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TOTAL HALF-LIVES FOR SELECTED NUCLIDES

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Total half-lives for selected nuclides

Abstract – Measurements of the half-lives of ^{3}H, ^{10}Be, ^{14}C, ^{26}Al, ^{40}K, ^{39}Ar, ^{53}Mn, ^{87}Rb, ^{92}Nb, ^{129}I, ^{138}La, ^{147}Sm, ^{176}Lu, ^{174}Hf, ^{180}Ta, ^{187}Re, ^{186}Os, ^{190}Pt, ^{204}Pb, ^{210}Pb, ^{210}Po, ^{222}Rn, ^{224}Th, ^{226}Ra, ^{227}Ac, ^{228}Ra, ^{228}Th, ^{230}Th, ^{232}Th, ^{231}Pa have been compiled and evaluated. The effect of the ^{14}C half-life value on carbon dating ages is discussed as well as the stability of ^{204}Pb.

INTRODUCTION

In the past, many compilations and evaluations of half-lives have been made which have uncritically accepted authors' values and uncertainties. They have merely recommended weight-averaging reported results. This evaluation attempts to reassess each experiment in the literature including an estimate of the standard deviation utilizing, where possible, an estimate of the systematic error. The long-lived nuclides of light elements are of interest for their use in dating methods and for calculating cosmic-ray exposure ages of meteorites. The heavy mass nuclides are of interest in determining geological ages using the Re-Os or the Lu-Hf dating methods, in supplying information on the natural radioactive decay chains and in the case of tantalum because it represents the first long-lived state which is actually an isomer.

The impact of the recommended ^{14}C half-life of 5715 year on the carbon dating technique, which uses the Libby value of 5568 year, will be discussed. Also the possible primordial occurrence of ^{92}Nb is now definitely ruled out by the recommended half-life of 3.7×10^{7} year. Based on the recommended ^{26}Al half-life value, the ^{21}Ne production rate for calculating cosmic-ray exposure ages remains too high, compared to rates using the ^{53}Mn and ^{10}Be half-life values. It is shown that ^{204}Pb, which was previously thought to be radioactive, is stable.

It will be noted that many of the uncertainties recommended here considerably exceed, by up to an order of magnitude, uncertainties quoted by individual authors in their publications; *e.g.* ^{3}H, ^{210}Po, ^{222}Rn, ^{227}Ac, and ^{228}Th.

The general procedure followed in this paper has been to review each experiment and to revise the published values for the latest estimates of various parameters originally reported by the authors; *e.g.* improved data on branching ratios assumed, on the half-lives of other nuclides involved, on the isotopic abundance in a natural sample, the nuclidic masses and the physical constants such as the Avogadro's number. When detailed information on uncertainties was available in each experiment, the standard deviation was combined with one third of the systematic error to provide the uncertainty quoted in the table. The result of this procedure should be that the limit of error of the half-life would be obtained from the sum of the systematic error plus three standard deviations; *i.e.* 3σ. Where there was no adequate discussion of the systematic error and the total error was extremely small; *e.g.* 0.1 percent or less, a systematic error of 0.1 percent was estimated. One third of this amount, about 350 parts per million (ppm), was added to the published error to obtain the figure given in the various tables. The uncertainty listed for the recommended value in each table was calculated from a weighted average of the listed measurements using a variance weighting technique; either the reciprocal square of the author's reported uncertainty, or as revised according to the above scheme. Exceptions to the weighted average rule had to be made for some nuclides and will be discussed under the appropriate section for those nuclides. In such cases, recommendations were made using either a selected value considered superior to other listed measurements, or a weighted average was calculated for each of the different experimental techniques used and an unweighted average of these half-lives was recommended. All of the tables indicate the particular method chosen.

THE LIGHT ELEMENTS (A < 100)

For ^{3}H, a number of measurements have been reported for which the precision only is given. The reported values disagree by 20 to 30 standard deviations. The different techniques were weight-averaged and an unweighted average of these numbers was recommended.

For ^{14}C, Mann[1] discussed the problem of retention of a small amount of high specific activity (≈0.02%) carbon dioxide during the gas dilution phase. This systematic effect could cause up to a 30% spread in the resulting half-life and was eliminated by substituting a clean flask during subsequent dilution phases. Earlier measurements, which varied from 4700–7200 year, were performed either with very low enrichment (a few percent) or with the above mentioned dilution process with large systematic error. These results were discarded. In Mann's revision[2] of his earlier measurement, he mentions a discrepancy between mass spectrometric determination of the amount of ^{14}C atoms. Samples which were run at the USA National Bureau of Standards, NBS, in Washington, DC. and at the Atomic Weapons Research Establishment, AWRE, in Aldermaston, UK showed a lower reading on one of the three machines at NBS. Mann noted that the result obtained on the mass spectrometer at AWRE agreed with the results on the two other NBS instruments but chose not to use this information. In my analysis, I have averaged the results on the samples from all four instrument which has slightly lowered Mann's half-life. A weighted average gives 5692 ± 20 year, while an unweighted average gives 5715 ± 24 year. The unweighted average is recommended because the wide variation in authors estimates of systematic error sources tends to penalize those who do the best job of error analysis. The standard deviation is expanded to account for the variation in the weighted and unweighted averages and to allow for undisclosed systematic errors.

