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Long-lived Light Mass Element Half-lives (A<125) *

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I. 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-averaged reported results. This evaluation attempts to reanalyse each experiment in the literature including an estimate of the standard deviation utilizing, where possible, an estimate of the systematic error. This paper constitutes a preliminary step in the process of recommending values.

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.

Experimental data on the half-lives of selected nuclides have been evaluated and recommended values and uncertainties are presented for the following nuclides: ^{3}H, ^{10}Be, ^{14}C, ^{26}Al, ^{39}Ar, ^{40}K, ^{50}V, ^{53}Mn, ^{76}Ge, ^{87}Rb, ^{92}Nb, ^{107}Pd, ^{113}Cd, ^{115}In and ^{123}Te.

The impact of the recommended ^{14}C half-life of 5715 years on the carbon dating technique, which uses the Libby value of 5568 years, 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}.

Finally, 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.

II. Recommended Data

The recommended data are given in the following tables.

Table 1 - $T_{1/2}(^3H)$

Author	Reference	Value(years)	Comment
Jenks	1	12.46±0.1	
Jones, W. M.	2	$12.41^{+0.15}_{-0.25}$	
Jones, W. M.	3	12.262±.004	precision only
Popov	4	12.57±0.18	
Merritt	5	12.31±0.13	
Jordan	6	12.346±.003	precision only
Jones, P.M.S.	7	12.25±0.03	
Unterweger	8	12.43±0.05	
Recommended Value		12.3±0.1	

The uncertainties quoted by Jones[3] and Jordan[6] are statements of statisticals precision with no estimate of the systematic error. An indication of the systematic error is given by the spread in values measured by various methods, counting, calorimetry, helium growth. The measurement by Unterweger was performed on a tritiated water standard with a 17 years interval between measurements and to fit the measured activity, a half-life much larger than currently accepted was required. The recommended value is based on W. M. Jones[3], Jordan, P. M. S. Jones, and Unterweger and the standard deviation is based on the disagreement between W. M. Jones, Jordan and Unterweger.

Table 2 $T_{1/2}(^{10}Be)$

Author	Reference	Value x (10^{-6}years)	Comment
Hughes	9	2.0 n.u.	Revised from 2.9
McMillian	10	2.5±0.5	see ref. 12
Yiou	11	1.55±0.3	
McMillian	12	1.71±0.34	revision of 10
Emery	13	1.6±0.2	no details
Recommended Value		1.6±0.2	

The recommended value is based on agreement among Yiou, McMillian and Emery.

Table 3 $T_{1/2}$ (^{14}C)

Author	Reference	Value (years)	Comment
Mann	14	5760±50	see 18
Watt	15	5780±65	
Olsson	16	5680±40	
Godwin	17	5730±40	average of 14,15,16
Mann	18	5730±50	revision of 14
Bella	19	5660±30	
Emery	13	5736±84	no details
Recommended Value		5715±45	

Mann[14] 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 years, 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.

Because of the absence of any details on his measurement, Emery[13] was assigned one half the weight of the others in the unweighted average, and the listed error was adjusted from 59 years as originally quoted in the weighted average.

In Mann's revision of his earlier measurement he mentions a discrepancy between mass spectrometric determination of the amount of ^{14}C atoms. Samples which were run at NBS and Aldermaston 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 average the results on the samples from all four instrument which has slightly lowered Mann's half-life.

A weighted average of the data in table 3 (excluding Godwin) gives 5692±20 years, while an unweighted average gives 5715±24 years.

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[17]) and sixth (Johnson[106]) International Carbon-14 Conferences recognized that the best available half-life at that time for the decay of radiocarbon was 5730±40 years, the measurers of radiocarbon dates would continue to use 5568 years 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.

