^{228}Th – Comments on evaluation of decay data by A. L. Nichols

Evaluated: July/August 2001
Re-evaluated: January 2004 and April 2010

Evaluation Procedures

Limitation of Relative Statistical Weight Method (LWM) was applied to average numbers throughout the evaluation. The uncertainty assigned to the average value was always greater than or equal to the smallest uncertainty of the values used to calculate the average.

Decay Scheme

^{228}Th ($T_{½}$ = 698.6 days) decays 100 % by alpha-particle emission (Q(α) = 5520.08 (22) keV) to various excited levels and the ground state of ^{224}Ra ($T_{½}$ = 3.631 days). A reasonably well-defined decay scheme was derived from the alpha-particle studies of 1969Pe17, 1970Ba20, 1976BaZZ and 1993Ba72, and the gamma-ray measurements of 1977Ku15 and 1984Ge07. An additional gamma transition was added to the proposed decay scheme from equivalent studies of ^{224}Fr decay by 1981Ku02: 908.28-keV gamma ray depopulating the 992.65-keV nuclear level of ^{224}Ra. Weighted mean relative emission probabilities were calculated for the 131.612-, 166.410-, 205.99- and 215.985-keV gamma rays, while equivalent data for the other gamma transitions were adopted from the measurements of 1977Ku15; all of these relative emission probabilities were defined in terms of the 84.373-keV gamma ray (100 %).

^{20}O cluster decay has been observed by 1993Bo20 to be 1.13 (22) E-13. Subsequent reviews by 1995Ar33 and 1997Tr17 list a cluster-decay branching fraction of 1.13 (22) E-13 and 1.1 (2) E-13, respectively, based primarily on the earlier measurement.

Nuclear Data

The ^{228}Th decay chain is important in quantifying the environmental impact of the decay of naturally-occurring ^{232}Th. Certain radionuclides in this decay chain are noteworthy because of their decay characteristics: ^{224}Ra alpha decay to ^{220}Rn; ^{212}Bi and ^{208}Tl gamma-ray emissions. ^{208}Tl in particular emits high-energy gamma rays that represent a well-defined spectroscopic signature for this decay chain.

Half-life

The measurements of 1956Ki16, 1962Ma57, 1971Jo14 and 2002Un02 were adopted to give a least-squares weighted mean half-life of 698.55 (32) days. ^{228}Th half-life quoted in 2002Un02 is also listed within 1992Un01. Woods has recommended a half-life of 698.60 (23) days (2007BeZP), but without due consideration of the calculated uncertainty with respect to the measured values, see relevant footnotes.

Reference	Half-life (d)*
1918Me01	695.8 [1.905 y]†
1956Ki16	697.6 (7) [1.910 (2) y]
1962Ma57	696.9 (15) [1.908 (4) y]
1962Ma57	703 (7) [1.924 (20) y]‡
1971Jo14	698.77 (32)
2002Un02	698.60 (36)
Recommended value	698.55 (32)§

* Conversion factor: 1 tropical year ≡ 365.2422 days.
† Uncertainty not specified – not included in weighted mean analysis of the data set.
‡ Defined as an outlier.
§ Recommended uncertainty adjusted from ± 0.22 to ± 0.32, in alignment with the smallest uncertainty of the values used to calculate the average value.

Alpha Particles

Energies

All alpha-particle energies were derived from the structural details of the proposed decay scheme. While the energies of the main alpha-particle emissions have been directly measured by 1953As31, 1970Ba20, 1971Gr07, 1976BaZZ and 1991Ry01, the nuclear level energies of 1997Ar05 and evaluated Q-value of 5520.08 (22) keV (2003Au03) were used to determine the recommended energies and uncertainties of the alpha-particle emissions, while allowing for the significant recoil components.

Adopted nuclear levels of ^{224}Ra: J^{π} and origins (1997Ar05).