It should be noted that although the fifth (Godwin[3]) and sixth (Johnson[4]) International Carbon-14 Conferences recognized that the best available half-life at that time for the decay of radiocarbon was 5730 ± 40 year, the measurers of radiocarbon dates would continue to use 5568 year realizing that to obtain the correct dates, a factor of 1.03 must be used. The factor now becomes 1.026 with this recommended half-life.

For ^{39}Ar, the weighted average is 268 ± 8 year, where the 3% systematic error has been used rather than the 1% statistical error usually associated with this half-life.

For ^{40}K, the two significant decay branches of electron capture, ec, and negative beta decay, β^{-}, have been separately averaged and the total half-life has been calculated from the two decay constants. Most of the experiments have been reported at the 1% accuracy level. One similar experiment claims an accuracy of 0.1%. An unweighted average is recommended to treat all experiments on an equal level.

For ^{53}Mn, the early measurements assumed a constant cosmic ray flux over a period of 10 million years, which is a questionable assumption. Those early measurements have not been used.

For ^{92}Nb, Makino's result[5] for the specific activity measurement as reported is in error. The half-life should be 3.98 ± 0.76 x 10^{7} year. In Nethaway's measurement[6], he ignores all other measured (n,2n) cross section values for producing the m-state except his own[7]. The author notes a 10% effect is involved in treating the cross section for producing the long lived state. The author averages all total (n,2n) cross sections from 13 to 15 MeV, but selects the peak cross section for m-state production at 14.8 MeV. In this paper, I have renormalized the ^{238}U (n,f) flux monitor to the latest value of the Evaluated Nuclear Data File ENDF/B-V and I have recalculated the half life on the basis of 13–15 MeV average (n,2n) cross section difference for total and m-state production as well as 14.8 MeV differences. The former gives 3.79 x 10^{7} year and the latter 4.02 x 10^{7} year. An average is selected to represent this experiment.

THE MEDIUM ELEMENTS (100 < A < 200)

For ^{129}I, the most accurately quoted results are either unpublished or contain no details. An unweighted average of all data is recommended.

For ^{176}Lu, the two measurements which were performed with enriched samples do not agree. The difference is between four and seven standard deviations. An unweighted is recommended.

For ^{174}Hf, ^{180}Ta, and ^{186}Os, the most recent measurement has been selected in each case. This corresponds to either the only value, a value which is far superior to other measurements or it is a higher upper limit to the total half-life.

For ^{187}Re, an unweighted average is recommended to take account of the measurement by Naldrett[8], which is significantly lower than the other values.

THE HEAVY ELEMENTS (200 < A)

For ^{204}Pb, Riezler[9] used a nuclear emulsion technique to measure a sample of ^{204}Pb enriched to 27.0%. A peak was found between 8 μ and 9 μ in the emulsion, which from Faraggi's range energy curves[10] was attributed to an alpha energy of 2.6 MeV. The latest mass data on ^{204}Pb, ^{200}Hg, and ^{4}He imply an available alpha energy of 1.93 MeV, *i.e.* a peak below 6.5 μ. The peak has to be due to something other than the alpha decay of ^{204}Pb. There is no evidence that ^{204}Pb is radioactive. The most recent theoretical work[11] predicts a half-life value of 4.5 x 10^{35} year compared to Riezler's measurement of 1.4 x 10^{17} year.

For ^{210}Pb, the two most accurately quoted measurements do not agree. The difference is between seven and seventeen standard deviations. An unweighted average has been recommended.

For ^{210}Po, ^{222}Rn, ^{227}Ac and ^{228}Th, the recommended value is based on a weighted average of the measurements but the quoted value for the uncertainty has been increased to 0.1% (see discussion of results section).

For ^{230}Th, the results of Hyde[12] and Attree[13] have been revised with the latest parameters as well as with the assumption that all the thorium in their samples, which was not ^{230}Th, was ^{232}Th. Meadows[14] has recalculated all of the earlier measurements based on ^{226}Ra to the presently accepted half life of 1600 year.

For ^{232}Th, the recommended value is based on a weighted average of all measurements. The uncertainty has been increased from 0.5% to 0.7% to account for systematic errors.

