^{244}Cm - Comments on evaluation of decay data by V. P. Chechev

This evaluation was completed in February 2005 (see 2006Ch34) and then corrected in October 2009 with a literature cut-off by the same date.

1 Decay Scheme

The decay scheme is based on the evaluation of 2004Ch64. It can be considered essentially complete although some weak gamma-ray transitions have not been observed in ^{244}Cm alpha decay. Such gamma-rays were taken from the ^{240}Np β^--decay and the ^{240}Am electron capture and have been included in the decay scheme.

2 Nuclear Data

Q(α) value is from 2003Au03.

The evaluated half-life of ^{244}Cm is based on the experimental values given in Table 1.

Table 1. Experimental values of the ^{244}Cm half-life (in years).

Reference	Author(s)	Value	Measurement method
1954Fr19	Friedman et al.	17.9 (5)	α-activity relative to ^{242}Cm
1954St33	Stevens et al.	19.2 (6)	α-activity relative to ^{242}Cm
1961Cao1	Carnall et al.	17.59 (6)	Specific activity
1968Be26	Bentley	18.099 (32) [a]	2π α-counting
1972Ke29	Kerrigan and Dorsett	18.13 (4)	Calorimetry
1982Po14	Polyukhov et al.	18.24 (25)	Specific activity

[a] Revised value, recalculated in 2000Ho27.

The EV1NEW program has led to successive rejections of values from 1961Ca01 and 1954St33 due to their too large contribution to χ^2-value (more than 80 %). The LRSW method has increased 1.03 times the uncertainty of the value from 1968Be26. The weighted mean of the data set including only the four remaining values is 18.115, with the internal uncertainty 0.028 and $\chi^2/\nu = 0.25$. The smallest experimental uncertainty is 0.032, thus the recommended value of ^{244}Cm half-life is **18.11 (3) a**.

The recommended spontaneous fission partial half-life of ^{244}Cm is based on the experimental values given in Table 2.

Table 2. Experimental values of the ^{244}Cm spontaneous fission half-life (in 10^7 years).

Reference	Author(s)	Value	Measurement method
1952Gh27	Ghiorso et al.	1.4 (2) [a]	Ionization chamber
1963Ma56	Malkin et al.	1.46 (6)	Gas scintillator
1965Me02	Metta et al.	1.345 (8) [a]	α/SF counting, α with low geometry counter, SF with 2π parallel plate chamber
1967Ar09	Armani and Gold	1.33 (3)	Fission neutron counting, LiI detector
1970Ba11	Barton and Koontz	1.250 (7)	Low geometry fission fragment counting
1972Ha80	Hastings and Strohm	1.343 (6) [a]	α/SF counting, Si(Au) detector
1993Pa29	Pandey et al.	1.263 (5)	α/SF counting by sequential etching of alpha and fission tracks

[a] Revised value, recalculated in 2000Ho27.

The data set in Table 2 is discrepant. The LWEIGHT computer program has chosen the unweighted mean of 1.342 and expanded the uncertainty to 0.079 so its range includes the most precise value of 1993Pa29.

The recommended value of ^{244}Cm spontaneous fission half-life is 1.34 (8) × 10^7 years.

2.1 α Transitions

The energies of the alpha transitions have been obtained from the Q value and the ^{240}Pu level energies given in Table 3 from 2004Ch64.

Table 3. ^{240}Pu levels populated in the ^{244}Cm α-decay.

Level number	Energy (keV)	Spin and parity	Half-life	Probability of α-transition (%)
0	0.0	0^+	6561 (7) a	76.7 (4)
1	42.824 (8)	2^+	164 (5) ps	23.3 (4)
2	141.690 (15)	4^+		0.0204 (15)
3	294.319 (24)	6^+		0.00352 (18)
4	497.6 [a]	8^+		4 × 10^{-5}
5	597.34 (4)	1^-		5.5 (9) × 10^{-5}
6	648.85 (4)	3^-		4.2 (30) × 10^{-6} [b]
7	860.71(7)	0^+		1.49 (16) × 10^{-4}
8	900.32 (4)	2^+		5.0 (5) × 10^{-5}
9	938.06 (6)	(1^-)		4.7 (11) × 10^{-6} [b]

[a] Energy has been taken from ^{238}U(α, 2n γ)-reaction measurements of 1972Sp06.
[b] Deduced from P(γ+ce) decay-scheme probability balances.

