (Continued)

[g]. ($^{254}\text{Md}(1)$, $^{254}\text{Md}(2)$). The relative position in ^{254}Md of these two activities is not yet established.

REFERENCES FOR TABLE I

- [1]. M. J. Martin and P. H. Blichert-Toft, Nuclear Data Tables A 8, Nos. 1-2, (1970) 1.
- [2]. Nuclear Data Sheets 5, No. 3, (1971).
- [3]. P. Aguer, A. Peghaire and G. F. Liang, Nucl. Phys. A202 (1973) 37.
- [4]. Nuclear Data Sheets B 4, No. 5, (1970).
- [5]. E. F. Tret'yakov, N. I. Tret'yakova and V. F. Konyaev, Izv. Akad. Nauk SSSR, Ser. fiz. 35 (1971) 2306; Bull. Acad. Sci. USSR, Phys. Ser. 35 (1972) 2094.
- [6]. W. Lourens, B. O. Ter Brink and A. H. Wapstra, Nucl. Phys. A152 (1970) 463.
- [7]. W. Kurcewicz, K. Strzeczniwicki, J. Zylicz, S. Chojnacki, T. Morek and I. Yutlandov, Acta Phys. Polonica B2 (1971) 451.
- [8]. T. Valkeapää, J. Heinonen and G. Gräeffe, Phys. Scripta 5 (1972) 119.
- [9]. C. M. Lederer, private communication (July, 1975) (to appear in Table of Isotopes, Seventh Edition).
- [10]. R. Vaninbroukx, Euratom Report EUR-5194e (1974).
- [11]. J. E. Cline, USAEC Report IN-1448 (rev.), (Jan., 1971); see also J. E. Cline, R. J. Gehrke and L. D. McIsaac, USAEC Report ANCR-1069 (Supplement to IN-1448), (July, 1972).
- [12]. L. A. Kroger, C. W. Reich and J. E. Cline, USAEC Report ANCR-1016 (1971) 68; L. A. Kroger and C. W. Reich (to be submitted for publication).
- [13]. N. Kaffrell, N. Trautmann and R. Denig, Z. Physik 266 (1974) 21.
- [14]. Nuclear Data Sheets 6, No. 6, (1971).
- [15]. I. Ahmad, F. T. Porter, M. S. Freedman, R. K. Sjöblom, J. Lerner, R. F. Barnes, J. Milsted and P. R. Fields, Phys. Rev. C. (to be published).
- [16]. R. Gunnink and R. J. Morrow, USAEC Report UCRL-51087 (July, 1971).
- [17]. R. G. Helmer and R. C. Greenwood, Nucl. Technology 25 (1975) 258.

Table I (Continued)

- [18]. I. Ahmad, R. F. Barnes, R. K. Sjolom and P. R. Fields, J. Inorg. Nucl. Chem. 34 (1972) 3335.
- [19]. I. Ahmad, A. M. Friedman and J. P. Unik, Nucl. Phys. A119 (1968) 27.
- [20]. I. Ahmad and M. Wahlgren, Nucl. Instr. and Methods 99 (1972) 333.
- [21]. Nuclear data Sheets B 3, No. 2 (1969).
- [22]. M. R. Schmorak, private communication (July, 1975) (to appear in Nuclear Data Sheets).
- [23]. L. G. Multhau, K. G. Tirsell and R. A. Meyer, Phys. Rev. C (to be published).
- [24]. E. Browne and F. Asaro, USAEC Report UCRL-19530 (1969) 8.
- [25]. I. Ahmad and J. Milsted, Nucl. Phys. A239 (1975) 1.

these two quantities were derived for the various nuclides is indicated in footnotes to the table.

In a number of cases, several measurements of the nuclide half-life have been made; and it is frequently found that the measured values differ from each other by amounts that are much larger than the quoted uncertainties. In these cases, we have listed (1) an "averaged" value for the half-life and its uncertainty, together with (2) the range (above and below the average) spanned by the measured values and (3) the number of measurements included. In arriving at those measurements to be included, we have occasionally discarded some older measurements (where more recent ones seemed more reliable) and some whose quoted uncertainties were significantly larger than those of the ones used. Where indicated in the References Column, these "averaged" values were taken from the recent compilation of Vaninbroux⁽¹⁹⁾. In the remainder of the cases, the listed value is a weighted average of the measurements, with a $1/\sigma$ weighting factor used. The uncertainty given is the "internal" error, namely,

$$\sigma (T_{1/2}) = \sqrt{n / \sum_i w_i}$$

where n is the number of measurements and w_i is the weighting factor (i.e., $1/\sigma_i$) of the i^{th} measurement. Comparison of this internal-error estimate with the range of values gives some indication of how the differences among the measured values compare with their quoted uncertainties. As stated above, it is not the purpose of this procedure to produce "recommended" half-life values in these cases; it is merely intended to illustrate in a fairly concise way the status of the experimental situation.

In the table are listed the Q-values for each decay mode (except spontaneous fission). This gives the total energy available to the decay. The notation "SYST" accompanying a value indicates that is estimated from systematics. Listed next is the intensity of the transition directly from the parent state to the ground state of the daughter nucleus (excluding isomeric-transition decay). This has been included since, in many cases, it indicates the precision with which γ -ray intensities can be inferred from intensity-balance considerations within the decay scheme. These absolute intensities, where not directly measured (i.e., by $\alpha\gamma$ - or $4\pi \beta\gamma$ - coincidence measurements) are generally deduced by requiring that the sum of the transition (i.e., photon + conversion-electron) intensities of all the γ -rays feeding the ground state and the direct feeding from the parent nucleus equal 100%. Weak ground-state feeding indicates that, in principle, fairly precise absolute γ -ray intensities can be deduced, while strong direct feeding of the ground state generally indicates that the derived absolute-intensity values will be less precise.

