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COMMISSION OF THE EUROPEAN COMMUNITIES

THE HALF-LIVE OF SOME LONG-LIVED ACTINIDES : A COMPILATION

by

R. VANINBROUKX

1974

Joint Nuclear Research Centre
Geel Establishment - Belgium
Central Bureau for Nuclear Measurements - CBNM

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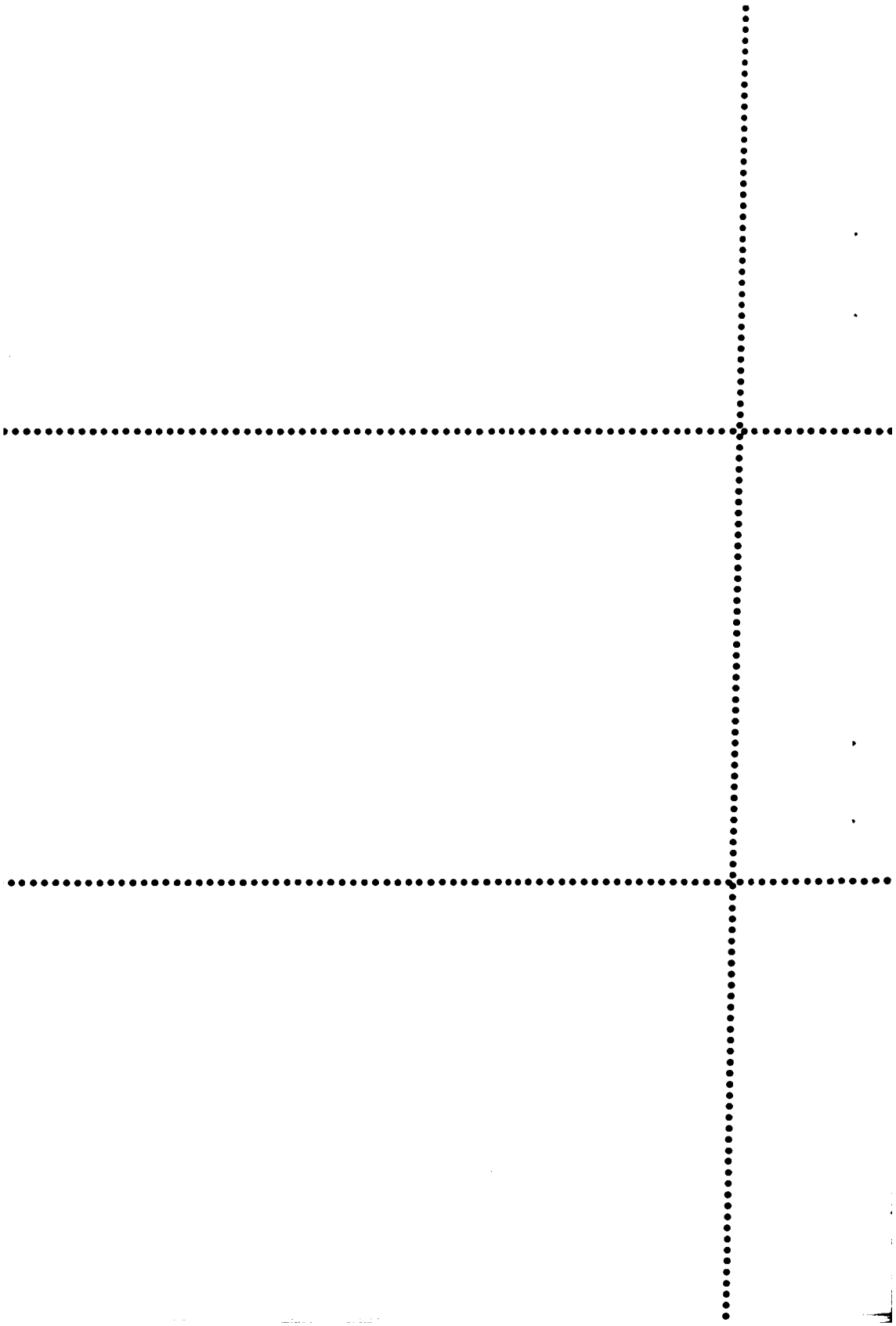

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ABSTRACT

A compilation of the reported half-lives of some of the most commonly used long-lived actinides is given. « Best » values and limits of errors are proposed. The compilation shows where further accurate measurements are necessary in order to resolve existing discrepancies.