DISCUSSION OF RESULTS

In most cases, the recommended values and uncertainties in the tables are based on variance weighted averages. The recommended values listed are given in units of second (s), day (d), and year (a). Although it has been previously discussed[15], some words on the problem of error estimation can not be stated too often.

Various measurements in the tables below quote uncertainties that both disagree with and exclude many other good measurements from consideration. Undoubtedly, systematic errors have not been carefully considered in these publications. If one uses variance weighting indiscriminately in such cases, one penalizes the authors who attempt the difficult task of estimating the systematic error, while benefiting the authors who make no such attempt to determine all of their sources of error, (an admittedly difficult task). Some authors below have reported values for a half-life and later revised their results for the experiment, when additional data points became available. The difference between the two reported values has been as large as twenty standard deviations of the first reported value. This implies that, statistically speaking, the two reported values for that experiment could not have been estimating the same parameter. The problem no doubt involves a complete underestimate of the true uncertainty in the measurement.

In the review of nuclear data by the International Atomic Energy Agency[16], their general comment on uncertainties included a statement questioning the validity of any presently stated uncertainties of less than 0.1% for half-lives. The same criteria has also been applied here in a few cases. No half-life has been recommended with an accuracy of better than 0.1%. The rationale for this rule is that systematic errors up to ten times smaller than the total statistical uncertainty quoted could have an appreciable effect on that total uncertainty, if there were a number of such errors. Recommending values at accuracy levels of a few hundred parts-per-million (ppm) would imply that all potential errors in the experiment at the level of ten ppm had been investigated, documented and their effect on the result taken into account. An experiment, in which such a thorough study has been both performed and documented, has yet to be reported to my knowledge. In addition, many of these very precise results are based on the examination of only one sample.

The recommended data are given in the following tables.

TABULATED RESULTS

Table 1. Total Half-life of ^{3}H

Author	$T_{½}$/(a)	Comment
Jenks[17]	12.46 ± 0.1	He growth
Jones[18]	12.41 +0.15 −0.25	absolute counting
Jones[19]	12.262 ± 0.008	He growth; revised error
Popov[20]	12.57 ± 0.18	calorimetry
Merritt[21]	12.31 ± 0.13	absolute counting
Jordan[22]	12.346 ± 0.007	calorimetry; revised error
Jones[23]	12.25 ± 0.03	He growth
Rudy[24]	12.323 ± 0.008	calorimetry; revised error
Unterweger[25]	12.43 ± 0.05	tritiated H_2O; counting
Simpson[26]	12.32 ± 0.03	counting
Budick[27]	12.29 ± 0.15	counting.; no details; error x 1.5
Oliver[28]	12.38 ± 0.03	Neutron irradiated Li; He growth
Oliver[29]	12.38 ± 0.04	Tritiated H_2O; He growth
Recommended Value	12.32 ± 0.03 a;	*Unweighted Average of Techniques*

Table 2 Total Half-life of ^{10}Be

Author	$T_{½}$/(10^6 a)	Comment
Hughes[30]	2.0 ± n.u.	not used; Value revised from 2.9
McMillian[31]	2.5 ± 0.5	not used; see reference 33
Yiou[32]	1.55 ± 0.3	
McMillian[33]	1.71 ± 0.34	revision of reference 31
Emery[34]	1.6 ± 0.2	no details; error x 1.5
Makino[35]	1.48 ± 0.15	
Hofmann[36]	1.51 ± 0.06	accelerator mass spectrometry
Weighted Average	1.52 ± 0.05 x 10^6 a;	*Recommended Value*

Table 3 Total Half-life of ^{14}C

Author	$T_{½}$/(a)	Comment
Libby[37]	5568 ± 30	Weighted Average of 3 (1949/50) values
Mann[1]	5760 ± 50	not used; revised; see reference 2
Watt[38]	5780 ± 65	mass spectrometry, proportional counting
Olsson[39]	5680 ± 40	mass spectrometry, proportional counting
Godwin[3]	5730 ± 40	not used; average of references 1, 38, 39
Hughes[2]	5730 ± 50	revision of reference 1
Bella[40]	5660 ± 30	
Emery[34]	5736 ± 84	no details; error x 1.5
Recommended Value	5715. ± 30. a;	*Unweighted Average*

Table 4 Total Half-life of ^{26}Al

Author	$T_{1/2}/(10^5$ a)	Comment
Rightmire[41]	7.1 ± 0.3	Revised using references 42,43
Norris[44]	7.1 ± 0.2	GeLi; Mass Spectrometry
Middleton[45]	7.0 ± 0.6	Mass Spectrometry
Thomas[46]	7.8 ± 0.5	not used; GeLi; verified others
Recommended Value	7.1 ± 0.2 x 10^5 a;	*Weighted Average*