Also given in the table are energy and absolute-intensity values for a prominent γ ray (or γ rays) associated with the various decay modes (except spontaneous fission) of each nuclide. Because of the wide-spread use of γ -ray spectroscopy for quantitative assay of radioactivity and of the many applications involving such assay, these data are of considerable importance.

We have given only qualitative indicators for the status of the conversion-electron data and of the deduced decay scheme. In this notation, A indicates a quite well studied and reasonably complete situation; B denotes some data, but an incomplete situation; while

C indicates only fragmentary data or decay scheme. If no c.-e. data exist, this column is left blank, while if the decay scheme is completely unknown, a C is still indicated in that column. Clearly, the borders between these various symbols are not sharply drawn. The notations "mag.", "emuls." and "Si" in the c.-e. status column indicate that magnetic spectrometers, magnetic spectrographs, and silicon detectors, respectively, were utilized in conversion-electron measurements.

Where the various quantities are not known, generally no entry appears in the table.

At the right in the table are given the references from which the data have been taken and appropriate comments. The numbering of the references refers to those at the bottom of the table and is separate from that employed in the text. While it would have been generally desirable to refer in all cases to the original papers for the data included in Table I, this was not done because of the quite extensive referencing which this would have required.

A large body of data on the spontaneous-fission isomers, whose existence and properties provide a striking illustration of the influence of shell-structure effects on the formation of a second minimum in the nuclear potential well, is not included here. It was felt that a treatment of these interesting nuclear states lay outside the scope of this meeting.

2. Discussion of Specific Points

Because of the widespread use of γ -ray spectroscopy as a means of both qualitative and quantitative assay of radioactivity, the γ -ray-energy and especially the absolute-intensity data are of great importance. For this reason, comments pointing up discrepancies and differences in

reported intensity values are occasionally included in Table I (see, e.g., ^{232}U). The intensity of the prominent 185.71-keV γ ray from the ^{235}U decay represents an interesting situation. Only one measurement of this quantity is reported⁽²⁰⁾ -- in an APS Bulletin Abstract in 1957 -- and no uncertainty was quoted. Hence, quantitative assay of ^{235}U samples using only γ -ray spectrometry involves data of unknown accuracy.

The absolute intensities of the γ rays from the more common Pu isotopes present unresolved problems at this time, in that the two most extensive reported measurements^(21,22) exhibit considerable disagreements. This situation has been studied in detail in the context of safeguards research by Ottmar and Weitkamp⁽²³⁾, who compare isotopic ratios of Pu isotopes determined from mass-spectrometric analyses with those determined from γ -ray spectrometry. These results are shown in Table II. Ottmar and Weitkamp report:

For computation of the γ -spectrometric isotopic ratio values as listed in the Table, absolute γ intensities have been used. The results in columns 3 and 4 are calculated from the only two comprehensive sets of absolute γ intensities of plutonium and americium isotopes published until now^(21,22). The agreement of the two sets of results with each other and with the mass-spectrometric data is poor. This indicates that the reported error values for the absolute intensities are too optimistic.

Among other things, they conclude:

One prerequisite for the accurate γ -spectrometric determination of plutonium isotopic ratios is the availability of better nuclear data. Since absolute γ intensities can hardly be measured to the degree of accuracy necessary, intensity ratios should be determined as outlined in Chapter 4. This requires samples with very accurately known isotopic composition.

TABLE II

Results of a gamma spectrometric determination of isotopic ratios in plutonium.

(This table is taken from Ottmar and Weitkamp⁽²³⁾.)

Isotopic ratio	Mass spectrometric value	γ-spectrom. values calculated with absolute intensities from refs.		γ lines used for analysis (keV)		Error components(*)†		
		(21)	(22)	²³⁹ Pu γ	Other γ	F _I	F _H	F _P
²³⁹ Pu/ ²³⁸ Pu	3118 (10)*	3260 (6)	4809 (22)	203.55	152.77	4	0.2	2
		3333 (14)	4513 (32)	769.38	742.77 ⁺	2	0.2	12
		2753 (4)	3680 (21)	769.38	766.41 ⁺	2	0.2	2
		2855 (10)	6673 (18)	769.38	786.30	2	0.2	8
²³⁹ Pu/ ²⁴⁰ Pu	10.512(0.4)	12.57(10)	40.41(25)	161.45	160.35	4	0.3	5
		12.74(8)	40.21(22)	646.02	642.30	5	0.3	2.5
²³⁹ Pu/ ²⁴¹ Pu	121.39 (1.1)	113.7 (10)	139.6 (22)	203.55	208.00	8	1.1	0.3
²³⁹ Pu/ ²⁴¹ Am	901.6 (2.3)	635.2 (11)	671.0 (26)	422.57	419.19	5	0.3	6
		846.9 (20)	1214 (33)	451.45	454.58	7	0.3	13
		588.1 (18)	1232 (31)	640.15	641.37	7	0.3	11
		604.6 (4)	819.9 (11)	646.02	652.37 ⁺	3	0.3	0.6
		498.3 (9)	639.0 (24)	652.19	652.38	5	0.3	4
		607.6 (5)	618.7 (11)	658.99	652.37	4	0.3	0.7
		601.0 (9)	---	686.16	538.70	6	0.3	2.7
		599.4 (7)	913.2 (23)	717.76	721.92	4	0.3	2.6

†F_I, F_H, F_P denote errors for the ratios of absolute intensities, half-lives and measured peak areas, respectively.

*Values in parentheses are errors in percent (emphasis ours).

⁺Possible interference from fission-product γ rays.

