^{232}U - Comments on Evaluation of Decay Data
by Andy Pearce

Introduction

This evaluation was completed in August 2008 drawing in part on the mass-chain evaluation of Artna-Cohen[1]. Some references not in the NSR database were identified by cross-referencing with the evaluation of Nichols[2]. The literature available up until January 2008 was included.

1 Decay Scheme

The decay scheme (nuclear level energies, half lives and spins of ^{228}Th) are based upon the adopted levels and gammas from Artna-Cohen[1].

2 Nuclear Data

Uranium-232 decays primarily by alpha decay to excited states in ^{228}Th. A small branching of exotic decay via ^{24}Ne emission and a smaller branching of spontaneous fission have been reported[3-5]. The Q-value for alpha decay is taken from Audi, Wapstra and Thibault[6-7]. The alpha decay branching is reported as essentially 100 %.

Seven published values of the half life were found in literature from which three independent values with uncertainties were used for analysis. The value of 1964Ch05[8] determined by calorimetry has been adjusted taking into account the Q-values of Audi, Wapstra and Thibault[6-7]. The authors of 1979Ag04[9] measured the half life by two methods and both are stated here, although an arithmetic mean of the two has been used in analysis. Similarly the authors of 1964Ch05[8] performed measurements by two methods and an arithmetic mean is taken for subsequent analysis. Sufficient experimental details were published in 1964Ch05 to allow the values to be recalculated using, for example, current values of Q, however doing so has no significant effect on the data. The adopted value has been determined by a LRSW weighted mean of the values from 1954Se26[10], 1964Ch05[8] and 1979Ag04[9]. Overall the data are not consistent, however no valid reason could be found to exclude or prefer any of the three values. The discrepancies probably reflect the difficulties in measuring half lives of the order of several decades, and the uncertainty of the adopted value is large. The available data are presented in table 1.

There have been several publications on the spontaneous fission/cluster decay of ^{232}U[3-5] suggesting that ^{24}Ne cluster decay has been misidentified in earlier work as spontaneous fission. This leads to significantly lower values for branching to spontaneous fission than in previous evaluations. The value quoted here for spontaneous fission is that from 1990Bo16[4] and that for cluster decay is a weighted mean of the values from 1985Ba18[3] and 1990Bo16[4]. The earlier data from Jaffey and Hirsh[10] has not been published in open literature. Analysis of their data in the light of recent work would appear to confirm the cluster decay branching ratio at approximately 2×10^{-10} per 100 decays. The available data are presented in table 2.

Table 1. Measured half lives of alpha decay of ^{232}U. The reports 1949Go01 and 1949Ja01 were not used in analysis as they were presented without uncertainties.

Reference	Value (years)	Uncertainty (years)	Method
1949Go01[11]	30	-	Ingrowth from ^{232}Pa
1949Ja01[12]	70.5	-	Ingrowth from ^{236}Pu
1954Se26	73.6	1	Isotope dilution mass spec and proportional counting
1964Ch05 [A]	72.1	0.5	Calorimetry
1964Ch05 [B]	71.4	0.6	Alpha counting
1964Ch05 [mean]	71.75	0.30	1 σ uncertainty increased to 0.36
1979Ag04 [A]	69.0	0.4	Isotope dilution mass spec and LS/proportional counting
1979Ag04 [B]	68.81	0.38	Relative activity vs. ^{233}U
1979Ag04 [mean]	68.90	0.39	-
1986Ag01	68.90	0.39	Relative activity vs. ^{233}U; same data as half of 1979Ag01, republished
LRSW	70.6	11	$\chi^2/\nu = 19$, ext. unc = 1.1
Adopted	**70.6**	**11**	**LWM/expanded**

Table 2. Branching ratios for cluster decay and spontaneous fission, calculated where necessary from the partial decay constants using the recommended half life. The cluster decay value of Jaffey and Hirsh has been calculated by doubling the spontaneous fission value (in cluster decay one fragment will be detected compared with two in spontaneous fission).