CONTENTS

1. Introduction

In addition to its general importance an accurate knowledge of the half-lives of the actinides is of particular interest in the quantitative determination, by a radioactivity measurement, of the number of atoms present in a sample (e.g. samples for cross section measurements). Combined with a determination (e.g. by mass spectrometry) or a knowledge of the isotopic composition, the measurement of the radioactivity is the most simple and probably also the most accurate mean for the nondestructive determination of the amount of material in a sample, provided that the decay constants of all the present nuclides are accurately known. Unfortunately, as already stated by Hanna et al. in 1969 [1], several new half-life measurements reported during the last years (e.g. for ^{233}U, ^{234}U, ^{241}Pu, ^{241}Am) were in serious disagreement with the previously accepted values. The same authors reported that at that time the half-life of ^{239}Pu seemed to have escaped so far this malady and they assigned an error of $\pm$ 0.2% to the adopted mean value. Two years later a carefully performed new measurement [2] yielded a value quoted with an accuracy of $\pm$ 0.2% but differing 1.3% from the previously adopted mean. A further typical example is that of ^{241}Am. In 1967, as a result of two previously reported values, (458.1 $\pm$ 0.5)y [3] and (457.7 $\pm$ 1.8)y [4] a mean of 458y was adopted [5]. In 1967 and 1968 three new values were reported: (432.7 $\pm$ 0.6)y [6], (436.6 $\pm$ 3.0)y [7] and (433 $\pm$ 7)y [8] and in 1971 a value of (433 $\pm$ 2)y was proposed [9]. One year later Jove and Robert published a new value of (426.3 $\pm$ 2.1)y [10]. These examples show that it is very difficult to evaluate reported half-lives. In this report we do not attempt to give an evaluation but rather give a compilation of published data, along with what we consider to be "best" values and limits of errors. One of the

aims of this compilation is to show where high accuracy measurements still seem to be recommended in order to resolve some existing discrepancies, including the apparent systematic differences between values obtained with α-counting, calorimetric and mass spectrometric techniques.

2. Compilation of reported half-lives

Half-life values of some of the most commonly used long-lived actinides (generally only those reported since about 1950) are compiled. The literature data are summarized in the tables A1 to A14 of the appendix. Where available, the material used for the determinations is specified (% of the isotope under investigation relative to the element). The percentages, usually determined by mass spectrometric analysis, are given as quoted by the authors (atomic % or weight %). Furthermore a very brief description of the methods used is given. Unfortunately, often the methods are not well described and important data are missing: e.g. stoichiometry, chemical purity, (both very important when the number of atoms are determined by gravimetric methods), investigation of possible radioactive impurities and their contribution to the counting rates, etc.

The half-life values are given with the errors quoted by the authors. Generally it is difficult, and even impossible, to compare these errors, as often they are not clearly defined. In some cases it is the standard error of the mean of several individual results. In other cases it may be the standard deviation, or the pure statistical error, or a combination of statistical and systematic errors, even summed up in different ways by different authors. It may be 1σ, 2σ, or 3σ-errors, etc.

2.1 ^{232}U (Table A1)

The two reported values, quoted with an error of $\pm$ 1.3%, differ by 2.6%. Since the most recent value is based on a determination of the specific activity of highly enriched material by two independent methods a higher confidence can be attributed to it. Therefore, one can adopt for the half-life of ^{232}U a value of

$$(72 \pm 2)y$$

The rather high uncertainty is of less importance for the definition of U-samples by activity measurements. In most U-samples ^{232}U is only present as a contamination. Due to its high specific activity the contribution of ^{232}U and daughters to the counting rates can be determined accurately and directly, without a need for an accurate knowledge of the decay constant, by α- or γ-spectrometric analysis.

2.2 ^{233}U (Table A2)

Accurate knowledge of the ^{233}U half-life is of importance for the determination of fission cross sections. Some earlier experiments will have to be revised when a precise reliable value becomes available [1]. ^{233}U is sometimes useful to spike uranium samples of low specific activity for the purposes of quantitative analysis [25]. The ^{233}U-spike material can be standardized accurately by α-counting, but an accurate value for the half-life is essential. Unfortunately, the spread of the measured values is many times larger than that expected from the claimed accuracies. Hanna et al. [1] estimated from the published data (1952-1969) a best value of $(1.593 \pm 0.024)10^5$y.

The reported values can be subdivided into 3 groups.