The probabilities of the transitions $\alpha_{0,i}$ (i = 0, 1, 2, 3, 7) have been obtained by averaging experimental data (Table 4). The experimental results from 1998Ga19 agree well with the evaluated probabilities of the most intense alpha-transitions. The probabilities of the remaining α-transitions have been deduced using the experimental values and the values obtained from P(γ+ce) decay-scheme balances (see footnotes).

Table 4. Experimental and recommended α-transition probabilities (%) in the ^{244}Cm decay.

	α-energy (keV)	1956 Hu96	1960 As11, 1984 Asaro	1963 Dz07	1966 Ba07	1984 BuZJ	1996 Bu50	1996 Sa24	1997 Ka59	1998 Ga19	1998 Ya17	2002 Da21	Recommended
$\alpha_{0,0}$	5805	76.7 (6)	-	76.2 (20)	76.4 (20) [a]	76.98 (5)	76.8 (7)	76.9 (5)	-	76.63 (18)	76.31 (5)	77.16 (11)	76.7 (4) [b]
$\alpha_{0,1}$	5763	23.3 (6)	-	23.8 (9)	23.6 (9) [a]	23.00 (5)	23.2 (5)	23.1 (5)	-	23.34 (18)	23.69 (6)	22.80 (5)	23.3 (4) [c]
$\alpha_{0,2}$	5664	0.017 (3)	0.023 (2)	0.021 (2)	0.02	0.0163 (7)	-	0.0135 (2)	-	0.0205 (15)	-	0.020 (1)	0.0204 (15) [d]
$\alpha_{0,3}$	5515	-	0.0036 (3)	0.003 (1)	0.0034	-	-	-	0.003 42 (9)	0.0038 (5)	-	0.012 (1)	0.003 52 (18) [e]
$\alpha_{0,4}$	5315		~ 1.5 10^{-4}		~ 4 10^{-5}								4 10^{-5} [f]
$\alpha_{0,5}$	5215	-	1.5 10^{-4}	-	1 10^{-4}	-	-	-	4.2 (9) 10^{-5}	-	-	-	5.5 (9) 10^{-5} [g]
$\alpha_{0,7}$	4960	-	1.55 (16) 10^{-4}	-	3 10^{-4}	-	-	-	1.42 (16) 10^{-4}	-	-		1.49 (16) 10^{-4} [h]
$\alpha_{0,8}$	4920	-	5.0 (5) 10^{-5}	-	1.3 10^{-4}	-	-	-	4.9 (8) 10^{-5}	-	-	-	5.0 (5) 10^{-5} [i]

[a] No uncertainties are quoted by the authors. The uncertainties have been adopted by the evaluator based on the analogy of the spectra obtained with magnetic spectrometers in 1963Dz07and 1966Ba07.
[b] This set of experimental values is discrepant. The LWEIGHT computer program has recommended a weighted average and expanded the uncertainty so the range includes the most precise value from 1998Ya17.
[c] Obtained from the relation $P(\alpha_{0,1}) = 100 - P(\alpha_{0,0})$ per 100 disintegrations. An unweighted average of the discrepant set of the experimental values is 23.31, a weighted average is 23.11.
[d] Weighted average of the values from 1956Hu96, 1960As11, 1963Dz07, 1998Ga19 and 2002Da21. The lower values from 1984BuZJ and 1996Sa24 have been omitted as outliers. These values conflict greatly with the ratio $P(\gamma_{2,1})/P(\gamma_{1,0}) = 0.067\ (7)$ measured in 1972Sc01. The uncertainty of the evaluated $\alpha_{0,2}$ probability has been adopted from the experimental result of 1998Ga19.
[e] Average of values from 1960As11, 1963Dz07, 1997Ka59 and 1998Ga19. The EV1NEW computer program using a limitation of relative statistical weights of 0.5 has expanded the uncertainty from 1997Ka59 to 0.00025 and recommended a weighted average and an internal uncertainty.