Table 5 Total Half-life of ^{39}Ar

Author	$T_{1/2}$/(a)	Comment
Zeldes[47]	265 ± 30	
Stoenner[48]	268 ± 8	Revised ^{37}Ar $T_{1/2}$ by Kishore[49]
Recommended Value	268. ± 8. a;	*Weighted Average*

Table 6 Total Half-life of ^{40}K

Author	$T_{1/2}/(10^9$ a)	Comment - electron capture (ec), beta (β^-) branch or total decay
Orban[50]	0.5	not used; ec; cloud chamber
Gleditsch[51]	11. ± 2.	not used; ec; GM counter
Ahrens[52]	11.6 ± 0.2	not used; ec; radiogenic
Graf[53]	1.48 ± 0.07	not used; β^-; GM counter
Stout[54]	1.29 ± 0.08	not used; β^-; GM counter
Floyd[55]	1.54 ± 0.39	not used; total; GM counter
Sawyer[56]	12. ± 1.	not used; ec; stilbene crystal
Graf[57]	12. ± 2.	not used; ec; GM counter
Spiers[58]	1.18	not used; total; ion chamber, GM
Faust[59]	1.14 ± 0.10	not used; total;
Sawyer[60]	1.27 ± 0.05	not used; total; 4π counter
Houtermans[61]	1.31 ± 0.07	not used; total; 4π counter
Smaller[62]	1.76 ± 0.05	not used; β; KI crystal
Delaney[63]	1.24 ± 0.01	not used; β^-
Good[64]	1.46 ± 0.03	β^-; KI crystal
Burch[65]	11.7 ± 0.5	not used; ec; ion chamber
Suttle[66]	1.34 ± 0.03	not used; β^-
	13.4 ± 0.2	not used; ec
Kono[67]	1.36 ± 0.05	β^-; KI crystal
Backenstoss[68]	11.3 ± 0.5	not used; ec; NaI crystal
McNair[69]	1.44 ± 0.01	β^-; NaI crystal
Wetherill[70]	12.2 ± 0.6	not used; ec; radiogenic
Wetherill[71]	11.7 ± 0.4	ec; radiogenic
Kelly[72]	1.46 ± 0.03	β^-; KI crystal
Saha[73]	12.3 ± 0.6	ec; NaI; stilbene
	1.37 ± 0.04	β^-
Glendenin[74]	1.40 ± 0.015	β^-; liquid scintillator
Fleishman[75]	1.45 ± 0.4	β^-; scintillating gel
Brinkman[76]	1.36 ± 0.02	β^-; liquid scintillator
Leutz[77]	12.2 ± 0.3	ec; NaI, CsI, KI
	1.40 ± 0.002	β^-
Feuerhake[78]	1.41 ± 0.02	β^-; scintillating gel
DeRuytter[79]	12.2 ± 0.2	ec; NaI
Egelkraut[80]	11.8 ± 0.5	ec; KI, NaI
	1.40 ± 0.07	β^-
Venkataramaiah[81]	1.31 ± 0.06	not used; β^-
Gopal[82]	1.13 ± 0.06	not used; β^-
Cesana[83]	12.3 ± 0.04	ec; GeLi
Recommended Value	1.26 ± 0.01 x 10^9 a;	*Unweighted Average*

Table 7 Total Half-life of ^{53}Mn

Author	$T_{1/2}/(10^6$ a)	Comment
Sheline[84]	2.	not used
Kaye[85]	1.9 ± 0.5	not used
Hohlfelder[86]	10.8 ± 4.5	not used
Matsuda[87]	2.9 ± 1.2	not used
Hondo[88]	3.7 ± 0.2	revised; mass spectrometry, specific activity
Woelfle[89]	3.8 ± 0.6	revised; activation cross section
Heimann[90]	3.7 ± 0.4	revised; ^{53}Mn/^{26}Al in meteorites
Weighted Average	3.7 ± 0.2 x 10^6 a;	*Recommended Value*