Table 4 $T_{1/2}$ (^{26}Al)

Author	Reference	Value (10^{-5}years)	Comment
Rightmire	20	7.14±0.32	Revised using 21
Norris	22	7.05±0.24	
Thomas	23	7.8±0.5	
Recommended Value		7.17±0.18	

The specific activity measurement by Rightmire has been revised using the Ge(Li) measurement of gamma ray intensities by Samworth[21] to obtain the positron branching ratio more accurately.

Table 5 $T_{1/2}$ (^{39}Ar)

Author	Reference	Value (years)	Comment
Zeldes	24	265±30	
Stoenner	25	268±8	Revised ^{37}Ar half-life by Kishore (ref. 26)

The weighted average is 268±8 years, where the 3% systematic error quoted by Stoenner has been used rather than the 1% statistical error usually associated with the half-life.

Table 6 $T_{1/2}$ (^{40}K)

Author	Reference	Value x (10^{-9}years)	Comment
Gleditsch	27	11±2	electron capture
Ahrens	28	11.8±0.2	electron capture
Graf	29	1.47±0.07	β decay
Stout	30	1.29±0.08	β decay
Floyd	31	1.54±0.39	total decay
Sawyer	32	12±1	
Graf	33	12±2	electron capture
Spiers	34	1.18	total decay
Faust	35	1.13±0.10	total decay
Sawyer	36	1.3-1.4	β decay
Houtermans	37	1.31±0.07	total
Smaller	38	1.75±0.05	β decay
Delaney	39	1.23±0.01	β decay
Good	40	1.46±0.03	β decay
Burch	41	11.7±0.5	electron capture
Suttle	42	1.33±0.03 13.3±0.2	β decay electron capture
McNair	43	1.44±0.01 11.6±0.2	β decay electron decay
Backenstoss	44	11.3±0.5	electron capture
Wetherill	45	12.2±0.6	electron capture
Kelly	46	1.45±0.03	β
Glendenin	47	1.40±0.015	β
Fleishman	48	1.45±004	β precision only
Brinkman	49	1.35±0.02	β
Leutz	50	12.1±0.3 1.40±0.002	ε c β
Wetherill	51	11.6±0.4	ε c
Kono	52	1.36±0.05	β
Feuerhake	53	1.42±0.02	β
DeRuytter	54	12.2±0.2	γ
Egelkraut	55	11.8±0.5 1.40±0.07	ε c

Saha	56	12.3±0.6 1.37±0.04	ε c β
Venkataramaish	57	1.31±0.06	β
Gopal	58	1.13±0.06	β
Cesana	59	12.3±0.04	ε c

The half-life is determined by averaging the beta branch using Good, Suttle, McNair, Kelly, Glendenin, Fleishman, Brinkman, Leutrz, Kono, Egelkraut, Saha, and Feuerhake, and by averaging the electron capture branch using Backenstoss, McNair, Wetherill, Saha, Egelkraut, Leutz, DeRuytter, and Cesana.

Table 7 $T_{1/2}$ (^{50}V)

Author	Reference	Value (10^{-17} years)	Comment
Bauminger	60	.005	
McNair	61	>.08	electron capture
		>.12	β-
Watt	62	.06	
Sonntag	63	>0.9	electron capture
		>0.69	β-
Pape	64	>7.	β-
		>8.8	electron capture
Alburger	65	$1.5^{+0.3}_{-0.7}$	
Simpson	66	$1.2^{+0.8}_{-0.4}$	
Recommended Value		$1.4^{+0.5}_{-0.6}$	

The recommended value is based on the Alburger and Simpson measurements.

Table 8 $T_{1/2}$ (^{53}Mn)

Author	Reference	Value x (10^{-6} years)	Comment
Kaye	67	1.9±0.5	
Hohlfelder	68	10.8±4.5	
Matsuda	69	2.9±1.2	
Hondo	70	3.71±0.14	revised
Wolfle	71	3.84±0.62	revised
Heimann	72	3.73±0.41	revised

The early measurements assumed a constant cosmic ray flux over a period of 10 million years, which is a questionable assumption. Hondo's measurement was revised for the ^{54}Mn half-life of 312 days rather than 303 days used by the author. Wolfle's measurement was revised for the ^{54}Mn half-life of 312 days rather than 308 days used by the author. Heimann's measurement was revised for the ^{26}Al half-life of 0.714×10^{6} years rather than 0.75×10^{6} years used by the author. The recommended value is $3.7 \pm 0.2 \times 10^{6}$ years.