Reference	Spontaneous Fission (%)	Cluster Decay (^{24}Ne) (%)
2000Bo46	$2.8\ (6) \times 10^{-12}$	-
1990Bo16	$< 10^{-12}$	$8.7\ (8) \times 10^{-10}$
1985Ba18	-	$2.0\ (5) \times 10^{-10}$
Jaffey & Hirsh (unpublished)	$9\ (3) \times 10^{-11}$	$1.8\ (12) \times 10^{-10}$
Adopted	$\mathbf{2.8\ (6) \times 10^{-12}}$	$\mathbf{5\ (3) \times 10^{-10}}$

2.1 Alpha-particleTransitions

The energies of the alpha-particle transitions have been determined from the Q-value and the adopted levels from Artna-Cohen[1]. Alpha-particle hindrance factors were calculated using ALPHAD[13]. The values so obtained are presented in table 3.

Table 3. Adopted level and alpha-particle transition energies

Transition	Level Energy (keV)	Transition Energy (keV)	Alpha-particle Emission Energy (keV)	HF
α_0	0	5413.63 (9)	5320.24 (9)	1
α_{58}	57.759 (4)	5355.87 (9)	5263.48 (9)	1.04 (3)
α_{187}	186.823 (4)	5226.81 (9)	5136.64 (9)	16.4 (4)
α_{328}	328.003 (4)	5085.63 (9)	4997.90 (9)	112.0 (24)
α_{378}	378.179 (10)	5035.45 (9)	4948.59 (9)	6490 (80)
α_{396}	396.078 (5)	5017.55 (9)	4931.00 (9)	5270 (50)
α_{519}	519.192 (6)	4894.44 (9)	4810.01 (9)	710 (50)
α_{831}	831.823 (10)	4581.81 (9)	4502.77 (9)	10.6 (8)
α_{874}	874.473 (18)	4539.16 (9)	4460.86 (9)	33 (9)

2.2 Gamma-ray Transitions and Internal Conversion Coefficients

Gamma-ray transition energies (Table 5) are calculated from the differences in level energies from Artna-Cohen[1]. Transition energies calculated from the level scheme are compared with those derived from measured values in table 6. No precise measurements have been reported for the energy of the 831 keV E0 transition.

Table 5. Recommended gamma-ray emission energies, rescaled to be compatible with the values of 1971He23. Values from 1971He23 have been recalculated based on improved calibration standards from 2000He14. The uncertainties of the recalculated values have been increased to be not less than those in the original publication.

Nominal energy (keV)	57	129	141	191	209	270	328
1971He23	57.78 (6)	129.1 (1)	-	-	-	270.2 (5)	-
1973Ta25	57.78 (6)	-	-	-	-	-	-
1977Ku15	57.77 (6)	129.07 (6)	-	-	-	270.2 (2)	-
1979Bo30	-	129.070 (16)	-	-	209.238 (21)	270.235 (21)	328.004 (11)
1979He10	57.752 (13)	129.065 (3)	-	-	-	270.245 (7)	-
1987Da28	57.758 (7)	129.067 (7)	141.02 (3)	191.353 (11)	209.254 (7)	270.245 (8)	328.004 (7)
1995Ba42	57.75 (2)	129.05 (2)	140.99 (2)	191.34 (2)	209.25 (2)	270.24 (2)	328.02 (4)
LWEIGHT4	57.757 (6)	129.0655 (27)	140.999 (17)	191.351 (9)	209.252 (6)	270.2441 (13)	328.004 (6)
Adopted	57.752 (13)	129.065 (3)	140.999 (20)	191.351 (11)	209.252 (6)	270.245 (7)	328.004 (7)
Comments	From 1979He10	From 1979He10	LWEIGHT, uncert inc.	LWEIGHT, uncert inc.	LWEIGHT	From 1979He10	LWEIGHT

Table 5 (Cont.)

Nominal energy (keV)	332	338	478	503	546	773	817
1971He23	-	338.3 (4)	-	-	-	-	-
1973Ta25	-	-	-	-	-	-	-
1977Ku15	332.3 (3)	338.1 (2)	-	503.6 (3)	-	773.4 (5)	817 (1)
1979Bo30	-	338.321(10)	-	-	-	-	-
1979He10	332.371 (6)	338.320 (5)	-	503.819(23)	-	-	-
1987Da28	332.37 (5)	338.324 (7)	478.34 (5)	503.83 (5)	546.48 (5)	774.1 (2)	816.7 (1)
1995Ba42	332.36 (2)	338.31 (2)	478.45 (4)	503.69 (20)	546.45 (2)	774.06 (10)	816.49 (12)
LWEIGHT4	332.370 (6)	338.3209 (37)	478.41 (5)	503.818 (21)	546.454 (19)	774.05 (9)	816.62 (7)
Adopted	332.371 (6)	338.320 (5)	478.41 (5)	503.819 (23)	546.454 (21)	774.05 (9)	816.62 (7)
Comments	From 1979He10	From 1979He10	LWEIGHT	From 1979He10	LWEIGHT, uncert. inc.	LWEIGHT, uncert inc.	LWEIGHT, uncert inc.