As a daughter nucleus from ^{239}U decay, ^{239}Np is important in a number of applications such as, e.g., measurements of the neutron capture cross section of ^{238}U . As indicated in Table I, the absolute intensities of the two prominent γ -rays near ~ 0.2 MeV are known with precisions somewhat better than 2%. A γ -ray doublet at ~ 106 keV, more intense than either of these two, also occurs in the ^{239}Np decay. Its use in quantitative spectral analysis is not generally advisable, partly because at that energy absorption within the samples can be important and partly because it lies in the energy region of the K x-rays from the near-lying elements.

The intensity of the prominent 59.5-keV γ -ray from ^{241}Am decay is now quoted with an uncertainty of $\sim 1\%$. We have derived the value given in Table I from a $1/\sigma$ -weighted average of the two most recent measurements, $35.3 \pm 0.6\%$ ⁽²⁴⁾ and $36.3 \pm 0.4\%$ ⁽²⁵⁾. It is interesting and perhaps fortuitous that this value is now back to what it was in 1957⁽²⁶⁾ and used by IAEA, namely 35.9%, although the uncertainty is now roughly a factor of 2 smaller.

The low-energy (≤ 30 keV) photons from ^{241}Am are frequently used as intensity-calibration standards for low-energy photon detectors. Five peaks are commonly utilized, namely the $L\ell$, $L\alpha$, $L\eta\beta$, and $L\gamma$ lines at 11.9, 13.9, 17.8, and 20.8 keV, respectively, and the 26.35-keV γ ray. A detailed treatment of the absolute-intensity values of these lines has been reported by Campbell and McNelles⁽²⁷⁾. They conclude that the uncertainties in these absolute intensities range from $\sim 2.5\%$ for the $L\alpha$ line to $\sim 4\%$ for weaker $L\ell$ and 26.35-keV lines.

IV. SELECTED SPONTANEOUS-FISSION DATA

The spontaneous-fission half-life data are summarized in Table I above. The subjects of prompt and delayed neutron yields and energy spectra from spontaneous fission are characterized by an extensive literature; and we consequently confine our remarks here to brief comments concerning a few recent developments.

1. $\bar{\nu}$ Values from Spontaneous Fission

The subject of $\bar{\nu}$, the average number of neutrons emitted per fission, has been treated exhaustively in the excellent recent review by Manero and Konshin⁽²⁸⁾. Since that time a few additional measurements of $\bar{\nu}$ from the spontaneous fission of several nuclides have been reported. However, these values are in essential agreement with those given in⁽²⁸⁾, so that this review still presents a good overall picture of the status of spontaneous-fission $\bar{\nu}$ values.

The value of $\bar{\nu}$ for the spontaneous fission of ^{252}Cf occupies a central position in the area of $\bar{\nu}$ measurements since it is the "standard" relative to which other $\bar{\nu}$ values are measured. This is the case not only for the other spontaneously fissioning isotopes but also -- and more important -- for the fissionable isotopes as well. However, at the present time there are still discrepancies in the value of this quantity as determined using different measurement techniques (see the discussion in (29) and (28)). In this context, it is appropriate to point out that a remeasurement of $\bar{\nu}$ for ^{252}Cf is currently in progress⁽³⁰⁾. This experiment utilizes the manganese-bath technique; and particular attention has been given to identifying the various sources of error and to the quantitative determination of their effects. At the time of the

writing of this review the results from this experiment are not available.

2. Neutron energy spectra from spontaneous fission

The prompt-neutron energy spectrum following spontaneous fission is customarily assumed to be well described by a Maxwellian distribution function, viz.

$$N(E) \propto E^{\frac{1}{2}} \exp(-1.5E/E_{av.}),$$

with the quantity $E_{av.}$ being determined from the data. The two most widely studied fission-neutron spectra are those from spontaneous fission of ^{252}Cf and thermal-neutron-induced fission of ^{235}U . The extensive data on these two energy spectra have quite recently been carefully evaluated by Grundl and Eisenhauer⁽³¹⁾ to determine to what extent they can be described by a Maxwellian function. These authors conclude that, over the energy range 0.25 to 8 MeV, the reference Maxwellian shapes differ from the final evaluated shapes by $\lesssim 2\%$, with the average-energy parameters ($E_{av.}$) determined to be 2.13 ± 0.027 MeV and 1.97 ± 0.014 MeV, respectively, for ^{252}Cf spontaneous fission and ^{235}U thermal-neutron-induced fission.

In the area of the energy distribution of delayed neutrons following spontaneous fission, we wish to call attention to a series of quite interesting experiments being carried out at the OSIRIS Facility at Studsvik, Sweden. In these experiments the individual delayed-neutron precursors, produced in thermal-neutron fission of ^{235}U , are isolated for detailed study using on-line isotope separation. While these studies do not provide "integral" energy-spectral information, they can (in principle) yield such information when combined with the

appropriate fission-product yields. A number of interesting features of the delayed-neutron energy distributions of individual precursors are observed, such as the occurrence of both discrete and continuous components. A summary of the present status of these results has been prepared by Professor Rudstam. This is included as Appendix B of this review.

V. COMMENTS AND OBSERVATIONS

To make the most effective use of available resources in the area of Nuclear Data, good communication among the measurers, the users, and the compilers and evaluators of nuclear data should exist. The field of neutron cross sections provides an excellent example of one category of nuclear data in which a fruitful interaction has existed among these three components of nuclear-data activity. At the present time, however, no relationship of comparable scope exists within the area of radioactive-nuclide decay data. This situation has been commented on before (see, e.g., (1,32)).

Because of the use of radioactivity in a number of widely varied applied areas and scientific disciplines, the "user community" of decay data is quite diverse. Consequently, the identification of a satisfactorily representative sample of such users represents a formidable problem.