Nuclear level	Nuclear level energy (keV)	J^{π}	Origins
0	0.0	0 +	^{224}Fr β^- decay, ^{224}Ac EC decay, **^{228}Th α decay**, $^{226}Ra(p,t)$, $^{226}Ra(\alpha,\alpha'2n\gamma)$, $^{226}Ra(^{58}Ni,^{60}Ni)$
1	84.373 ± 0.003	2 +	^{224}Fr β^- decay, ^{224}Ac EC decay, **^{228}Th α decay**, $^{226}Ra(p,t)$, $^{226}Ra(\alpha,\alpha'2n\gamma)$, $^{226}Ra(^{58}Ni,^{60}Ni)$
2	215.985 ± 0.004	1 –	^{224}Fr β^- decay, ^{224}Ac EC decay, **^{228}Th α decay**, $^{226}Ra(p,t)$, $^{226}Ra(\alpha,\alpha'2n\gamma)$, $^{226}Ra(^{58}Ni,^{60}Ni)$
3	250.783 ± 0.005	4 +	^{224}Fr β^- decay, ^{224}Ac EC decay, **^{228}Th α decay**, $^{226}Ra(\alpha,\alpha'2n\gamma)$, $^{226}Ra(^{58}Ni,^{60}Ni)$
4	290.36 ± 0.04	(3) –	^{224}Fr β^- decay, ^{224}Ac EC decay, **^{228}Th α decay**, $^{226}Ra(\alpha,\alpha'2n\gamma)$, $^{226}Ra(^{58}Ni,^{60}Ni)$
5	433.07 ± 0.10	(5) –	^{224}Fr β^- decay, **^{228}Th α decay**, $^{226}Ra(\alpha,\alpha'2n\gamma)$, $^{226}Ra(^{58}Ni,^{60}Ni)$
6	479.20 ± 0.18	(6 +)	**^{228}Th α decay**, $^{226}Ra(p,t)$, $^{226}Ra(\alpha,\alpha'2n\gamma)$, $^{226}Ra(^{58}Ni,^{60}Ni)$
7	916.34 ± 0.07	0 +	^{224}Fr β^- decay, **^{228}Th α decay**, $^{226}Ra(p,t)$
8	992.65 ± 0.06	(2 +)	^{224}Fr β^- decay, **^{228}Th α decay**

Measured and recommended energies of the main alpha-particle emissions of ^{228}Th.

	E_α (keV)					
	1953As31	1970Ba20	1971Gr07	1976BaZZ	1991Ry01	Recommended value*
$\alpha_{0,8}$	–	–	–	–	–	4448.00 (23)
$\alpha_{0,7}$	–	–	–	–	–	4522.97 (23)
$\alpha_{0,6}$	–	–	–	–	–	4952.5 (3)
$\alpha_{0,5}$	–	–	–	–	–	4997.76 (24)
$\alpha_{0,4}$	–	5136.1	–	–	–	5137.97 (22)
$\alpha_{0,3}$	5173	5171.5	–	–	–	5176.86 (22)
$\alpha_{0,2}$	5208	5208.9	–	–	–	5211.05 (22)
$\alpha_{0,1}$	5388.5 (10)	5338.6	5340.54 (15)	5339.2 (10)	5340.36 (15)	5340.35 (22)
$\alpha_{0,0}$	5421 (1)	5420.0	5423.33 (22)	5420.6 (10)	5423.15 (22)	5423.24 (22)

* Determined from the nuclear level energies of 1997Ar05 and evaluated Q-value of 5520.08 (22) keV (2003Au03).

Emission Probabilities

An alpha-particle emission probability of 73.4 (5) % was derived for alpha decay directly to the ground state of ^{224}Ra, based on the various alpha-particle studies. This value and the gamma-ray data were used in conjunction with the theoretical internal conversion coefficients to determine a normalisation factor of 0.0119 (3) per 100 disintegrations for the relative emission probabilities of the gamma rays (see below).

Published alpha-particle emission probabilities per 100 disintegrations of ^{228}Th.