Table 6. Recommended gamma-ray transition energies and internal conversion coefficients. Measured transition energies are those obtained from gamma-ray emission energies via the recoil correction, whereas derived transition energies are those determined from the level scheme.

Measured Energy (keV)	Transition Energy (keV)		Multi-polarity from ENSDF	Conversion Coefficients			
	Measured	Derived		α_K	α_L	α_{M+}	α_T
57.752 (13)	57.752 (13)	57.759 (4)	E2	-	112.2 (16)	41.1 (5)	153.2 (22)
129.065 (3)	129.065 (3)	129.064 (6)	E2	0.264 (4)	2.54 (4)	0.933 (41)	3.74 (6)
140.999 (20)	140.999 (20)	141.013 (12)	E1	0.1689 (24)	0.0362 (5)	0.01169 (14)	0.217 (3)
191.351 (11)	191.350 (11)	191.356 (11)	E2	0.1710 (24)	0.443 (7)	0.162 (7)	0.776 (11)
209.252 (6)	209.252 (6)	209.255 (7)	E1	0.0672 (10)	0.01333 (19)	0.00429 (5)	0.0848 (12)
270.245 (7)	270.245 (7)	270.244 (6)	E1	0.0376 (6)	0.00716 (10)	0.002297 (25)	0.0470 (7)
328.004 (7)	328.005 (7)	328.003 (4)	E1	0.0245 (4)	0.00455 (7)	0.001458 (16)	0.0305 (5)
332.371 (6)	332.372 (6)	332.369 (7)	E1	0.0238 (4)	0.00441 (7)	0.001414 (16)	0.0297 (5)
338.320 (5)	338.321 (5)	338.319 (7)	E1	0.0229 (4)	0.00424 (6)	0.001358 (16)	0.0285 (4)
478.41 (5)	478.41 (5)	478.395 (18)	E1	0.01118 (16)	0.0198 (3)	0.000631 (7)	0.01379 (20)
503.819 (23)	503.820 (23)	503.820 (11)	E1	0.01009 (15)	0.001775 (25)	0.000565 (6)	0.01243 (18)
546.454 (21)	546.455 (21)	546.470 (18)	E1	0.00861 (12)	0.001500 (21)	0.000478 (5)	0.01058 (15)
774.05 (9)	774.05 (9)	774.064 (11)	E2	0.01204 (17)	0.00333 (5)	0.001199 (13)	0.01649 (23)
816.62 (7)	816.62 (7)	816.714 (18)	M1+E2 (δ=1)	0.028 (18)	0.006 (3)	0.0019 (7)	0.036 (21)
-	-	831.823 (10)	E0	-	-	-	-

Internal conversion coefficients have been determined using the BrIcc code[14], using the gamma-ray multipolarities and mixing ratios from the evaluation of Artna-Cohen[1]. No mixing ratio could be found in literature for the 817 keV transition and a mixing ratio of 1 has been assumed. Measured and adopted conversion coefficients are compared in table 9.

Table 9. Comparison of available measured conversion coefficients with the values calculated with the BrIcc code. Adopted values are from the BrIcc code in all cases.