Table 9 $T_{1/2}$ (^{76}Ge)

Author	Reference	Value x(10^{-22}years)	Comment
Leccia	73	>0.2	
Bellotti	74	>0.8	first excited state
		>2.	ground state
Avignone	75	>1.3	
Forster	76	>1.9	
Simpson	77	>1.6	first excited state
		>3.2	ground state
Goulding	78	>4.	

The recommended value is based on Goulding's preliminary data.

Table 10 $T_{1/2}$ (^{87}Rb)

Author	Reference	Value x(10^{-10}years)	Comment
Geese-Bahnisch	79	$4.3\pm^{+0.3}_{-0.2}$	
Fritze	80	4.6±0.5	
Aldrich	81	5.0±0.2	
Libby	82	5.07±0.2	
Flynn	83/47	4.7±0.1	
Ovchinnikova	84	5.0±0.2	
McNair	85	5.25±0.10	
Egelkraut	86	5.82±0.1	
Leutz	87	5.80±0.12	
Brinkman	49	5.22±0.15	
McMullen	88	4.72±0.04	
Neumann	89	$4.88^{+0.06}_{-0.10}$	
Davis	90	4.89±0.04	
Akatsu	91	5.56±0.025	
Recommended Value		4.88±0.05	

The most accurate measurements of those of Neumann and Davis, who remeasured McMullen's sample. The recommended value is based on these two measurements. The recent measurement by Akatsu was ignored.

Table 11 $T_{1/2}$ (^{92}Nb)

Author	Reference	Value (10^{-7} years)	Comment
Apt	92	~17	
Makino	93	3.5±0.4	revised
Nethaway	94	3.9±0.5	revised
Recommended Value		3.7±0.5	

Makino's result for the specific activity measurement as reported is in error. It should give $T_{1/2} = 3.98 \pm 0.76 \times 10^7$ years.

In Nethaway's measurement, he ignores all other measured (n,2n) cross section values for producing the m-state except his own (ref. 95) 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 evaluation, 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 3.79×10^7 years and the latter 4.02×10^7 years. An average is selected to represent this experiment.

The recommended value is $3.7 \pm 0.5 \times 10^7$ years.

Table 12 $T_{1/2}$ (^{107}Pd)

Author	Reference	Value (10^{-6}years)	Comment
Flynn	96	6.5±0.3	enriched sample

Table 13 $T_{1/2}$ (^{113}Cd)

Author	Reference	Value(10^{-5}years)	Comment
Martell	97	>0.6	natural Cd
Kalkstein	98	>0.5	natural Cd
Selig	99	>3.	natural Cd
Watt	100	>1.3	natural Cd
Greth	101	9.3±1.9	96.38% ^{113}Cd

The recommended value is based on the 96.3% enriched ^{113}Cd measurement by Greth.

Table 14 $T_{1/2}$ (^{115}In)

Author	Reference	Value(10^{-14}years)	Comment
Martell	97	6±2	
Cohen	102	~1	
Beard	103	7.05±1.51	revised
Watt	100	5.1±0.4	
Pfeiffer	104	4.41±0.25	

The recommended value is based on Pfeiffer's measurement. This was a Indium loaded liquid scintillator measurement.