The first 6 results (1952-1967), all based on α-counting techniques, yield a mean of $(1.617 \pm 0.008)10^5$y. Then (1967-1968) two results yielding a mean of $(1.554 \pm 0.003)10^5$y have been published. One of the two values was obtained by α-counting, the other one by calorimetric techniques. Therefore, the more than 4% lower value can not be explained only by the apparently systematic discrepancy between half-life values obtained by α-counting and by calorimetry [2, 19]. For the third group (1969-1973) three values, all near to $1.59\ 10^5$y, are available [22-24]. The excellent agreement between these results and especially between the ANL and CBNM values, based on carefully and accurately performed measurements using several independent methods, solves the previously existing discrepancies. From these measurements following "best" value can be adopted:

$$(1.592 \pm 0.003)10^5\text{y}$$

2.3 ^{234}U (Table A3)

The half-life of ^{234}U is of great importance since the decay of this isotope is dominant in most uranium samples. Accurate knowledge of the ^{234}U-decay constant will allow, from activity measurements and knowledge of the isotopic composition, an accurate calculation of the amount of U, especially ^{235}U, in most of the targets used for cross section measurements. Here also, due to the large spread in reported values, the situation till to 1971 was unsatisfactory. The values reported between 1952 and 1965 yield a mean of $(2.50 \pm 0.03)10^5$y. The mean of three new values (1969-1971) is $(2.443 \pm 0.004)10^5$y. Since the CBNM [30] value is based on a high degree of technique variation (several independent methods, several materials), and is confirmed, within the limits of claimed errors, by the ANL- [29] and AECL- [31] values one can adopt as "best"value, as already recommended by the 1972 - IAEA Panel on Neutron Standard Reference Data [87]

and in agreement with the value selected by De Volpi [20]:

$$(2.446 \pm 0.007)10^5 y$$

The 0.3% error (3σ-basis) seems, at present, to be satisfactory.

2.4 ^{235}U (Table A4)

For the determination, by activity measurements, of the amount of ^{235}U in highly enriched U-samples, with very low ^{234}U-concentrations ($\leq 0.1\%$) the half-life of ^{235}U is needed. The mean of the values reported before 1971 is $(7.03 \pm 0.10)10^8 y$. The stated uncertainty is the standard deviation; it was commonly thought that the accuracy was not better than 2-4% [38, 39]. Such a situation is certainly unsatisfactory for accurate cross section determinations.

Fortunately, Jaffey et al. [38] applied improved techniques with the goal of reducing the error to not more than $\pm 0.2\%$. The result of their carefully performed measurements was $(7.038 \pm 0.005)10^8 y$, thus agreeing within 0.1% with the mean mentioned above. The quoted error (less than 0.1%) however is only the statistical standard error of the mean based on the scatter of the observed data. Employing the same error philosophy as for the CBNM-measurements on ^{234}U [30] by adding to the 3σ-statistical error an upper limit of $0.005\ 10^8 y$ for possible systematic effects, as estimated by the authors, one gets an error of $\pm 0.3\%$. Since this result is obtained from the most accurate measurements one should (at least as long as no further accurate measurements are reported) adopt as "best" value

$$(7.038 \pm 0.020)10^8 y$$

In order to be sure that possible systematic effects are not

underestimated a second high accuracy determination, preferably with several independent methods, is desirable.

2.5 ^{236}U (Table A5)

The half-life of ^{236}U is of less importance for the definition by activity measurements of commonly used U-samples, where only small concentrations of ^{236}U are present.
The reported values are spread over about 5%. According to Flynn et al. [41] likely sources of systematic errors could explain the deviation of the first result in Table A5 but no explanation could be given for the discrepancy between the two other values. Therefore it is not very meaningful to propose a best value as long as no new accurate measurements are performed. As long as results of such measurements are not available one can adopt the most accurate result, but with an appreciably higher uncertainty:

$$(2.34 \pm 0.02)10^{7}\,y$$

2.6 ^{238}U (Table A6)

Jaffey et al. [38] performed careful measurements on highly depleted material. The ^{238}U-activity of the two samples used was respectively 90.7% and 99.7% of the total α-activity. Since the obtained value for the half-life is confirmed by another precise measurement [45] one can adopt the ANL-value as "best" value, but with an increased error, as obtained for ^{235}U (3σ statistical+ systematic error):

$$(4.468 \pm 0.010)10^{9}\,y$$

2.7 ^{238}Pu (Table A7)

Little information is available. Because of the uncertainties on the Cm-isotopic composition and the ^{242}Cm half-life for the

method based on the growth of ^{238}Pu [46] one should attribute a higher confidence to the results obtained by the calorimetric method, however with a considerably higher uncertainty as quoted, mainly because of the generally existing discrepancy between results obtained by calorimetric methods and counting techniques. Several figures between 87.4y and 87.8y, all attributed to calorimetric determinations performed at Mound Laboratory, are reported without details [47-50]. It seems likely that the more recent values are revised figures of the previous ones. As long as no new accurate measurements are performed one can adopt for the half-life of ^{238}Pu:

$$(87.8 \pm 0.8)y$$

2.8 ^{239}Pu (Table A8)