Energy (keV)	BrIcc		1971He23[25]		1982Ma52[35]	
	α_K	α_L	α_K	α_L	α_K	α_L
57.752 (13)	-	112.2 (16)	-	117 (3)	-	85 (5)
129.065 (3)	0.264 (4)	2.54 (4)	0.23 (1)	2.45 (8)		2.74 (12)
140.999 (20)	0.1689 (24)	0.0362 (5)	0.11 (5)	-	-	-
191.350 (11)	0.1710 (24)	0.443 (7)	0.20 (2)	-	-	-
209.252 (6)	0.0672 (10)	0.01333 (19)	0.058 (1)	-	-	-
270.245 (7)	0.0376 (6)	0.00716 (10)	0.025 (3)	-	0.042 (3)	-
338.320 (5)	0.0229 (4)	0.00424 (6)	0.008 (1)	-	0.030 (2)	

3 Atomic Data

All values of atomic data (ω_K, ω_L, n_{KL}, relative probabilities of the X-ray and Auger emissions) were derived from Schönfeld and Janßen[15].

4 Alpha-particle Emissions

The alpha-particle emission probabilities were calculated from the balance of the gamma-ray decay scheme using GTOL[16]. The adopted emission probabilities of the three strongest transitions α_0, α_{58} & α_{187} are in good agreement with a weighted mean of the available measured data[17-21], and those of α_{328} & α_{831} are in agreement with the measured values of 1964Le17[19]. However, there are significant unexplained differences between the recommended values and the values measured by Baranov[21] for the emission probabilities of α_{328}, α_{381} and α_{396}. Further measurements of the weak alpha-particle and gamma-ray transitions would be necessary to fully resolve these issues.

Table 4. Alpha-particle emission probabilities. Note the value quoted in the table may not match the published value exactly, as the values have been adjusted to a common scale (by dividing by the probability of the most intense emission) to take into account undetected alpha-particle emissions.

Trans.	Alpha-particle emissions per 100 decays							Adopted values (%)
	1955As28	1955Go32	1963Le17	1965Be15	1966Ba49	LWEIGHT	GTOL	
α_0	68 (1)	68.0	-	67.8 (7)	68.6 (6)	68.0 (4)	69.1 (6)	69.1 (6)
α_{58}	32 (1)	34.1	-	32.2 (3)	31.2 (4)	31.7 (7)	30.6 (6)	30.6 (6)
α_{187}	0.32 (3)	-	-	0.30 (9)	0.28 (2)	0.294 (23)	0.325 (6)	0.325 (6)
α_{328}	-	-	6 (2) $\times 10^{-3}$	-	2.9 (2) $\times 10^{-4}$	6 (2) $\times 10^{-3}$	6.22 (9) $\times 10^{-3}$	6.22 (9) $\times 10^{-3}$
α_{378}	-	-	-	-	1.7 (3) $\times 10^{-4}$	1.7 (4) $\times 10^{-4}$	5.1 (6) $\times 10^{-5}$	5.1 (6) $\times 10^{-5}$
α_{396}	-	-	-	-	2.1 (3) $\times 10^{-4}$	2.1 (4) $\times 10^{-4}$	4.8 (4) $\times 10^{-5}$	4.8 (4) $\times 10^{-5}$
α_{519}	-	-	-	-	-	-	5.4 (4) $\times 10^{-5}$	5.4 (4) $\times 10^{-5}$
α_{831}	-	-	2.4 (7) $\times 10^{-5}$	-	-	2.4 (7) $\times 10^{-5}$	2.14 (16) $\times 10^{-5}$	2.14 (16) $\times 10^{-5}$
α_{874}	-	-	-	-	-	-	3.3 (9) $\times 10^{-6}$	3.3 (9) $\times 10^{-6}$

5 Electron Emissions

Auger and conversion electron emissions per 100 decays were calculated from the gamma-ray data and conversion coefficients according to the method of Schönfeld and Janßen[22] using version 3.10 of the code EMISSION.

6 Photon Emissions

6.1 X-ray Emissions

The X-ray intensities per 100 decays have been calculated from the gamma-ray data and conversion coefficients using version 3.10 of the code EMISSION.

6.2 Gamma-ray Emissions

The gamma-ray emission energies have been taken from 1979He10[23] where possible, in which precise measurements were made by measuring energy differences against accepted calibration standards. Only the directly measured values have been taken as the decay scheme used to derive further values was incomplete. These values have been adjusted to reflect the updated calibration standards given in 2000He14[24]. Where gamma-ray lines are not present in 1979He10, weighted means of the values in 1971He23[25], 1973Ta25[26], 1977Ku15[27], 1979Bo30[28], 1987Da28[29] and 1995Ba42[30] were taken. The values in these publications were first rescaled by a least-squares fit to be compatible with 1979He10. In most cases the energy shift incurred by doing so was very small.