E_α(keV)	P_α				
	1953As31	1969Pe17	1970Ba20	1976BaZZ	1993Ba72
4448.00 (23)	-	-	-	-	-
4522.97 (23)	-	-	-	-	-
4952.5 (3)	-	-	-	-	-
4997.76 (24)	-	-	-	-	-
5137.97 (22)	-	-	~ 0.05	-	-
5176.86 (22)	0.2	-	0.18	-	-
5211.05 (22)	0.4	-	0.36	-	-
5340.35 (22)	28	26.7 (2)	26.7	26.6 (5)	26.0 (8)
5423.24 (22)	71	[73.3 (2)]	72.7	72.4 (10)	74.0 (6)

Alpha-particle emission probability data of 1969Pe17 are effectively normalised to 73.3 (2) % and 26.7 (2) %.

1976BaZZ measurements require re-normalisation to (100 – 0.36 – 0.18 – 0.05) = 99.41 %
(72.4 + 26.6) N = 99.41
N = 1.00414 to give P_α(5423.24 keV) of 72.7 %, and uncertainty of ± 1.0;
and P_α(5340.35 keV) of 26.7 %, and uncertainty of ± 0.5.

1993Ba72 studies also require re-normalisation to give P_α(5423.24 keV) of 73.6 % and uncertainty of ± 0.6; and P_α(5340.35 keV) of 25.8 %, and uncertainty of ± 0.8.

A weighted mean value of 73.4 (5) % (0.734 (5)) was determined for P_α(5423.24 keV) from the data of 1976BaZZ and 1993Ba72, which has been matched against a value of 26.0 (5) % (0.260 (5)) for P_α(5340.35 keV).

The absolute emission probabilities of the majority of the other alpha particles were calculated from population-depopulation of the nuclear level of ^{224}Ra and the gamma-ray normalisation factor. Although a consistent decay scheme was derived, further detailed alpha-particle measurements are required to develop and support the overall correctness of the proposed decay scheme. A hindrance factor (HF) of 1.000 for the 5423.24-keV alpha-particle emission yields r_0(^{224}Ra) of 1.5339 (3) fm, whereas the recommended value is 1.5332 (8) fm (1998Ak04).

Adjusted alpha-particle emission probabilities per 100 disintegrations of ^{228}Th, and hindrance factors.

E_α(keV)	P_α						HF
	1953As31	1969Pe17	1970Ba20	1976BaZZ	1993Ba72	Recommended value*	
4448.00 (23)	-	-	-	-	-	4.5 (7) x 10^{-6}	7.2
4522.97 (23)	-	-	-	-	-	1.7 (3) x 10^{-5}	7.0
4952.5 (3)	-	-	-	-	-	2.4 (5) x 10^{-5}	4600
4997.76 (24)	-	-	-	-	-	1.0 (2) x 10^{-5}	21400
5137.97 (22)	-	-	~ 0.05	-	-	0.036 (6)	44
5176.86 (22)	0.2	-	0.18	-	-	0.218 (4)	12.5
5211.05 (22)	0.4	-	0.36	-	-	0.408 (7)	10.7
5340.35 (22)	28	26.7 (2)	26.7	26.7 (5)	25.8 (8)	26.0 (5)	0.958
5423.24 (22)	71	[73.3 (2)]	72.7	72.7 (10)	73.6 (6)	73.4 (5)‡	1.000
						Σ100.1 (7)	

* Recommended emission probabilities of the low-intensity α transitions were derived from the evaluated gamma-ray emission probabilities and theoretical internal conversion coefficients.

‡ P_α(5423.24 keV) of 73.4 (5) % is effectively the weighted mean of the re-normalised studies (1976BaZZ, 1993Ba72), which has been subsequently matched with P_α(5340.35 keV) of 26.0 (5) %.

Gamma Rays

Energies

Although energies of the gamma-ray emissions have been measured by 1968Da21 and 1997Ku15 in particular, the well-defined nuclear level energies of 1997Aro5 were used to determine the recommended energies and associated uncertainties of the gamma-ray emissions between the various populated-depopulated levels because of their more extensive origins.

Measured and recommended gamma-ray energies.