The half-life of ^{239}Pu is very important for fission cross section determinations. Before the 1971-value of Oetting [2] was published the situation seemed to be very satisfactory. The mean of 8 values [19, 52-58] (including one calorimetric determination [19] was $(2.4365 \pm 0.0041)10^4$y. The mean of 4 values [19, 56-58] quoted by the authors with an accuracy of $\pm$ 0.2% or better was also $(2.4365 \pm 0.0044)10^4$y. Only one calorimetric value [51], with a claimed error of 1%, deviated 1.1% from the mean. The situation was completely perturbed by the recent calorimetric determination of Oetting on a very pure material, yielding a half-life value (claimed to be 0.2% accurate) which is 1.3% lower than the mentioned mean. High accuracy measurements are urgently needed to resolve this discrepancy. Measurements will be started soon at CBNM. Until new data are available one can adopt as half-life:

$$(2.430 \pm 0.025)10^4y$$

2.9 ^{240}Pu (Table A9)

The reported values, with a mean of 6.52 10^3y, are spread over 8%, although most values are claimed to be better than 1% accurate.
The mean of 4 values, [19, 54, 57, 61] quoted with an error less than 1%, is (6.62 ± 0.10)10^3y. Combining both means with the precise calorimetric value of Oetting one can adopt:

$$(6.55 \pm 0.07)10^3 y$$

Accurate measurements should be performed in order to reduce the uncertainty.

2.10 ^{241}Pu (Table A10)

Here we have a very particular situation. Four measurements [64-67], using the ^{241}Am-growth method, yield a mean of (14.0 ± 0.15)y. Three mass spectrometric measurements [69-73] yield (14.9 ± 0.25), the mean of the two most precise measurements [70-73] being (15.0 ± 0.1)y. One measurement [69] based on the changes of the reactivity yields a value between both means.
The discrepancies of up to 7% between the different methods, especially the growth- and mass spectrometric method, should be resolved by careful measurements using all available independent methods. As long as results of such measurements are not available one should adopt:

$$(14.5 \pm 0.5)y$$

The 0.34y isomeric state reported by Stepan and Nisle [68, 74] was not observed by other investigators [70, 75].

2.11 ^{242}Pu (Table A11)

The spread of the reported values, with a mean of $3.77\ 10^5$y is 6%. The mean of the two values determined relative to the half-lives of ^{240}Pu and ^{239}Pu is $(3.87 \pm 0.01)10^5$y. Since the error on the reference half-lives is not considerably higher than 1% one can adopt for the ^{242}Pu-half-life:

$$(3.87 \pm 0.05)10^5\text{y}$$

2.12 ^{244}Pu (Table A12)

The mean of the two values measured on enriched material, relative to ^{239}Pu, ^{240}Pu, and ^{242}Pu, is $(8.23 \pm 0.05)10^7$y. On the basis of an uncertainty of about 1% on the reference half-lives one can adopt

$$(8.2 \pm 0.1)10^7\text{y}$$

2.13 ^{241}Am (Table A13)

Comments have been given in the introduction. One can adopt the mean of the four recent determinations:

$$(432 \pm 4)\text{y}$$

2.14 ^{252}Cf (Table A14)

Since 1965 four accurate values (quoted errors of 0.2 to 0.4%) have been published for the half-life of ^{252}Cf, a nuclide often used as a standard for neutron sources. One can adopt the mean of these values:

$$(2.64 \pm 0.02)\text{y}$$

3. Conclusions

From the available data "best" values are proposed, together with estimated uncertainties. These figures are summarized in table 1. If accuracies of 0.2-0.3% would be pursued a lot of new accurate determinations should be performed. The most urgent measurements are the Pu-isotopes (for which the half-lives are not better known than to about 1%), especially ^{239}Pu and ^{241}Pu, and ^{252}Cf. Less urgent, but still interesting, are ^{232}U, ^{235}U, ^{236}U, and ^{241}Am. Special efforts should be made in order to resolve the discrepancies between the values obtained with α-counting, calorimetric and mass spectrometric techniques.