The existence of different categories of measurers of decay data needs to be recognized. The vast majority of information constituting the present base of decay data has been provided by those interested in nuclear-structure physics. Generally speaking, these workers are not aware of the specific data needs of applied users, particularly specific accuracy requirements. This is especially true with respect to absolute γ -ray intensities and half-life values, which are necessary for any applications where quantitative assay of γ radioactivity is required. High-precision measurements of these quantities are not generally required in order to extract the interesting basic nuclear-physics information from a decay study. In addition, the measurement

of these quantities with the desired precisions (say, <5% for absolute γ -ray intensities) requires specialized calibration techniques and instrumentation. For these reasons many of the data needs of users are inadequately satisfied at the present time.

Important in the development of a program to meet the requirements for decay data is recognition of the importance of radioactive-nuclide metrology. This metrology function would be mainly to develop and improve selected measurement techniques to provide a recognized capability for performing measurements requiring high precision. While in fact these measurements are of basic nuclear-physics quantities, the orientation of the effort would be to provide specific information for application to specific problems. Such a metrology program would most effectively be organized around existing capability in major laboratories engaged in nuclear research in order to provide continuity and the required technical support in associated disciplines. Examples of high-precision measurements of selected decay-scheme parameters for applications-oriented purposes are provided by work carried on in several Western-European laboratories (see, e.g., Refs. (33,34)).

Attention should also be given to the desirability of utilizing a common data content and format for the organization of decay data to meet applied needs. A common base of data presents a number of advantages to the applied user, among which we indicate two. First, it possesses "traceability", that is, it provides a standard origin for the data used by different groups. Second, it permits uniformity in the application of decay data to the quantitative measurement of radioactivity. Examples of applied needs include environmental monitoring and radiological health-hazard evaluations. In the preparation of

regulations and guidelines by regulatory agencies to insure uniformity in the reported results of measurements, the standardization of reference material afforded by a common data base is a necessity and has legal implications. A structure for such data modeled along that for the ENDF/B decay-data file might be useful.

Interest has been expressed concerning what type of presentation (computer media or published form) of decay data is the most convenient from the point of view of the user. It is our opinion that such data should certainly be available in a simple and easily readable form, i.e., in print. Compared with categories of nuclear data such as, e.g., neutron cross sections, the amount of information involved is relatively small and having it available in handbooks, reports or tables makes its use quite straightforward and simple. If required for some applications, e.g., for use in data-analysis codes, the relevant data can readily be prepared in a suitable computer-based medium. (In fact, the decay data on ENDF/B-IV are stored on computer tape, although they are also available in the form of computer listings in a "people-readable" format⁽²⁾ if desired.)

VI. REFERENCES

1. Fission Product Nuclear Data (Proc. Conf. Bologna, 1973), IAEA - 169, IAEA, Vienna (1974).
2. C. W. Reich, R. G. Helmer, M. H. Putnam, Radioactive-Nuclide Decay Data for ENDF/B, US AEC Report ANCR-1157 (August, 1974).
3. O. Nathan, S. G. Nilsson, "Collective Nuclear Motion and the Unified Model", Ch. 10, Alpha-, Beta-, and Gamma-Ray Spectroscopy (K. Siegbahn, Ed.), North-Holland, Amsterdam, (1966).
4. S. G. Nilsson, Mat. Fys. Medd. Dan. Vid. Selsk. 29 (1955) No. 16; C. Gustafson, I.-L. Lamm, B. Nilsson, S. G. Nilsson, Ark. Fys. 36 (1967) 613; S. G. Nilsson, C. F. Tsang, A. Sobieczewski, Z. Szymanski, S. Wycech, C. Gustafson, I.-L. Lamm, P. Möller, B. Nilsson, Nuclear Physics A131 (1969) 1.
5. M. E. Bunker, C. W. Reich, Revs. Mod. Phys. 43 (1971) 348.
6. C. J. Gallagher, S. A. Moszkowski, Phys. Rev. 111 (1958) 1282.
7. R. S. Hager, E. C. Seltzer, Nuclear Data A 4 (1968) 1.
8. P. F. Dittner, C. E. Bemis, Jr., Phys. Rev. A 5 (1972) 481.
9. W.-D. Schmidt-Ott, J. S. Hansen, R. W. Fink, Z. Physik 250 (1972) 191.
10. J. A. Bearden, A. F. Burr, Revs. Mod. Phys. 39 (1967) 125.
11. M. J. Martin, P. H. Blichert-Toft, Nuclear Data Tables A8 (1970) 1.
12. J. Blachot, R. deTourreil, CEA Report-N-1526 (1972); C. Devillers, J. Blachot, M. Lott, B. Nimal, J. P. Noel, N'Guyen Van Dat, R. deTourreil, Nuclear Data in Science and Technology (Proc. Conf. Paris, 1973), Vol. I, 477, IAEA SM-170/63, IAEA, Vienna (1973).
13. A. Tobias, Data for the Calculation of Gamma Radiation Spectra and Beta Heating from Fission Products (Revision 3), Central Electricity Generating Board Report RD/B/M2669 CNDG (73) P4 (June, 1973).
14. G. Rudstam, Fission Product Nuclear Data (Proc. Conf. Bologna, 1973), Review Paper 12, Vol. II, 1. IAEA-169, IAEA Vienna (1974).
15. M. R. Schmorak, Private Communication (July, 1975).
16. C. M. Lederer, Private Communication (July, 1975).
17. N. B. Gove, Private Communication (May, 1973)
18. A. Zelenkov, Review Paper B6 submitted to this conference.