Table 8 Total Half-life of ^{87}Rb

Author	$T_{1/2}/(10^{10}$ a)	Comment
Orban[50]	4.45	not used; Cloud chamber
Strassmann[91]	4.45	not used; Pure ^{87}Sr in Rb mica
Eklund[92]	5.8 ± 1.0	not used; Geiger counter
Haxel[93]	6.9 ± 0.7	not used; Geiger counter
Kemmerich[94]	6.0 ± 0.6	not used; Geiger counter
Curran[95]	6.15 ± 0.3	not used; Proportional counter
Lewis[96]	6.0 ± 0.3	not used; Scintillation counter
Flinta[97]	6.2 ± 0.2	not used;
MacGregor[98]	6.2 ± 0.3	not used; enriched ^{87}Rb
Geese-Baehnisch[99]	4.3 + 0.3 − 0.2	not used;
Fritze[100]	4.6 ± 0.5	not used; Geological ^{87}Sr/^{87}Rb
Aldrich[101]	5.0 ± 0.2	not used; Geological ^{87}Sr/^{87}Rb
Libby[102]	5.07 ± 0.2	not used; Geiger counter
Flynn[103]	4.7 ± 0.1	not used; Liquid scintillation counter
Ovchinnikova[104]	5.0 ± 0.2	not used; Geological ^{87}Sr/^{87}Rb
Rausch[105]	4.72 ± 0.08	not used; 4π proportional counting
McNair[106]	5.25 ± 0.10	not used; 4π counting
Egelkraut[107]	5.82 ± 0.1	not used; Scintillation counter
Beard[108]	5.53 ± 0.10	not used; Scintillation counter
Leutz[109]	5.80 ± 0.12	not used; Scintillation counter
Kovach[110]	4.77 ± 0.10	not used; Scintillation counter
Thode[111]	4.60 ± 0.06	not used; Mass spectrometry
Brinkman[76]	5.22 ± 0.15	not used;
McMullen[112]	4.72 ± 0.04	not used; Mass spectrometry
Neumann[113]	4.88 + 0.06 − 0.10	4π proportional counting
Davis[114]	4.89 ± 0.04	McMullen revised
Akatsu[115]	5.56 ± 0.025	not used
Recommended Value	4.88 ± 0.05 x 10^{10} a;	*Unweighted Average*

Table 9 Total Half-life of ^{92}Nb

Author	$T_{1/2}/(10^7$ a)	Comment
Apt[116]	17	not used
Makino[5]	3.5 ± 0.4	revised
Nethaway[6]	3.9 ± 0.5	revised
Weighted Average	3.7 ± 0.5 x 10^7 a;	*Recommended Value*

Table 10 Total Half-life of ^{129}I

Author	$T_{1/2}/(10^7$ a)	Comment
Katcoff[117]	1.72 ± 0.09	proportional counter, mass spectrometry
Russel[118]	1.56 ± 0.06	
Emery[119]	1.57 ± 0.06	No details; error x 1.5
Kuhry[120]	1.97 ± 0.14	Liquid scintillation
Recommended Value	1.7 ± 0.1 x 10^7 a;	*Unweighted Average*

Table 11 Total Half-life of ^{138}La

Author	$T_{½}/(10^{11}$ a)	Comment
Turchinetz[121]	1.15 ± 0.1	not used; revised
Glover[122]	1.13 ± 0.04	not used; revised
DeRuytter[123]	1.04 ± 0.02	not used
Ellis[124]	1.53 ± 0.3	not used; revised; GeLi
Marsol[125]	1.23 ± 0.18	revised; GeLi
Cesana[83]	1.25 ± 0.12	not used; revised; GeLi
Taylor[126]	1.25 ± 0.12	revised; GeLi
Sato[127]	1.03 ± 0.04	GeLi
Norman[128]	1.05 ± 0.05	revised; GeLi
Masuda[129]	2.5 ± 0.2	not used; β^- branch; radiogenic
Weighted Average	1.06 ± 0.04 x 10^{11} a;	*Recommended Value*

Table 12 Total Half-life of ^{147}Sm

Author	$T_{½}/(10^{11}$ a)	Comment
Hevesy[130]	1.8	not used; Geiger counter
Herzfinkiel[131]	2.0	not used; ion chamber
Mader[132]	1.5	not used; Ion chamber
Libby[133]	0.91	not used
Hosemann[134]	1.5 ± 0.1	not used; geiger counter
Cuer[135]	1.3 ± 0.1	not used; nuclear emulsion
Picciotto[136]	0.99 ± 0.05	not used; nuclear emulsion
Beard[137]	1.25 ± 0.06	not used; 4π geiger counter
Leslie[138]	1.15 ± 0.03	not used
Beard[139]	1.06 ± 0.04	liquid scintillation; corrected for wrong Sm content.
Karras[140]	1.13 ± 0.05	not used; ion chamber
Mac Farlane[141]	1.15 ± 0.05	not used
Wright[142]	1.05 ± 0.02	not used; liquid scintillator
Donhoffer[143]	1.04 ± 0.03	not used; Liquid scintillator
Valli[144]	1.08 ± 0.02	not used; Ionization chamber, liquid scintillation
Gupta[145]	1.06 ± 0.02	97% enriched
Al-Bataina[146]	1.05 ± 0.04	97.5% enriched
Weighted Average	1.06 ± 0.02 x 10^{11} a;	*Recommended Value*