Table 15 $T_{1/2}$ (^{123}Te)

Author	Reference	Value (10^{-13}years)	Comment
Heintze	105	≥100 ≥1	K-capture L-capture
Watt	100	1.2±0.1	K-capture
Selig	99	≥5	L-capture

The recommended half-life is based on Watt's measurement in the low background laboratories at Glasgow and Aldermaston, which has been revised for the isotopic abundance value for ^{123}Te of 0.908% rather than the 0.87% assumed. This measurement is preferred to the others where the number of counts were lost in the background and assumed to be zero.

References

1. G. H. Jenks, F. H. Sweeton, J. A. Ghormley, Phys. Rev. 80, 990 (1955).

2. W. M. Jones, Phys. Rev. 83, 537 (1951).

3. W. M. Jones, Phys. Rev. 100, 124 (1955).

4. M. M. Popov, U. V. Gagarinskii, M. D. Sevin, U. M. Morozov. At Energia. 4, 296 (1958).

5. J. S. Merritt, J. G. V. Taylor. AECL-2510 (1966).

6. K. C. Jordan, B. C. Blanke, W. A. Dudley, J. Inorg. Nucl. Chem. 29, 2129 (1967).

7. P. M. S. Jones, J. Nucl. Materials 21, 239 (1967).

8. M. P. Unterweger, B. M. Coursey, F. J. Schima, W. B. Mann, Int. J. Appl. Rad. Isotopes 31, 64 (1980).

9. D. J. Hughes, C. Eggler, C. M. Huddleston, Phys. Rev. 71 269 (1947).

10. E. M. McMillian, Phys. Rev. 72, 591 (1947).

11. F. Yiou, G. M. Raisbeck, Phys. Rev. Lett. 29, 372 (1972).

12. E. M McMillian, Phys. Rev. 6C, 2296 (1972).

13. J. F. Emery, S. A. Reynolds, E. I. Wyatt, Nucl. Sci. Eng. 48, 319 (1972).

14. W. B. Mann, W. F. Marlow, E. E. Hughes, Int. J. Appl. Rad. Isotopes 11, 57 (1961).

15. D. E. Watt, D. Ramsden, H. W. Wilson, Int. J. Appl. Rad. Isotopes 11, 68 (1961).

16. I. U. Olsson, I. Karlen, A. H. Turnbull, N. J. D. Prosser, Ark. f. Fys. 22, 237 (1962).

17. H. Godwin, Nat. 195, 984 (1962).

18. E. E. Hughes, W. B. Mann, Int. J. Appl. Rad. Isotopes 15, 97 (1964).

19. F. Bella, M. Alessio, P. Fratelli, Nuovo Cim. 63B, 232 (1968).

20. R. A. Rightmire, T. P. Kohman, H. Hintenberger, F. Naturforschg. 13a, 847 (1958).

21. E. A. Samworth, E. K. Warburton, G. A. P. Engelbertink, Phys. Rev. 5C 138 (1972).

22. T. L. Norris, A. J. Gancarz, D. J. Rokop and K. W. Thomas, J. Geophys. Res. 88 (supplement) B333 (1983).

23. J. H. Thomas, R. L. Row, R. T. Skelton and R. W. Kavanagh Phy. Rev C30 385 (1984).

24. R. W. Stoenner, O. A. Schaeffer, S. Katcoff, Sci. 148, 1325 (1965).

25. R. Kishore, R. Colle, S. Katcoff, J. B. Cumming, Phys. Rev. 12C, 21 (1975).

26. H. Zeldes, B. H. Ketelle, A. R. Brosi, C. R. Fultz, R. F. Hibbs, Phys. Rev. 86, 811 (1952).

27. E. Gleditsch, T. Graf, Phys. Rev. 72, 640 (1947).

28. L. H. Ahrens, R. D. Evans, Phys. Rev. 74, 279 (1948).