E_γ (keV) 1968Da21	1977Ku15	1977Ku25	Recommended value*
-	74.4 (1)‡	-	74.38 (4)
-	84.371 (3)†	84.371 (3)	84.373 (3)
131.6 (8)	131.610 (4)†	131.610 (4)	131.612 (5)
-	142.0 (5)‡	-	142.71 (11)
166.5 (8)	166.407 (4)†	166.407 (4)	166.410 (6)
-	182.2 (2)‡	-	182.29 (10)
-	205.93 (5)	-	205.99 (4)
216.1 (6)	215.979 (5)†	215.979 (5)	215.985 (4)
-	228.5 (2)	-	228.42 (18)
-	700.5 (5)‡	-	700.36 (7)
-	742.2 (5)	-	741.87 (6)
-	832.0 (2)	-	831.97 (7)
-	-	-	908.28 (6)
-	992.9 (10)	-	992.65 (6)

† Identical value and uncertainty also reported by 1977Ku25.
‡ Data derived from coincidence measurements.
* Determined from the nuclear level energies of 1997Ar05.

Emission Probabilities

Gamma-ray emission probabilities have been partially or fully determined in the measurements of 1977Ku15, 1982Sa36 and 1984Ge07. However, the data derived by 1982Sa36 are significantly lower by 20 % to 30 % compared with the equivalent values measured by 1977Ku15 and 1984Ge07, and therefore they were set aside from in the weighted mean analysis. Weighted mean relative emission probabilities were calculated for the 131.612-, 166.410-, 205.99- and 215.985-keV gamma rays, while equivalent data for the other gamma emissions were directly adopted from the measurements of 1977Ku15. An additional gamma transition was added to the proposed decay scheme from the equivalent studies of ^{224}Fr decay by 1981Ku02 as a 908.28-keV gamma ray depopulating the 992.65-keV nuclear level of ^{224}Ra - this gamma transition may have been observed in the α decay of ^{228}Th by 1977Ku15, but was adjudged by them to be background radiation (within the 911.2-keV peak). All of these relative emission probabilities were defined in terms of the emission probability of the 84.373-keV gamma ray (100.0 %).

Published gamma-ray emission probabilities.

E_γ (keV)	P_γ 1969Pe17*	1977Ku15†	1982Sa36‡	1984Ge07§
74.38 (4)	-	4.0 (14)	-	-
84.373 (3)	1.21(6)	12100 (600)	1.9 (1)	100.0 (16)
131.612 (5)	-	1240 (60)	0.17 (2)	10.70 (15)
142.71 (11)	-	0.013 (4)	-	-
166.410 (6)	-	960 (50)	0.13 (1)	8.49 (12)
182.29 (10)	-	0.052 (18)	-	-
205.99 (4)	-	184 (9)	-	-
215.985 (4)	-	2390 (130)	0.30 (2)	1.61 (5)
228.42 (18)	-	0.18(3)	-	20.78 (25)
700.36 (7)	-	~ 0.03	-	-
741.87 (6)	-	0.014 (4)	-	-
831.97 (7)	-	0.14 (2)	-	-
908.28 (6)	-	-	-	-
992.65 (6)	-	~ 0.015	-	-

* Emission probability expressed in terms of photons per 100 disintegrations.
† Emission probabilities expressed in terms of photons per 10^6 disintegrations.
‡ Emission probabilities published relative to Pγ(238.63 keV) for ^{212}Pb of 43.0 %.
§ Emission probabilities published relative to Pγ(84.373 keV) of 100.0 %.

Measured and recommended gamma-ray emission probabilities relative to Pγ(84.373 keV) of 100 %.

E_γ (keV)	P_γ^{rel}			
	1977Ku15	**1982Sa36**	**1984Ge07**	**Recommended value***
74.38 (4)	0.033 (12)	-	-	0.033 (12)
84.373 (3)	100 (5)	100 (5)	100.0 (16)	100.0 (16)
131.612 (5)	10.25 (50)	8.9 (10)†	10.70 (15)	10.7 (2)
142.71 (11)	0.000 11 (3)	-	-	0.000 11 (3)
166.410 (6)	7.9 (4)	6.8 (5)†	8.49 (12)	8.44 (12)
182.29 (10)	0.000 43 (15)	-	-	0.000 43 (15)
205.99 (4)	1.52 (7)	-	1.61 (5)	1.58 (4)
215.985 (4)	19.8 (11)	15.8 (11)†	20.78 (25)	20.7 (3)
228.42 (18)	0.001 5 (3)	-	-	0.001 5 (3)
700.36 (7)	~ 0.000 25	-	-	0.000 25 (8)
741.87 (6)	0.000 12 (3)	-	-	0.000 12 (3)
831.97 (7)	0.001 2 (2)	-	-	0.001 2 (2)
908.28 (6)	-	-	-	0.000 14 (4)
992.65 (6)	~ 0.000 12	-	-	0.000 12 (3)