Relative gamma-ray emission probabilities were determined by a weighted mean of values in 1966Ah02[31], 1977Ku15[27], 1984Ge07[32] and Banham & McChrohon[33]. Data for many of the less intense gamma-ray emissions have only been reported in 1977Ku15. In determining means, values were normalised to the 129 keV gamma-ray transition rather than the most intense 60 keV transition due to the experimental difficulties in measuring gamma-ray emissions below 100 keV. There were three absolute emission probability measurements, two by 1984Ge07[32] and one by Banham & McChrohon[34]. The reference value of the normalisation factor was determined from the weighted mean of the absolute values of the 129 keV line and is 6.86 (7) $\times 10^{-4}$ per 100 decays. The normalisation factor was also calculated with the code GABS[34] and by balance of the feeding to the 1st excited state and the figures thus obtained were 7.0 (3) × 10^{-4} per 100 decays and 7.08 (16) ×10^{-4} per 100 decays respectively. These values are statistically compatible with the reference value.

The intensity of the 831 keV E0 transition is given by 1963Le17 as 2 (1) × 10^{-6} per 100 decays. The 831 keV transition is E0, thus, it emits only electrons.

Table 7. Relative gamma-ray emission probabilities, normalised to 100 emissions for the 129 keV line. Note one additional significant figure is quoted in columns 2-6 over that which would normally be quoted; this is intentional to allow statistics to be calculated. The 817 keV line is quoted by 1977Ku15 as ~ 0.0011; the uncertainty assumed is a relative uncertainty of ± 100 % at 3σ, giving a relative emission probability of 0.0011 ± 0.0004.

Energy (keV)	**Gamma-ray emissions per 100 emissions at 129 keV**				
	1966Ah02	**1977Ku15**	**1984Ge07**	**Banham 1986**	**Adopted**
57.752 (13)	256 (26)	298.9 (118)	291.5 (65)	292.5 (42)	292 (4)
129.065 (3)	100	100	100	100	100
140.999 (20)	-	0.00453 (189)	-	-	0.0045 (19)
191.351 (11)	-	0.0453 (40)	-	-	0.0453 (40)
209.252 (6)	-	0.0155 (38)	-	-	0.0155 (38)
270.245 (7)	4.62 (90)	4.264 (198)	-	4.660 (68)	4.62 (9)
328.004 (7)	4.10 (88)	3.774 (161)	-	4.168 (62)	4.12 (9)
332.371 (6)	-	0.0717 (44)	-	-	0.0717 (44)
338.320 (5)	-	0.05396 (249)	-	-	0.0540 (25)
478.41 (5)	-	0.00208 (80)	-	-	0.0021 (8)
503.819 (23)	-	0.02113 (130)	-	-	0.0211 (13)
546.454 (21)	-	0.00147 (91)	-	-	0.0015 (9)
774.05 (9)	-	0.00679 (115)	-	-	0.0068 (12)
816.62 (7)	-	~0.0011	-	-	0.0011 (4)
831.823 (10)	-	E0	-	-	E0

Table 8. Recommended gamma-ray emission probabilities.

Energy (keV)	**Multipolarity**	**Gamma-ray Emission Probability per 100 decays**
57.752 (13)	E2	0.200 (4)
129.065 (3)	E2	0.0686 (7)
140.999 (20)	E1	3.1 (13) × 10^{-6}
191.351 (11)	E2	3.1 (3) × 10^{-5}
209.252 (6)	E1	1.1 (3) × 10^{-5}
270.245 (7)	E1	0.00317 (7)
328.004 (7)	E1	0.00283 (7)
332.371 (6)	E1	4.9 (3) × 10^{-5}
338.320 (5)	E1	3.70 (18) × 10^{-5}
478.41 (5)	E1	1.4 (6) × 10^{-6}
503.819 (23)	E1	1.45 (9) × 10^{-5}
546.454 (21)	E1	1.0 (6) × 10^{-6}
774.05 (9)	E2	4.7 (8) × 10^{-6}
816.62 (7)	M1+E2 (δ=1)	8 (3) × 10^{-7}
831.823 (10)	E0	0 [TI 2 (1) × 10^{-6}]

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