19. R. Vaninbroukx, Half-Lives of Some Long-Lived Actinides: A Compilation, Euratom Report EUR-5194e (1974).
20. R. C. Pilger, F. S. Stephens, F. Asaro, I. Perlman, Bull. Am. Phys. Soc., Ser. II 2 (1957) 394.
21. R. Gunnink, R. J. Morrow, US AEC Report UCRL-51087 (July, 1971).
22. J. E. Cline, US AEC Report IN-1448 (rev.) (January, 1971); J. E. Cline, R. J. Gehrke, L. D. McIsaac, US AEC Report ANCR-1069 (Supplement to IN-1448) (July, 1972).
23. H. Ottmar, C. Weitkamp, Symposium on Practical Applications of Research and Development in the Field of Safeguards (Proc. Conf. Rome, 1974), IAEA, Vienna, (1974).
24. A. Peghaire, Nuclear Instr. and Methods 75 (1969) 66.
25. J. Legrand, J. P. Perolat, C. Bac, J. Gorry, Int'l J. Appl. Rad. and Isotopes 26 (1975) 179.
26. L. B. Magnusson, Phys. Rev. 107 (1957) 161.
27. J. L. Campbell, L. A. McNelles, Nuclear Instr. and Methods 117 (1974) 519.
28. F. Manero, V. A. Konshin, At. Energy Rev. 10 (1972) 637.
29. E. J. Axton, Neutron Standard Reference Data (Proc. Conf. Vienna, 1972), 261, IAEA-P1-246-2/31, IAEA, Vienna (1974).
30. J. R. Smith, Private Communication (August, 1975).
31. J. A. Grundl, C. M. Eisenhauer, Bull. Am. Phys. Soc. Ser. II 20 (1975) 145; and Proc. Conf. on Nuclear Cross Sections and Technology, Washington, D.C., (1975) (to be published).
32. C. W. Reich, R. G. Helmer, Bull. Am. Phys. Soc., Ser. II 20 (1975) 134; and Proc. Conf. on Nuclear Cross Sections and Technology, Washington, D.C., (1975) (to be published).
33. H. H. Hansen, E. deRoost, W. van der Eijk, R. Vaninbroukx, Z. Physik 269 (1974) 155, and references contained therein.
34. K. Debertin, U. Schötzig, K. F. Walz, H. M. Weiss, Private Communication (March, 1974).

APPENDIX A

THE ENDF/B DECAY-DATA FILE

As mentioned in Chapter 1 above, a file of actinide-nuclide decay data is currently being prepared for inclusion in Version V of ENDF/B. It will contain data on 46 nuclides and isomeric states. It thus seems appropriate within the context of this meeting to present a discussion of the philosophy underlying the ENDF/B decay-data file and to describe its organization and the types of information it contains.

As originally set up for Version IV of ENDF/B, the decay data file was oriented toward the specific objective of providing a data base adequate for use in summation-type calculations of the fission-product decay-heat source term in reactor cores. However, in the planning of the file organization and content it was recognized that such a file -- within the ENDF/B structure -- should address itself to as broad a range of reactor-related applications (and, by implication, to use in other areas as well) as possible, within the limits of a realistic content and size. As such, the file was not intended to replace such broadly based data compilations as the Nuclear Data Sheets or the Table of Isotopes (see Chapter 2 above) but rather to represent a carefully evaluated subset of those data, oriented toward the needs of a certain identified group of users and presented in a format readily usable by them. The Version-IV data file which was set up to satisfy these requirements has been discussed in detail elsewhere^(2,32).[†] For ENDF/B-V, the content has been expanded somewhat to permit detailed information on more radiation forms.

[†] The numbering of the references is that used in the text.

The file is most simply discussed by reference to actual examples of specific data sets. We have chosen two examples, ^{85m}Kr and ^{128}I , to serve as vehicles for the discussion. Although not actinides, these relatively simple cases provide a good orientation to the file structure.

Decay-data sets, in card-image format, as prepared for our laboratory, or "working", file for ^{85m}Kr and ^{128}I are shown in Tables A-I and A-II, respectively. (The process by which they are transcribed into final ENDF/B format will be mentioned below.) The first card contains the following information: 7 and A values (in the form 1000 7 + A) followed immediately by an isomer flag. A blank or zero in the latter column indicates the ground state of the nucleus, a 1,2,... indicates a first, second,... isomeric state. (Isomers are arbitrarily restricted to nuclear states with half-lives > 0.1 sec and are listed as separate "nuclides" in the file.) Following this on the first card are the chemical symbol, the spin and parity of the state and a number indicating the number of "comment cards" to follow.

Next comes a group of cards which provide the documentation for and pertinent comments about the data set. These are followed by a card giving the half-life, its uncertainty, the units, the number of decay modes of the nuclide and the number of energy spectra to be listed.

This is followed by cards (equal in number to the indicated number of decay modes) giving the following information about each decay mode: the type of decay; whether or not an isomeric state in the daughter is fed; the Q-value in keV for the decay mode; its uncertainty; the branching ratio (in percent) of the decay mode; and its uncertainty. The decay modes thus far treated are denoted as follows: β^- , 1; electron capture and/or β^+ , 2; isomeric-transition, 3; α -particle, 4; neutron, 5; spontaneous fission, 6; and proton, 7. If one type of

TABLE A-I. Sample listing of decay data for ^{85m}Kr decay prepared in the INEL format.

Z	A	IS	$I\pi$	No. of Comment Cards
36	85	1	KR	1/2- 4

COMMENTS AND DOCUMENTATION

PREPARED FOR FILE : 1/75 CWR
 REFERENCES: Q- 1973 REVISION OF WAPSTRA-GOVE MASS TABLES.
 OTHER- F.K. WOHN, W.L. TALBERT, JR. AND J.K. HALBIG,
 NUCL. PHYS. A152, 561 (1970).