Table 1: Proposed half-life values

Nuclide	Half-life
^{232}U	$(72 \pm 2)y$
^{233}U	$(1.592 \pm 0.003)10^5 y$
^{234}U	$(2.446 \pm 0.007)10^5 y$
^{235}U	$(7.038 \pm 0.020)10^8 y$
^{236}U	$(2.34 \pm 0.02)10^7 y$
^{238}U	$(4.468 \pm 0.010)10^9 y$
^{238}Pu	$(87.8 \pm 0.8)y$
^{239}Pu	$(2.430 \pm 0.025)10^4 y$
^{240}Pu	$(6.55 \pm 0.07)10^3 y$
^{241}Pu	$(14.5 \pm 0.5)y$
^{242}Pu	$(3.87 \pm 0.05)10^5 y$
^{244}Pu	$(8.2 \pm 0.1)10^7 y$
^{241}Am	$(432 \pm 4)y$
^{252}Cf	$(2.64 \pm 0.02)y$

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5. Appendix

Tables A1 to A14 summarize the most interesting literature data.

Material : % isotope investigated means the abundance, in atomic % or weight % (as given by the authors), of the isotope for which the half-life is determined.

Method : U-determination by isotopic dilution means always mass spectrometric isotopic dilution analysis.

Table A1. Half-life of ^{232}U

Author (Year)	Material % isotope investig.	Method	Half-life in units of one y	Remarks
Sellers at al. (1954) [11]	0.14	$2\pi\alpha$-counting; ^{232}U determination by isotopic dilution mass spectrometric analysis	73.6 ± 1.0	
Chilton et al. (1964) [12]	99.2	calorimetry and $2\pi\alpha$-counting; U-determ. by coulometry	71.7 ± 0.9	

Table A2. Half-life of ^{233}U

Author (Year)	Material % isotope investig.	Method	Half-life in units of 10^5 y	Remarks
Hyde (1952) [13]	96.4	$2\pi\alpha$-counting; gravimetric U-determ.	1.62 ± 0.01	
Sellers et al. (1955) [14]		α-activity determin. with counters of known geometry; gravimetric U-determin.	1.615 ± 0.004	
Bigham et al. (1959) [15]	99.7	$2\pi\alpha$-counting; U-determin. by isotopic dilution; radiochemical purity analysis by α-spectrometry	1.603 ± 0.008	recalculated by Hanna [1] from the ratio $\lambda_{nat\ U}/\lambda_{^{233}U}$
Dokuchaev and Osipov (1959) [16]	~ 95	low geom. α-counting; gravimetric U-determ.; radiochem. purity analysis by α-spectrometry	1.626 ± 0.008	
Popplewell (1961) [17]	99.8	low geom. α-counting; gravimetric U-determ.	1.615 ± 0.009	
Ihle et al. (1967) [18]	87.8	liquid scintill. α-counting; gravim. U-determ.; radiochem. purity analysis by α spectrometry	1.621 ± 0.003	
Oetting (1968) [19]	96.9	calorimetry; gravimetric U determ.	1.554 ± 0.003	original value of 1.540 corrected for ^{232}U daughters as quoted by De Volpi [20]
Keith (1968) [21]	> 99.9	low geometry α-counting; U-determ. by isotopic dilution	1.553 ± 0.010	

continued on next page

Table A2-bis.

Author (Year)	Material % isotope investig.	Method	Half-life in units of 10^5 y	Remarks
Durham (1969) [22]		low geom. α-counting	1.583 ± 0.007	
Jaffey et al. (1974) [23]	99.5	intermed. geom. α-counting; U-determ. by titration; radiochem. purity analysis by α-spectrometry	1.5911 ± 0.0015	the quoted error is only the standard error
Vaninbroukx et al. (1974) [24]	> 99.9	4πα-, liq. scint. and low geom.-α counting; U-determ. by coulometry and isotopic dilution; radiochem. purity analysis by α- and γ-spectrometry	1.5925 ± 0.0040	

Table A3. Half-life of ^{234}U

Author (Year)	Material % isotope investig.	Method	Half-life in units of 10^5 y	Remarks
Kienberger (1952) (26)	94.7	2πα-counting; gravimetric U-determ.; chemical purity determ. by spectrographic analysis	2.520 ± 0.008	according to De Volpi (20) error should be 0.033 10^5y
Fleming et al. (1952) (27)	96.0	intermed. geom. α-counting; gravimetric U-determ.; chemical purity by spectrographic analysis	2.475 ± 0.016	
Bigham et al. (1959) (15)	0.6	2πα-counting; U-determ. by isotopic dilution; radiochem. analysis by α spectrometry	2.519 ± 0.025	calculated by Hanna (1) from data on "enriched U"
White et al. (1965) (28)	1.2	low geom. α-counting; U-determ. by gravimetry, spectrophotometry, and coulometry; radiochemical analysis by α-spectrometry	2.47 ± 0.03	
Meadows (1969) (29)	0.7-1.1	2πα- and low geom. α-counting; U-determ. by titration	2.439 ± 0.014	
De Bièvre et al. (1971) (30)	0.2-99.9	4πα-, liq. scint., and low geom. α-counting; U-determ. by gravimetry, coulometry and isotopic dilution; radiochemical analysis by α-spectrometry	2.446 ± 0.007	
Lounsbury and Durham (1971) (31)	1.1	low geom. α-counting; U-determ. by isotopic dilution	2.444 ± 0.012	