29. T. Graf, Phys. Rev. 74, 831 (1948).

30. R. W. Stout, Phys. Rev. 75, 1107 (1949).

31 J. J. Floyd, L. B. Borst. Phys. Rev. 75, 1106 (1949).

32. G. A. Sawyer, M. L. Wiedenbeck, Phys. Rev. 76, 1535 (1940).

33. T. Graf, Rev. Sci. Inst. 21, 285 (1950).

34. F. W. Spiers, Nat. 165, 356 (1950).

35. W. R. Faust, Phys. Rev., 78, 624 (1950).

36. G. A. Sawyer, M. L. Wiedenbeck, Phys. Rev., 79, 490 (1950).

37. F. G. Houtermans, O. Haxel, J. Heintze, Z. Physik 128, 657 (1950).

38. B. Smaller, J. May, M. Freedman, Phys. Rev. 79, 940 (1950).

39. C. F. G. Delaney, Phys. Rev. 81, 158 (1951).

40. M. L. Good, Phys. Rev. 81, 891 (1951).

41. P. R. J. Burch, Nat. 172, 361 (1953).

42. A. D. Suttle, W. F. Libby, Anal. Chem. 27, 921 (1955).

43. A. McNair, R. N. Grover, H. W. Wilson, Phil. Mag. 1, 199 (1956).

44. G. Backenstoss, K. Goebel Z. Naturforschg. 10a, 920 (1955).

45. G. W. Wetherill, G. J. Wasserberg, L. T. Aldrich, G. R. Tilton, R. J. Hayden, Phys. Rev. 103, 987 (1956).

46. W. H. Kelly, G. G. Beard, R. A. Peters, Nucl. Phys. 11, 492 (1959).

47. L. E. Glendenin, Ann. N.Y. Acad. Sci. 91, 166 (1961).

48. D. G. Fleishman, V. V. Glazunov. Sov. At. Eng. 12, 338 (1962).

49. G. A. Brinkman, A. H. W. Aten, Jr., J. Th. Veenboer, Physica 31, 1305 (1965).

50. H. Leutz, G. Schulz, H. Wenninger, Z. Phys. 187, 151 (1965).

51. G. W. Wetherill, Sci. 126, 545 (1957).

52. S. Kono, J. Phys. Soc. Japan 10, 495 (1955).

53. I. Feuerhake, A. Hinzpeter, Naturwissenshaften 53,272 (1966).

54. A. W. DeRuytter, A. H. W. Aten, Jr., A. Van Dulmen, C. Krol-Konig, E. Zuidema, Physica 32, 991 (1966).

55. K. Egelkraut, H. Leutz, Physik Verhandl. 11, 67 (1960).

56. N. K. Saha, J. B. Gupta, Proc. Natl. Inst. Sci. India 26 No. 5 (1960).

57. P. Venkataramaiah, H. Sanjeevaiah, B. Sanjeevaiah, Ind. J. Pure, Appl Phys., 9, 133 (1971).

58. K. Gopal, H. Sanjeevaiah, B. Sanjeevaiah, Am. J. Phys., 40, 721 (1972).

59. A. Cesana, M. Terrani, Anal. Chem. 49, 1156 (1977).

60. E. R. Bauminger, S. G. Cohen, Phys. Rev. 110, 953 (1958).

61. A. McNair, Phil. Mag 6 559 (1961).

62. D. E. Watt, R. L. G. Keith, Nucl. Phys. 29, 648 (1962).

63. C. Sonntag, K. O. Mucnnich, Z. Phys. 197 300 (1966).

64. A. Pape, S. M. Rafaei, J. C. Sens, Phys. Rev. C15, 1937 (1977).

65. D. E. Alburger, E. K. Warburton, J. B. Cumming Phy. Rev. C29, 2294 (1984).

66. J. J. Simpson, P. Jagarn, A. A. Pilt. Phys. Rev. C31, 575 (1985).

67. J. H. Kaye, P. J. Cressy, J. Inorg. Nucl. Chem. 27,1889 (1965).

68. J. J. Hohlfelder, Phys. Rev. 106, 1126 (1969).