$T_{1/2}$	σ	Units	No. of Decay Modes	No. of Spectra		
4.480	0.008	H	2	3		
Decay Mode	Final-state isomer	Q	σ	Branching	σ	
1	0	991.7	2.0	78.8	1.3	
3	0	304.47	0.05	21.2	1.3	
$\langle E_{\text{elect.}} \rangle$	σ	$\langle E_{\text{phot.}} \rangle$	σ	$\langle E_{\text{h.p.}} \rangle$	σ	
251.62		157.14				
Normalization	σ	No. of Transitions	Radiation Type	$\langle E_{\beta^-} \rangle$	σ	
0.788	0.013	1	1	226.1	2.0	
E_{β^-}	σ	I_{β^-}	σ			
840.7	2.0	100.0				
Normalization	σ	No. of Entries	Radiation Type	$\langle E \rangle$	σ	
1.0		2	9	0.792		
K x-ray Int.	σ	L x-ray Int.	σ	ann. rad. Int.	σ	source flag
2.05		0.13				1
3.96		0.23				3
Normalization	σ	No. of Transitions	Radiation Type	$\langle E_{\gamma} \rangle$	σ	
1.40		2	0	156.35		
E_{γ}	σ	I_{γ}	σ	Multipolarity		Source flag
150.99	0.05	53.8	1.8	M1		1
	0.0400	0.0008	0.0045	0.0002	0.0010	0.0001
304.47	0.05	10.0	0.4	M4		3
	0.432	0.020	0.064	0.003	0.013	0.001

TABLE A-II. Sample listing of decay data for ^{128}I decay, prepared in the INEL format.

Z

A

IS

$T_{1/2}$

σ

Units

No. of

Decay Modes

No. of

Spectra

Comment Cards

53

128

I

1+

3

COMMENTS AND DOCUMENTATION

PREPARED FOR FILE: 1/75

CWR

REFERENCES: Q- 1973 REVISION OF WAPSTRA-GOVE MASS TABLES.

OTHER- SEE R.L. AUBLE, NUCL. DATA SHEETS 9, 157(1973)

$T_{1/2}$

σ

Units

No. of

Decay Modes

No. of

Spectra

24.99

0.02

M

2

4

Decay Mode

final-state isomer

Q

σ

Branching

σ

1

0

2127.

5.

93.9

2

0

1258.

5.

6.1

$\langle E_{\text{elect.}} \rangle$

σ

$\langle E_{\text{phot.}} \rangle$

σ

$\langle E_{\text{h.p.}} \rangle$

σ

751.1

85.2

Normalization

σ

No. of transitions

Radiation type

$\langle E_{\beta^-} \rangle$

σ

1.0

4

1

751.1

E_{β^-}

σ

I_{β^-}

σ

544.

5.

0.012

1158.

5.

1.9

1684.

5.

15.

2127.

5.

77.

Normalization

σ

No. of transitions

Radiation type

$\langle E_{\beta^+} \rangle$

σ

1.0

2

2

0.0013

E

σ

$I_{\text{e.c.}}$

σ

I_{β^+}

σ

510.

5.

0.14.

0.0

1258.

5.

6.

0.002

Normalization

σ

No. of Entries

Radiation type

$\langle E \rangle$

σ

1.0

1

9

1.28

K x-ray Int.

σ

L x-ray Int.

σ

ann. rad. Int.

σ

Source flag

4.48

0.72

0.004

2

Normalization

σ

No. of transitions

Radiation type

$\langle E_{\gamma} \rangle$

σ

0.16

7

0

83.88

E_{γ}

σ

I_{γ}

σ

Multipolarity

Source flag

442.91

0.07

100.

1

526.62

0.10

9.6

1

613.1

0.5

0.015

0.004

1

743.5

0.2

0.9

0.1

2

969.4

0.4

2.4

0.3

1

1139.7

0.2

0.060

0.008

1

1434.5

0.5

0.0033

0.0007

1

decay (e.g., β^-) feeds both the ground state and an isomeric state in the daughter nucleus, this is treated as two distinct decay modes. Any radiations (e.g., an isomeric transition) associated with the decay of the daughter-nucleus isomeric state are listed with the daughter-nucleus decay data.

The next card contains the average-energy information in keV/disintegration) in the order: $\langle E \text{ electron} \rangle$; its uncertainty; $\langle E \text{ photon} \rangle$; its uncertainty; $\langle E \text{ heavy particle} \rangle$; and its uncertainty. These average energies contain the following contributions. $\langle E \text{ electron} \rangle$ includes the average energy from all processes involving electrons, such as β^- , β^+ , conversion electrons and Auger electrons. The photon term includes not only γ rays, but also all other electromagnetic radiation (e.g., x rays and annihilation radiation) emitted in the decay process. The third energy includes contributions from α -particle emission, proton and neutrons. (It could also include spontaneous-fission-fragment contributions as well, if desired.)

Next comes the listing of the various radiation spectra. Each listing consists of two types of cards. The first of these contains the following information: a normalization factor (to convert relative intensities to absolute intensities); its uncertainty; the number of individual transitions listed; the radiation type; the average energy (in keV per decay) associated with the radiation type; and its uncertainty. The numbering of the radiation types is similar to that given above for the decay modes with the additional conventions: 8 denotes discrete electrons (e.g., conversion electrons); 9 denotes photons not arising as transitions between nuclear states; and 0 denotes γ radiation. The second of these card types contains the specific spectral information,

with one card for each individual transition. Except for the cases discussed below, the data given here are listed in the order: energy, its uncertainty; intensity and its uncertainty. For e.-c. and β^+ decay (radiation type 2, see Table A-II) two sets of intensity information are given: namely that of the electron-capture component of the transition and that of the β^+ component. In this case the average energy listed is that of the β^+ component only. For β^+ and β^- transitions, provision is also made for including a "multipolarity flag", giving the spectrum shape of the particular transition. The symbol "1U" indicates a first-forbidden unique shape; and the computer program takes this into account in its calculation of $\langle E_\beta \rangle$ for that transition. In the absence of such a notation (which is the case for allowed or first-forbidden non-unique transitions) an allowed shape is assumed.