Table A4. Half-life of ^{235}U

Author (Year)	Material % isotope investig.	Method $R=\frac{\text{activity } ^{235}U}{\text{activity } ^{238}U}$ $R'=\frac{\text{activity } ^{235}U}{\text{activity } ^{234}U}$	Half-life in units of 10^8 y	Remarks
Nier (1939) [32]	nat U	measurement of R from Pb/U-ratios	7.04 ± 0.15	recalculated value, cited by Jaffey [36]
Knight (1950) [33]	"enriched ^{235}U"	measurement of the specific activity	7.10 ± 0.16	"
Sayag (1951) [34]	nat U	measurement of R and R' by ionization chamber energy analysis	6.94 ± 0.25	"
Fleming et al. (1952) [27]	99.9	intermed. geom. α-counting; gravimetric U-determ.; chem. purity by spectrogr. analysis	7.13 ± 0.16	
Würger et al. (1957) [35]	nat U	measurement of R and R' by ion chamber and α-γ coincidence counting	6.84 ± 0.15	recalculation by Jaffey [36] yields 6.92 10^8y
White et al. (1965) [28]	99.3	low geom. α-counting; U-determ. by gravimetry, spectrophotometry, and coulometry; radiochem. analysis by α-spectrometry	7.13 ± 0.09	
Deruytter et al. (1965) [36]	nat U	measurement of R and R' using solid state detectors	6.92 ± 0.09	recalculation by Jaffey [38] yields 6.97 10^8y

continued on next page

Table A4-bis.

Author (Year)	Material % isotope investig.	Method $R=\frac{\text{activity } ^{235}U}{\text{activity } ^{238}U}$ $R'=\frac{\text{activity } ^{235}U}{\text{activity } ^{234}U}$	Half-life in units of 10^8 y	Remarks
Banks and Silver (1966) [37]	nat U	measurement of R by mass spectrometric determination of $^{207}Pb/^{206}Pb$	$7.09 \pm ?$	recalculation by Jaffey [38] yields $7.02\ 10^8$ y
Jaffey et al. (1971) [38]	> 99.9	intermed. geom. α-counting; U-determ. by titration; radiochem. purity by α-spectrometry	7.038 ± 0.005	quoted error is only standard error

Table A5. Half-life of ^{236}U

Author (Year)	Material % isotope investig.	Method	Half-life in units of 10^7 y	Remarks
Jaffey et al. (1951) [40]	22.1-37.6	activity determ. by ion chamber energy analysis; U-determination by neutron induced fission counting	2.46 ± 0.06	
Fleming et al. (1952) [27]	97.0	intermed. geom. α counting; gravimetric U-determination; chemical purity by spectrographic analysis	2.391 ± 0.018	
Flynn et al. (1972) [41]	99.6	intermed. geom. α counting; U-determin. by titration; radiochem. purity by α-spectrometry	2.3415 ± 0.0014	

Table A6. Half-life of ^{238}U

Author (Year)	Material % isotope investig.	Method	Half-life in units of 10^9 y	Remarks
Kienberger (1949) [42]	depleted U	$2\pi\alpha$-counting; gravimetric U-determ.	4.49 ± 0.01	
Kovarik and Adams (1955) [43]	nat U	α-activity determin. by ion chamber; no specification about U determ.	4.507 ± 0.009	
Leachman and Schmitt (1957) [44]	depleted U	$2\pi\alpha$-counting; U-determin. by gravimetry and colometric analysis	4.56 ± 0.03	
Steyn and Strelow (1960) [45]	nat U	liq. scint. α counting (separation of β-emitting daughters before counting and correction for growth); gravimetric U-determin.		
Jaffey et al. (1971) [38]	> 99.9	intermed. geom. α-counting; U-determ. by titration; radiochem. purity by α-spectrom.	4.4683 ± 0.0024	quoted error is only standard error