* Weighted mean values adopted when judged appropriate.
† Significantly lower than equivalent data of 1977Ku15 and 1984Ge07 by 20 % to 30 %; judged to be an outlier, and therefore not considered in any weighted mean analysis.

Multipolarities and Internal Conversion Coefficients

The nuclear level scheme specified by Artna-Cohen has been used to define the multipolarities of the gamma transitions on the basis of known spins and polarities (1997Ar05). Limited studies of the internal conversion coefficients support the proposed transition types: E2 for both the 84.373- and 166.410-keV gamma rays (1953As31, 1966Co40, 1968Du06, 1969Pe17 and 1970SpZW).

Internal conversion coefficients as determined by measurement.

Reference	E_γ (keV)	α					Measurement technique
		α_L	α_{L2}	α_{L3}	α_{M+}	α_{total}	
1953As31	84.373 (3)	-	-	-	-	16	deduced from measured P_γ and P_α populating 84.37-keV nuclear level of ^{224}Ra
	166.410 (4)	-	-	-	-	1.2	deduced from measured P_γ and P_α populating 251-keV nuclear level of ^{224}Ra
1966Co40	84.373 (3)	14 (3)	7.6	6.3	3.8 (9)	18 (4)	P_{ce} measured by means of photographic emulsion technique
1968Du06	84.373 (3)	-	-	-	-	19.6 (14)	deduced from α-gated γ-ray spectra
1969Pe17	84.373 (3)	-	-	-	-	21.4 (9)	deduced from α-gated γ-ray spectra

Conversion electron spectra: Measurements of L- and M-subshell internal conversion ratios (1970SpZW).

E_γ (keV)	L_1/L_2	L_1/L_3	L_2/L_3	M_1/M_2	M_1/M_3	M_2/M_3
84.373 (3)	0.0388 (19)	0.0519 (21)	1.343 (10)	0.0471 (46)	0.0571 (57)	1.2187 (85)

The 908.28-keV gamma ray was identified as the only mixed multipolarity (M1 + E2), and was arbitrarily assigned a mixing ratio of 1.0 with an uncertainty of ± 0.2. Recommended internal conversion coefficients have been determined from the frozen orbital approximation of Kibédi *et al*. (2008Ki07), based on the theoretical model of Band *et al*. (2002Ba85, 2002Ra45). Uncertainties of ± 1.5 % were adopted for all of the E1 and E2 gamma transitions (with minor upward adjustments associated with the significant figures for α_L and α_{M+}).

Gamma-ray emissions: multipolarities and theoretical internal conversion coefficients (frozen orbital approximation).

E_γ (keV)	Multipolarity	α_K	α_L	α_{M+}	α_{total}
74.38 (4)	[E2]	–	28.3 (4)	10.3	38.6 (6)
84.373 (3)	E2	–	15.57 (22)	5.63	21.2 (3)
131.612 (5)	E1	0.194 (3)	0.0406 (6)	0.0124	0.247 (4)
142.71 (11)	[E2]	0.279 (4)	1.368 (20)	0.493	2.14 (3)
166.410 (6)	E2	0.225 (4)	0.691 (10)	0.248	1.164 (17)
182.29 (10)	[E1]	0.089 4 (13)	0.017 57 (25)	0.005 63	0.112 6 (16)
205.99 (4)	(E1)	0.067 1 (10)	0.012 92 (18)	0.004 08	0.084 1 (12)
215.985 (4)	E1	0.060 0 (9)	0.011 48 (16)	0.003 72	0.075 2 (11)
228.42 (18)	[E2]	0.124 4 (18)	0.178 (3)	0.063 6	0.366 (6)
700.36 (7)	E1	0.005 02 (7)	0.000 834 (12)	0.000 256	0.006 11 (9)
741.87 (6)	[E2]	0.011 96 (17)	0.003 22 (5)	0.001 07	0.016 25 (23)
831.97 (7)	E2	0.009 70 (14)	0.002 40 (4)	0.000 79	0.012 89 (18)
908.28 (6)	[50%M1 + 50%E2] δ = 1.0 (2)	0.019 0 (24)	0.003 6 (4)	0.001 4	0.024 (3)
992.65 (6)	[E2]	0.007 05 (10)	0.001 569 (22)	0.000 511	0.009 13 (13)