Table 13 Total Half-life of ^{176}Lu

Author	$T_{½}/(10^{10}$ a)	Comment
Heyden[147]	4.	not used; GM counter
Libby[148]	7.3 ± 2.	not used; GM counter
Flammerfeld[149]	2.4	not used; GM counter
Arnold[150]	2.15 ± 0.10	not used; NaI
Dixon[151]	4.56 ± 0.3	not used; proportional counter
Glover[152]	2.1 ± 0.2	not used; NaI
Herr[153]	2.17 ± 0.35	not used; radiogenic
Mc Nair[154]	3.6 ± 0.1	not used; NaI
Brinkman[76]	3.59 ± 0.05	not used; NaI, βγ coincidence
Donhoffer[143]	2.18 ± 0.06	not used; liquid scintillation
Sakamoto[155]	5.0 ± 0.3	not used; NaI
Prodi[156]	3.27 ± 0.05	not used; liquid scintillation
Boudin[157]	3.3 ± 0.5	not used; radiogenic
Komura[158]	3.79 ± 0.03	71% enriched; GeLi, NaI
Norman[159]	4.08 ± 0.24	GeLi
Sguigna[160]	3.59 ± 0.05	54.4% enriched; γγ coincidence
Patchett[161]	3.57 ± 0.14	radiogenic
Sato[162]	3.78 ± 0.02	GeLi
Recommended Value	3.8 ± 0.1 x 10^{10} a;	*Unweighted Average*

Table 14 Total Half-life of ^{174}Hf

Author	$T_{1/2}/(10^{15}$ a)	Comment
Riezler[163]	4.3. n.u.	natural sample
Mac Farlane[141]	2.0 ± 0.4	10.14% enriched
Recommended Value	2.0 ± 0.4 x 10^{15} a;	*Selected Value*

Table 15 Total Half-life of ^{180}Ta

Author	$T_{1/2}/(10^{15}$ a)	Comment
Eberhardt[164]	> 0.00099	β^- branch
Bauminger[165]	> 0.023 ± 0.007	electron capture branch
	> 0.017 ± 0.006	β^- branch
Eberhardt[166]	> 0.0000046	K capture branch
Sakamoto[155]	> 0.015 ± 0.005	electron capture branch
Ardisson[167]	> 0.021	electron capture branch
Norman[168]	> 0.056	electron capture branch
	> 0.056	β^- branch
Cumming[169]	> 1.2	total; all branches
Recommended Value	> 1.2 x 10^{15} a;	*Selected Value*

Table 16 Total Half-life of ^{186}Os

Author	$T_{1/2}/(10^{15}$ a)	Comment
Viola[170]	2.0 ± 1.1	61.27% enriched
Recommended Value	2.0 ± 1.1 x 10^{15} a;	*Selected Value*

Table 17 Total Half-life of ^{187}Re

Author	$T_{1/2}/(10^{11}$ a)	Comment
Naldrett[171]	40. ± 10.	not used; geiger counter
Sugarman[172]	40. – 70.	not used; geiger counter
Dixon[173]	>1000.	not used; proportional counter
Suttle[174]	> 1.	not used; geiger counter
Herr[175]	0.05 – 2.5	not used; radiogenic
Herr[176]	~ 0.8	not used; radiogenic
Walton[177]	2.1 ± 0.5	not used; geiger counter
Naldrett[178]	3.2 ± 0.7	not used; geiger counter
Herr[179]	0.62 ± 0.07	not used; radiogenic
Kocol[180]	0.79	not used; geiger counter, only 1 measurement
Wolf[181]	1.2 ± 0.4	not used; geiger counter
Hirt[182]	0.43 ± 0.05	radiogenic
Brodzinski[183]	0.66 ± 0.13	not used; proportional counter
Watt[184]	~ 0.3	not used; low background measurement
Luck[185]	0.45 ± 0.02	radiogenic
Naldrett[8]	0.35 ± 0.04	liquid scintillator
Lindner[186]	0.423 ± 0.013	mass spectrometry
Recommended Value	4.2 ± 0.2 x 10^{10} a;	*Unweighted Average*

Table 18 Total Half-life of ^{190}Pt

Author	$T_{1/2}/(10^{11}$ a)	Comment
Hoffmann[187]	5.	not used
Porschen[188]	10.	not used; nuclear emulsion
Mac Farlane[141]	6.9 ± 0.5	0.76% enriched sample
Petrzhak[189]	4.7 ± 1.7	Natural Platinum; ion chamber
Graeffe[190]	5.4 ± 0.6	natural + enriched Platinum
Kauw[9]	22.	not used; nuclear emulsion; 0.76% enriched sample
Al-Bataina[146]	6.65 ± 0.28	natural Platinum
Weighted Average	6.5 ± 0.3 x 10^{11} a;	*Recommended Value*