Table A7. Half-life of ^{238}Pu

Author (Year)	Material % isotope investig.	Method	Half-life in units of one y	Remarks
Hoffman et al. (1957)[46]		growth of ^{238}Pu from ^{242}Cm by α-counting	86.4 ± 0.3	based on $T_{1/2}$ - ^{242}Cm 162.7d
Eichelberger et al. (1965) [47]		calorimetric determination	87.60 ± 0.06	
Jordan (1967) [48]		calorimetric determination	87.40 ± 0.04	should be corrected to (87.80±0.05) [49]
Benson (1969) [50]		calorimetric determination	87.75 ± 0.05	

Table A8. Half-life of ^{239}Pu

Author (Year)	Material % isotope investig.	Method	Half-life in units of 10^4 y	Remarks
Stout and Jones (1947)[51]		calorimetric activity determ.; gravim. Pu-determ.	2.411 ± 0.024	
Cunningham and Werner (1949)[52]		2πα-counting; gravimetric Pu-determ.	2.430 ± 0.037	
Westrum et al. (1949)[53]		2πα-and low geom. α-counting; gravim. Pu-determ; chemical purity by spectrographic analysis	2.440 ± 0.070	
Wallmann (1951)[54]	> 99.9	low geom. α-counting; gravim. Pu-determ.; chem. purity by spectr. anal.; radioch. purity by α-spectrometry	2.436 ± 0.010	
Farwell et al. (1954)[55]	99.9	2πα-counting; Pu-determ. by gravimetry and titration	2.440 ± 0.048	
Markin (1959)[56]	99.9	low geom. α-counting; gravim. Pu-determ.	2.441 ± 0.003	
Dokuchaev (1959)[57]	99.1	low geom. α-counting; gravim. Pu-determ.; radiochem. purity by α-spectrometry	2.439 ± 0.003	
Ihle et al. (1966)[58]	94.4	liq. scint. α-counting; gravim. Pu determ.; radiochem. purity by α-spectrometry	2.435 ± 0.006	

continued on next page

Table A8-bis

Author (Year)	Material % isotope investig.	Method	Half-life in units of 10^4 y	Remarks
Oetting (1968) (19)	94	calorimetric activity determ.; gravim Pu determ.	2.431 ± 0.005	corrected figure for the 1965-value of $(2.418 \pm 0.003) 10^4$ y (59)
Oetting (1971) (2)	> 99.9	calorimetric activity determ.; gravim. Pu determ. (electro refined Pu metal); chem. purity by spectrograph. analysis; radiochem. purity by α-spectrometry	2.4065 ± 0.0050	

Table A9. Half-life of ^{240}Pu

Author (Year)	Material % isotope investig.	Method	Half-life in units of 10^3 y	Remarks
Westrum (1951) [60]		2πα-counting; gravim. Pu-determ.; chemical purity by spectrographic analysis	6.24 ± 0.12	
Inghram et al. (1951) [61]		mass spectrometric determ. of $^{236}U/^{235}U$ (growing from ^{240}Pu and ^{239}Pu respectively)	6.58 ± 0.04	based on $T_{1/2}$-^{239}Pu = $2.44 \cdot 10^4$ y
Wallmann (1951) [54]	34.4	low geom. α-counting; gravim. Pu determ.; spectrographic purity analysis; radiochem. purity by α-spectrometry	6.76 ± 0.03	
Farwell et al. (1954) [55]	1.6	2πα-counting; Pu determ. by gravim. and titration	6.30 ± 0.60	
Butler et al. (1956) [62]	26.2	2πα-counting (specific activity) α-energy analysis	6.60 ± 0.10	
Dokuchaev (1959) [57]	7.6	low geom. α-counting; gravim. Pu-determ.; radiochemical analysis by α-spectrom.	6.62 ± 0.05	
Oetting (1968) [19]	95.7	calorimetric activity determ.; gravim. Pu determ.	6.524 ± 0.010	recalculated to $6.537 \cdot 10^3$ y by Schmorak [63] with $E(\alpha_o)$= 5.1677 MeV

Table A10. Half-life of ^{241}Pu

Author (Year)	Material % isotope investig.	Method	Half-life in units of one y	Remarks
Mac Kenzie et al.(1953)[64]		growth of ^{241}Am by α-spectrom.	14.1 ± 0.3	corrected by Ellis [9] on the basis $T_{1/2}$-^{241}Am = 433y
Rose and Milsted (1956)[65]	14.5	" " γ-spectrom.	13.8 ± 0.3	
Brown et al. (1960) [66]	76.5	" " α-spectrom.	14.1 ± 0.3	
Smith (1961) [67]	96.2	" " "	13.9 ± 0.3	
Nisle and Stepan (1970) (68)	94.0	changes in reactivity	14.63 ± 0.27	
Shields (1970) [69]		changes in isotopic ratios by mass spectrometry	14.6 ± 0.4	cited by Ellis [9]
Cabell and Wilkins (1971) (70-71)	31.9	" " "	15.10 ± 0.14	1968-value was 14.98y [72]
Zeigler and Ferris (1973) (73)	3.0	" " "	14.89 ± 0.11	pooled value of observations in 6 laboratories