The normalisation factor was calculated for the gamma-ray emission probabilities by averaging the values determined by three different routes:

(i) direct population of the ^{224}Ra ground state

$[\Sigma P_{\gamma i} (1 + \alpha_i)$ to ground state$]$ NF + 0.734 (5) = 1.00
NF = 0.000 119 (3)

(ii) population/depopulation of the 84.373-keV nuclear level of ^{224}Ra

$[P_\gamma(84.373$ keV$)(1 + \alpha(84.373$ keV$))$ - $\Sigma P_{\gamma i} (1 + \alpha_i)$ to 84.373-keV level$]$ NF = 0.260 (5)
NF = 0.000 119 (3)

(iii) all α emissions

ΣP_α NF = 1.00, and adopting α-particle emission probability to ^{224}Ra ground state of 0.734 (5) (see section on alpha-particle emissions)
NF = 0.000 119 (3)

Thus, a normalization factor of 0.000 119 (3) has been adopted in the determination of the absolute gamma-ray emission probabilities.

Atomic Data

The x-ray and Auger-electron data have been calculated using the evaluated gamma-ray data, and atomic data from 1996Sc06, 1998ScZM and 1999ScZX. Both the x-ray and Auger-electron emission probabilities were determined by means of the EMISSION computer program (version 4.01, 28 January 2003). This program incorporates atomic data from 1996Sc06 and the evaluated gamma-ray data.

K and L X-ray emission probabilities per 100 disintegrations of ^{228}Th.

			Energy (keV)	Photons per 100 disint.
XL		(Ra)	10.622 – 18.412	8.6 (4)
	XL_l	(Ra)	10.622	0.166 (6)
	XL_α	(Ra)	12.196 – 12.339	2.86 (9)
	XL_η	(Ra)	13.662	0.109 (4)
	XL_β	(Ra)	14.236 – 15.447	4.67 (15)
	XL_γ	(Ra)	17.848 – 18.412	1.09 (4)
XK_α	$XK_{\alpha2}$	(Ra)	85.43	0.018 0 (3)
	$XK_{\alpha1}$	(Ra)	88.47	0.029 5 (5)
$XK'_{\beta1}$	$XK_{\beta3}$	(Ra)	99.432	}
	$XK_{\beta1}$	(Ra)	100.13	} 0.010 34 (21)
	$XK_{\beta5}''$	(Ra)	100.738	}
$XK'_{\beta2}$	$XK_{\beta2}$	(Ra)	102.89	}
	$XK_{\beta4}$	(Ra)	103.295	} 0.003 39 (9)
	$XKO_{2,3}$	(Ra)	103.74	}

Electron energies were determined from electron binding energies tabulated by Larkins (1977La19) and the evaluated gamma-ray energies. Absolute electron emission probabilities were calculated from the evaluated absolute gamma-ray emission probabilities and associated internal conversion coefficients.

Data Consistency

A Q_α-value of 5520.08 (22) keV has been adopted from the atomic mass evaluation of Audi *et al.* (2003Au03) while in the course of formulating the decay scheme of ^{228}Th. This value has subsequently been compared with the Q-value calculated by summing the contributions of the individual emissions to the ^{228}Th alpha-decay process (i.e. α, electron, γ, etc.):

$$\text{calculated Q-value} \quad = \quad \sum (E_i \times P_i) \quad = \quad 5523\ (40)\ \text{keV}$$

Percentage deviation from the Q-value of Audi *et al.* is − (0.1 ± 0.7) %, which supports the derivation of a highly consistent decay scheme with a significant variant.

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