Table 19 Total Half-life of ^{204}Pb

Author	$T_{½}/(10^{17}$ a)	Comment
Kohman[191]	≥ 0.3	Slight indication of activity
Riezler[9]	1.4	E_{α} = 2.6 Mev > available energy
Recommended Value	Stable	

Table 20 Total Half-life of ^{210}Pb

Author	$T_{½}$/(a)	Comment
Antonoff[192]	16.5	not used; ZnS counting
Albrecht[193]	22.5 ± 0.4	not used
Curie[194]	22.	not used
Joliot-Curie[195]	23.	not used; α counting
Wagner[196]	25.	not used; ion chamber; 0.7 year counting
Tobailem[197]	19.40 ± 0.35	not used; 1/3 year counting
Merritt[198]	22.4 ± 0.4	4π proportional counter, 5½ years counting
Harbottle[199]	20.4 ± 0.3	ion chamber; 3/4 year counting
Pate[200]	23.3 ± 0.5	4π proportional counter, 5 years counting
Eckelmann[201]	21.4 ± 0.5	geological
Imre[202]	22.85 ± 0.70	β counting
Ramthun[203]	21.96 ± 0.51	calorimetry
Von Gunten[204]	22.2 ± 1.0	proportional counter
Hoehndorf[205]	22.26 ± 0.11	α spectrometry
Recommended Value	22.6 ± 0.1 a;	*Unweighted Average*

Table 21 Total Half-life of ^{210}Po

Author	$T_{½}$/(d)	Comment
Schweidler[206]	136.5	counted 6 years
Curie[207]	140.	γ counted ½ year
Dorabialska[208]	137.6 ± 0.6	calorimetry, α counting
Sanielevici[209]	138.7 ± 0.6	calorimetry
Beamer[210]	138.3 ± 0.14	calorimetry
Ginnings[211]	138.39 ± 0.14	calorimetry
Curtis[212]	138.37 ± 0.098	α counting; revised error
Eichelberger[213]	138.376 ± 0.05	calorimetry; revised error
Recommended Value	138.4 ± 0.1 d;	*Weighted Average with Uncertainty Rule*

Table 22 Total Half-life of ^{222}Rn

Author	$T_{½}$/(d)	Comment
Bothe[214]	3.825 ± 0.004	revised error
Curie[215]	3.823 ± 0.003	revised error
Tobailem[216]	3.825 ± 0.006	ion chamber; revised error
Marin[217]	3.8229 ± 0.0017	Counted 5½ $T_{½}$; revised error
Robert[218]	3.825 ± 0.005	revised error
Shimanskaia[219]	3.83 ± 0.03	Calorimetry
Butt[220]	3.82351 ± 0.0017	NaI; counted 40 $T_{½}$; revised error
Recommended Value	3.823 ± 0.004 d;	*Weighted Average with Uncertainty Rule*

Table 23 Total Half-life of ^{224}Th

Author	$T_{½}$/(s)	Comment
Tove[221]	1.05 ± 0.05	Scintillation detector
Valli[222]	1.03 ± 0.05	semi-conductor
Ibowski[223]	1.05 ± 0.02	α spectrometry
Weighted Average	1.05 ± 0.02 s;	*Recommended Value*

Table 24 Total Half-life of ^{226}Ra

Author	$T_{½}$/(a)	Comment
Watson[224]	1608.	not used; calorimetry
Braddick[225]	1603.	not used; α current
Curie[226]	1590.	not used; ion current
Ward[227]	1599.	not used; number α's emitted
Meitner[228]	1590.	not used; calorimetry
Gleditsch[229]	1691.	not used; growth rate
Guenther[230]	1603.	not used; He production
Kohman[231]	1622. ± 13.	number α's emitted
Gorshkov[232]	1573.	not used; calorimetry
Sebaoun[233]	1617. ± 12.	number α's emitted
Gorshkov[234]	1577. ± 9.	calorimetry
Martin[235]	1602. ± 8.	calorimetry
Ramthun[236]	1599. ± 7.	calorimetry
Weighted Average	1599. ± 4. a;	*Recommended Value*

Table 25 Total Half-life of ^{227}Ac

Author	$T_{½}$/(a)	Comment
Joliot-Curie[237]	21.7	not used
Hollander[238]	22.0 ± 0.3	ion chamber
Tobailem[239]	21.6 ± 0.4	ion chamber
Shimanskaya[240]	21.2 ± 0.8	calorimetry
Robert[241]	21.6 ± 0.3	calorimetry
Jordan[242]	21.773 ± 0.012	calorimetry; revised error
Recommended Value	21.77 ± 0.02 a;	*Weighted Average with Uncertainty Rule*