Table A11. Half-life of ^{242}Pu

Author (Year)	Material % isotope investig.	Method	Half-life in units of 10^5 y	Remarks
Butler et al. (1956) [76]		^{242}Pu activity relative to ^{238}Pu by α-spectrometry	3.65 ± 0.05	cited by Ellis [9] basis $T_{1/2}$ - ^{238}Pu = 87.75y
Butler et al. (1956) [62]	98.9	specific activity by ion chamber energy analysis	3.79 ± 0.05	
Mech et al. (1956) [77]	96.3 - 98.7	^{242}Pu activity relative to ^{240}Pu by α-spectrometry	3.88 ± 0.10	basis $T_{1/2}$ - ^{240}Pu = $6.537 \cdot 10^3$ y
Bemis et al. (1969) [78]	99.9	^{242}Pu activity relative to ^{239}Pu by α-spectrometry	3.869 ± 0.016	basis $T_{1/2}$ - ^{239}Pu = $2.440 \cdot 10^4$ y
Durham and Malson (1970) [79]	90	^{242}Pu activity relative to ^{238}Pu by α-spectrometry	3.66 ± 0.07	basis $T_{1/2}$ - ^{238}Pu = 87.4y

Table A12. Half-life of ^{244}Pu

Author (Year)	Material % isotope investig.	Method	Half-life in units of 10^7 y	Remarks
Diamond and Barnes (1956) [80]	0.05	separation of daughters; γ-measurement	7.6 ± 2.0	
Butler et al. (1956) [62]	0.08	separation of daughters; β-measurement	7.5 ± 2.0	
Fields et al. (1966) [81]	54 - 68	^{244}Pu activity relative to ^{240}Pu and ^{242}Pu by α-spectrometry	8.18 ± 0.26	basis $T_{1/2}$-^{240}Pu = $6.58 \cdot 10^3$ y and $T_{1/2}$ ^{242}Pu = $3.79 \cdot 10^5$ y
Bemis et al. (1969) [78]	74.2-76.9	^{244}Pu activity relative to ^{239}Pu by α-spectrometry	8.28 ± 0.10	basis $T_{1/2}$-^{239}Pu = $2.440 \cdot 10^4$ y

Table A13. Half-life of ^{241}Am

Author (Year)	Material % isotope investig.	Method	Half-life in units of one y	Remarks
Hall and Markin (1957) (3)		low geom. α counting; gravim. Am determ.; spectrographic purity analysis; radiochem. purity by α-spectrometry	458.1 ± 0.5	
Wallmann et al. (1958) (4)		idem	457.7 ± 1.8	
Oetting and Gun (1967) (6)		calorimetric activity determ.; gravim. Am determ.; chem. purity by spectrography and spark source mass spectrom.; radiochem. purity by α-spectrometry	432.7 ± 0.7	
Stone and Hulet (1968) (7)		low geom. α-counting; gravim. Am determ.; spectrogr. purity analysis; radiochem. purity by α-spectrom.	436.6 ± 3.0	same material as used by Oetting (6)
Brown and Probst (1968) (8)		low geom. α- and 2πα-counting coulometric Am determ.	433 ± 7	
Jove and Robert (1972) (10)		calorimetric activity determ.; gravim. Am determ.; spectrographic analysis; α-spectrometry	426.3 ± 2.1	

Table A14. Half-life of ^{252}Cf

Author (Year)	Material % isotope investig.	Method	Half-life in units of y	Remarks
Eastwood et al. (1957)[82]	50	measurement of the decay of spontaneous fission (ion chamber) and α counting rate ($2\pi\alpha$)	2.55 ± 0.15	
Metta et al. (1965) [83]	79.2	decay of spontaneous fission (2π-counting)	2.646 ± 0.004	
De Volpi and Porges (1969) [84]		decay of neutron emission rate with a manganese bath facility	2.621 ± 0.006	
Mijnheer and Van den Hauten (1973)[85]	50	idem	2.659 ± 0.010	
Spiegel (1974)	79.3	idem	2.638 ± 0.007	

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