69. H. Matsuda, S. Umemoto, M. Hondo, Radiochem Acta 15, 51, (1971).

70. M. Hondo, M. Imamuro, Phys. Rev. 4C, 1182 (1971).

71. R. Wolfle, W. Herr, U. Herpers, Radiochimica Acta 18, 207 (1972).

72. M. Heimann, P. P. Parekh, W. Herr, Geochim. Cosmochim Acta 38, 217 (1974).

73. F. Leccia et. al., Nuovo Cim. 78A, 50 (1983).

74. E. Bellotti et. al., Phys. Lett. 121B, 72 (1983).

75. F. T. Avignone III et. al., Phys. Rev. Lett. 50, 721 (1983).

76. A. Forster et. al., Phys. Lett. 138B, 301 (1984).

77. J. J. Simpson et. al., Phys. Rev. Lett. 53, 141 (1984).

78. F. S. Goulding et. al., IEEE Trans. Nucl. Sci. 32, 463 (1985).

79. I. Geese-Bahnisch, E. Huster, Naturwiss 21, 495 (1954); I. Geese-Bahnisch, Z Physik, 142, 565 (1955).

80. K. Fritze, F. Strassmann, Z. Naturforschg 11a, 277 (1956).

81. L. T. Aldrich, G. W. Wetherill, G. R. Tilton, C. L. Davis, Phys. Rev., 103, 1045 (1956).

82. W. F. Libby, Anal. Chem. 29, 1566, (1957).

83. K. F. Flynn, L. E. Glendenin, Phys. Rev., 116, 744 (1959)

84. G. V. Ovchinnikova, Geochemia, 5, 392 (1959).

85. A. McNair, H. W. Wilson, Phil. Mag. 6, 563 (1961).

86. K. Egelkraut, H. Leutz, Z. Physik, 161, 13, (1961).

87. H. Leutz, H. Wenninger, K. Ziegler, Z. Physik, 169, 409 (1962).

88. C. C. McMullen, K. Fritze, R. H. Tomlinson, Can. J. Phys., 44, 3033 (1960).

89. W. Neumann, E. Huster, Z. Physik 270, 121 (1974).

90. D. W. Davis, J. Gray, G. L. Cumming, H. Baadsgaard, Geochim. Cosmochim Acta 41 1745 (1977).

91. E. Akatsu, Radioisotopes 30 647 (1981).

92. K. E. Apt, J. D. Knight, D. C. Camp, R. W. Perkins, Geochim. Cosmochim. Acta 38, 1485 (1974).

93. T. Makino, M. Hondo, Geochim. Cosmochim. Acta 41, 1521 (1977).

94. D. R. Nethaway, A. L. Prindle, R. A. Van Konynenberg, Phys. Rev. 17C, 1409 (1978).

95. D. R. Nethaway, J. Inorg. Nucl. Chem 40, 1285 (1978).

96. K. F. Flynn, L. E. Glendenin, Phys. Rev. 185, 1591 (1969).

97. E. A. Martell, W. F. Libby. Phys. Rev. 80, 977 (1950).

98. M. I Kalkstein, Thesis, Univ Chicago (1952).

99. H. Selig, U. S. AEC document NYO-6626 (1954) Thesis, Carnegie Inst. Techn. (1955).

100. D. E. Watt, R. N. Glover, Phil. Mag. 7, 105 (1962).

101. W. E. Greth, S. Gangadharan, R. L. Wolke, J. Inorg. Nucl. Chem. 32, 2113 (1970).

102. S. G. Cohen, Nat. 167,779 (1951).

103. G. B. Beard, W. H. Kelly, Phys. Rev. 122, 1576 (1961).

104. L. Pfeiffer, A. P. Mills Jr, E. A. Chandross, T. Kovacs, Phys. Rev. 19C, 1035 (1979).

105. J. Heintze, Z. Naturforschg, 10a, 77 (1955).

106. F. Johnson, Sci. 149, 1326 (1965).

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