The data for radiation type 9, x rays and annihilation radiation, are entered somewhat differently. The first ("normalization") card has the same arrangement as for the other radiation types, but only the intensity data are given (since the energies in this case are in principle known). These are entered in the order: K-x-ray intensity, its uncertainty; L-x-ray intensity, its uncertainty; annihilation radiation intensity, its uncertainty; and a "source flag". This latter quantity indicates the decay process with which the radiation is associated, and hence indicates the Z-values of which the x-rays are characteristic. In Table A-I, for example, there are two sets of x-rays, one of which follows β^- decay (and hence is characteristic of Z=37) and one which is associated with isomeric-transition decay (and hence is characteristic of Z=36). Where measured x-ray intensities exist, they are listed here. In most cases, however, such measurements do not exist, and these

intensity data will have to be calculated from the other decay-scheme data, as mentioned in Section 1.1 above. The values listed in Table A-I are in fact theoretical values, calculated from the decay-scheme data by the procedures outlined in (11).

Radiation type 0 (γ radiation), when available, is always the last data set listed. Provision is made for the existence of two cards for each γ -ray transition. The first of these contains the following information: energy, its uncertainty; intensity, its uncertainty; multipolarity and a source flag, indicating with which decay process the γ ray is associated. (Although only pure multipoles are indicated, the alphanumeric information here can describe mixed multipoles and uncertainties in the contributions of these different multipoles.) If internal-conversion-coefficient data are known (or, in some cases, can be inferred), a second card is included. This contains the K-shell ICC (α_K), its uncertainty, α_L , its uncertainty, α_M and its uncertainty. To avoid confusion with the energy cards, the first 10 columns of these ICC cards (corresponding to the location of the energy value) are left blank, as shown in Table A-I.

More complicated decay processes can be treated within the structure of this data file. Delayed-neutron emission (β^- decay followed by neutron emission), for example would be listed as decay mode "15" - 1 for β^- and 5 for neutron. And, a γ ray emitted from an excited state of the nucleus remaining after the neutron emission would carry a source flag "15". Spectra characterized by both a discrete and a continuous component, such as delayed neutron spectra, are listed in the following manner. The discrete components are listed as usual: energy, uncertainty; intensity, and uncertainty. For the continuous component,

the energy values are chosen (and listed) at equally spaced intervals across the distribution, with a sufficient number of points chosen to permit a suitably accurate representation of the distribution. The intensity (and where appropriate, the uncertainty) values corresponding to these energy points are listed, not in the columns where the discrete data are given, but in the next two groups of columns (corresponding to positions of a fifth and a sixth entry). In this fashion, the discrete and the continuous components can be readily recognized.

Before the data described above are entered into ENDF/B, two separate processings are carried out. The first of these, carried out at our laboratory, consists primarily of listing all the data in an "energy-intensity" format and affects only the listings for radiation types 8, 9, and 0. Conversion-electron and Auger-electron spectra, which are not listed as such on our laboratory file, could be calculated theoretically from the data given in this file and entered as a listing of energy and intensity values for the various lines. Where desired, lines from a given subshell can be grouped as a single line, with an appropriate averaged energy for that shell. The x-ray and annihilation data are converted into a listing of energy and intensity values for the individual transitions. The partial ICC data for the various γ -ray transitions are deleted and the data cards for the individual transitions are prepared in the format: energy, uncertainty; intensity, uncertainty; total conversion coefficient, uncertainty; and the source flag.

Following this, these data are transmitted to the NNCSC at BNL for conversion to the standard ENDF/B format (e.g., half-lives in sec., energies in eV, etc.).

APPENDIX B

For the IAEA meeting on "Transactinium Isotope Nuclear Data"

Summary of delayed-neutron work at the Research Councils' Laboratory, Studsvik

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The isotope-separator-on-line facility "OSIRIS" has been used for a survey of delayed-neutron activities including accurate half-life determinations (17 new delayed-neutron precursors were detected in the course of the work). In addition to this, the energy spectra of the neutrons have been measured for 24 precursors. The results are summarized below, and references to the original publications or manuscripts are given.

Precursor	Half-life Measured sec	Energy spectrum of the delayed neutrons
$^{79}\text{(Zn,Ga)}$	$2.63 \pm 0.09^{\text{a)}}$	The energy spectrum has been measured ^{b)}
^{80}Ga	$1.66 \pm 0.02^{\text{a)}}$	The energy spectrum has been measured ^{b)}
^{81}Ga	$1.23 \pm 0.01^{\text{a)}}$	The energy spectrum has been measured ^{b)}
^{82}Ga	$0.60 \pm 0.01^{\text{a)}}$	
^{83}Ga	$0.31 \pm 0.01^{\text{a)}}$	
^{85}As	$2.08 \pm 0.05^{\text{a)}}$	
^{87}Br	$55.5 \pm 0.03^{\text{a)}}$	The energy spectrum contains several prominent peaks, notably at energies 130, 183, 253, and 440 keV. Smaller peaks are found at 315, 400, 534 and 614 keV ^{c)}