Table 26 Total Half-life of ^{228}Ra

Author	$T_{½}$/(a)	Comment
Curie[243]	6.7	not used
Dudley[244]	5.7 ± 0.2	
Mays[245]	5.75 ± 0.03	
Weighted Average	5.75 ± 0.03 a;	*Recommended Value*

Table 27 Total Half-life of ^{228}Th

Author	$T_{½}$/(a)	Comment
Meitner[246]	1.91 ± 0.02	
Kirby[247]	1.910 ± 0.002	α counting, 2 years
Mays[248]	1.908 ± 0.004	γ counting
Mays[248]	1.924 ± 0.020	α counting
Jordan[249]	1.9131 ± 0.0020	Calorimetry; 9.3 years; Revised error
Hoppes[250]	1.9113 ± 0.0021	Revised error
Recommended Value	1.912 ± 0.002 a;	*Weighted Average with Uncertainty Rule*

Table 28 Total Half-life of ^{230}Th

Author	$T_{½}$/(10^4 a)	Comment
Soddy[251]	7.42	Meadows recalculation
Soddy[252]	7.14 ± 0.36	Meadows recalculation
Soddy[253]	7.69 ± 0.30	Meadows recalculation
Curie[254]	8.23 ± 0.25	not used
Soddy[255]	7.32 ± 0.37	Meadows recalculation
Hyde[12]	7.99 ± 0.34	26.4% enriched
Attree[13]	7.61 ± 0.14	12.11% enriched
Meadows[14]	7.538 ± 0.030	99.65% enriched
Weighted Average	7.54 ± 0.03 x 10^4 a;	*Recommended Value*

Table 29 Total Half-life of ^{232}Th

Author	$T_{½}/(10^{10}$ a)	Comment
Kovarik[256]	1.39 ± 0.03	
Senftle[257]	1.42 ± 0.07	Na(I)
Piciotto[258]	1.39 ± 0.03	nuclear emulsion
Macklin[259]	1.45 ± 0.05	incidental to neutron cross section measurement
Farley[260]	1.41 ± 0.014	ion-chamber α spectrometry
LeRoux[261]	1.40 ± 0.007	liquid scintillator
Weighted Average	1.40 ± 0.01 x 10^{10} a;	*Recommended Value*

Table 30 Total Half-life of ^{231}Pa

Author	$T_{½}/(10^{4}$ a)	Comment
Von Grosse[262]	3.2 ± 0.3	not used
Van Winkle[263]	3.43 ± 0.03	not used; α counting
Kirby[264]	3.248 ± 0.026	calorimetry
Brown[265]	3.234 ± 0.023	α counting
Robert[266]	3.276 ± 0.011	Calorimetry
Recommended Value	3.25 ± 0.01 x 10^{4} a;	*Unweighted Average*

Table 31 Recommended Half-lives and Uncertainties

Nuclide	$T_{½}$/(year)	Nuclide	$T_{½}$/(year)	Nuclide	$T_{½}$/(year)
^{3}H	12.32 ± 0.03	^{138}La	1.06 ± 0.04 x 10^{11}	^{210}Po	138.4 ± 0.1 d
^{10}Be	1.52 ± 0.05 x 10^{6}	^{147}Sm	1.06 ± 0.02 x 10^{11}	^{222}Rn	3.823 ± 0.004 d
^{14}C	5715. ± 30.	^{176}Lu	3.8 ± 0.1 x 10^{10}	^{224}Th	1.05 ± 0.02 s
^{26}Al	7.1 ± 0.2 x 10^{5}	^{174}Hf	2.0 ± 0.4 x 10^{15}	^{226}Ra	1599. ± 4.
^{39}Ar	268. ± 8.	^{180}Ta	> 1.2 x 10^{15}	^{227}Ac	21.77 ± 0.02
^{40}K	1.26 ± 0.01 x 10^{9}	^{186}Os	2.0 ± 1.1 x 10^{15}	^{228}Ra	5.75 ± 0.03
^{53}Mn	3.7 ± 0.2 x 10^{6}	^{187}Re	4.2 ± 0.2 x 10^{10}	^{228}Th	1.912 ± 0.002
^{87}Rb	4.88 ± 0.05 x 10^{10}	^{190}Pt	6.5 ± 0.3 x 10^{11}	^{230}Th	7.54 ± 0.03 x 10^{4}
^{92}Nb	3.7 ± 0.5 x 10^{7}	^{204}Pb	*stable*	^{232}Th	1.40 ± 0.01 x 10^{10}
^{129}I	1.7 ± 0.1 x 10^{7}	^{210}Pb	22.6 ± 0.1	^{231}Pa	3.25 ± 0.01 x 10^{4}

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