Precursor	Half-life Measured, sec	Energy spectrum of the delayed neutrons
⁸⁸ Br	16.7±0.02 ^{a)}	Structure in the spectrum with peaks at 127, 160, 205, 235, 390, 540 and 670 keV ^{d,e)}
⁸⁹ Br	4.37±0.03 ^{a)}	Peaks (although not very pronounced) found at energies 270, 400, 610, 680, 740, 800 and 900 keV ^{f)}
⁹⁰ Br	1.96±0.05 ^{a)}	Energy spectrum without discrete structure ^{d)}
⁹¹ Br	0.541±0.005	The energy spectrum has been measured ^{f)}
⁹² Br	0.365±0.007 ^{a)}	
⁹² Rb	4.34±0.06 ^{a)}	
⁹³ Kr	1.33±0.05 ^{a)}	
⁹³ Rb	5.85±0.03 ^{a)}	The energy spectrum shows some structure with peaks at 155, 200, 235, 275, 330, 365 and 460 keV ^{f)}
⁹⁴ Rb	2.69±0.02 ^{a)}	The energy spectrum has been measured ^{g)}
⁹⁵ Rb	0.400±0.004 ^{a)}	The energy spectrum has been measured ^{g)}
⁹⁶ Rb	0.203±0.003 ^{a)}	
⁹⁷ Rb	0.172±0.003 ^{a)}	
⁹⁸ Rb	0.141±0.010 ^{a)}	
¹²³ Ag	0.39±0.03 ^{h)}	
¹²⁷ In	3.76±0.03 ^{h)}	
¹²⁸ (Cd,In)	0.94±0.05 ^{h)}	
¹²⁸ In	11±1 ^{h)}	
¹²⁹ In	0.99±0.02 ^{h)}	The combined spectrum for the two isomers at mass 129 has been measured ^{b)}
¹²⁹ In	2.5±0.2 ^{h)}	

Precursor	Half-life Measured sec	Energy spectrum of the delayed neutrons
^{130}In	$0.58 \pm 0.01^{\text{h)}}$	The energy spectrum has been measured: ^{b)}
^{131}In	$0.29 \pm 0.01^{\text{h)}}$	
^{132}In	$0.3 \pm 0.1^{\text{h)}}$	
^{133}Sn	$1.47 \pm 0.07^{\text{h)}}$	
^{134}Sn	$1.04 \pm 0.02^{\text{h)}}$	
		The energy spectrum contains one very prominent peak at 500 keV and, in addition, some smaller peaks at 320, 435, 760, 860 and 1020 keV ^{c)}
^{134}Sb	$10.3 \pm 0.4^{\text{h)}}$	The energy spectrum contains three large peaks at 1040, 1205, and 1450 keV ^{c)}
^{135}Sb	$1.82 \pm 0.04^{\text{h)}}$	
^{136}Sb	$0.82 \pm 0.02^{\text{h)}}$	The spectrum contains a single dominant peak at 429 keV and, in addition, a series of smaller peaks at 251, 313, 466, 525, 593, 692 and 766 keV ^{c)}
^{136}Te	$17.5 \pm 0.4^{\text{h)}}$	
^{137}I	$24.25 \pm 0.12^{\text{h)}}$	A spectrum with very pronounced structure. Large peaks are found at 272, 380, 487, 583, 756, 863, 965 and 1140 keV and smaller ones at 166, 325, 425, 515, 695 and 1063 keV ^{c)}
^{138}I	$6.46 \pm 0.15^{\text{h)}}$	Some structure, in particular at 370 keV, found in the spectrum ^{d,e)}
^{139}I	$2.30 \pm 0.05^{\text{h)}}$	The spectrum contains some evidence for structure with peaks at 130, 190, 290, 485 and 565 keV ^{f)}

Precursor	Half-life Measured sec	Energy spectrum of the delayed neutrons
^{140}I	$0.59 \pm 0.01^{\text{h)}}$	Indication of peaks at 450, 550 and 800 keV ^{d)}
^{141}I	$0.48 \pm 0.03^{\text{h)}}$	In the combined energy spectrum from ^{141}I and ^{141}Cs peaks are found at 160, 300, 395, 450 and 550 keV with indications of further peaks at 225, 340, 610 and 685 keV ^{f)}
^{141}Cs	$22.2 \pm 0.4^{\text{h)}}$	
^{142}Cs	$1.69 \pm 0.09^{\text{h)}}$	Peaks are found at 370 and 750 keV ^{d)}
^{143}Cs	$1.78 \pm 0.01^{\text{h)}}$	Peaks are seen at 125, 180, 225, 310 and 350 keV ^{f)}
^{144}Cs	$1.00 \pm 0.02^{\text{h)}}$	Little structure but some suggestion of peaks at 130 and 180 keV ^{d)}
^{145}Cs	$0.58 \pm 0.01^{\text{h)}}$	
^{146}Cs	$0.343 \pm 0.007^{\text{h)}}$	

The techniques used in the half-life measurements are described in ref. ^{a)}. The energy measurements were carried out using a ^3He -spectrometer, as described in ref. ⁱ⁾.

As a continuation of the studies on delayed neutrons a series of measurements of neutron branching ratios is being planned. The equipment is completed, and the experiments are ready to start.

References

- a. G. Rudstam and E. Lund, Delayed-Neutron Activities Produced in Fission, Mass Range 79-98, to be published in Phys. Rev.
- b. G. Rudstam and S. Shalev, work in progress.

- c. S. Shalev and G. Rudstam, Nucl. Phys. A230 (1974) 153.
- d. S. Shalev and G. Rudstam, manuscript under preparation for publication.
- e. S. Shalev and G. Rudstam, Proceedings of a Panel on Fission Product Nuclear Data, Bologna, 26-30 November 1973, Vol. III, p. 367.
- f. G. Rudstam and S. Shalev, Nucl. Phys. A235 (1974) 397.
- g. E. Lund and G. Rudstam, work in progress.
- h. E. Lund and G. Rudstam, Half-Lives of Delayed-Neutron Activities Produced in Fission. Mass Range 122-146, submitted to Nucl. Phys.
- i. G. Rudstam, S. Shalev and O. C. Jonsson, Nucl. Instr. and Methods 120 (1974) 333.

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