[f] Adopted from 1966Ba07.
[g] Deduced from the P(γ+ce)-probability balance at the 597-keV level (“5”).
[h] Weighted average of values from 1960As11, 1997Ka59.
[i] Weighted average of values from 1960As11, 1997Ka59 and a value of 5.2 (7) × 10^{-5}, calculated from P(γ+ce)-probability balance at the 900-keV level (“8”). The uncertainty is the smallest experimental one.

2.2 γ Transitions

The evaluated energies of gamma-ray transitions are virtually the same as the photon energies because nuclear recoil is negligible.

The probabilities, P(γ+ce), for gamma-ray transitions of 42.8-keV ($\gamma_{1,0}$), 98.9-keV ($\gamma_{2,1}$), 152.6-keV ($\gamma_{3,2}$), and 202-keV ($\gamma_{4,3}$) have been deduced from intensity balances, using the probabilities of α-particle transitions evaluated directly from experimental data.

For the 861-keV ($\gamma_{7,0}$) E0 transition its P(ce) value has been obtained from the (α–ce)-coincidence measurement of 1963Bj03: P(ce $\gamma_{7,0}$) + P(ce $\gamma_{7,1}$) = 9.5 (20) × 10^{-6} per 100 disintegrations.

The remaining P(γ+ce) values have been calculated from the gamma-ray emission probabilities and the total internal conversion coefficients (ICC’s). The ICC’s have been interpolated using the BrIcc package with the so called “*Frozen Orbital*” approximation (2008Ki07). The fractional uncertainties of α_K, α_L, α_M, α_T for pure multipolarities have been taken as 2 %.

Multipolarities are from 2004Ch64. These are based on conversion electron measurements of 1956Sm18, 1963Bj03, 1968Du06 and 1990Pe03.

3 Atomic Data

3.1. Fluorescence yields

The fluorescence yields are from 1996Sc06 (Schönfeld and Janβen).

3.2 X radiations

The Pu KX-ray energies and relative emission probabilities are from 1999Schönfeld, where the calculated energy values are based on X-ray wavelengths from 1967Be65 (Bearden). In Table 5 the recommended values of U KX-ray energies are compared with experimental values.

Table 5. Experimental and recommend values of Pu KX-ray energies (keV).

	1980Di13	1982Ba56	Recommended
$K\alpha_2$	99.55 (3)	99.530 (2)	99.525
$K\alpha_1$	103.76 (3)	103.741 (2)	103.734
$K\beta_3$	116.27	116.242 (2)	116.244
$K\beta_1$	117.26	117.233 (2)	117.228
$K\beta_{2,4}$	120.60 (15)	-	120.553
$KO_{2,3}$	121.55 (6)	-	121.543

In 1980Di13 the Pu KX-ray energies were measured in the alpha decay of ^{245}Cm. The relative emission probabilities of KX-rays were obtained as:

$$K\alpha_2 : K\alpha_1 : K\beta_3 : K\beta_1 : K\beta_{2,4} = 64.7\ (23) : 100.0\ (33) : 12.9\ (7) : 23.1\ (10) : 8.9\ (5).$$

3.3. Auger Electrons

The energies of Auger electrons have been calculated from atomic electron binding energies.

The P(KLX)/P(KLL), P(KXY)/P(KLL) ratios have been taken from 1996Sc06.

4 α Emissions

The energy of alpha particles to the ground state of ^{240}Pu, $E(\alpha_{0,0})$, are from the absolute measurement of 1971Gr17 but including the correction of −0.19 keV recommended by A. Rytz in 1991Ry01.

The energies of all other α-particles have been deduced from Q_α and ^{240}Pu level energies including the recoil energy corrections.

In Table 6 the recommended values of α-particle energies are compared with experimental results obtained with magnetic alpha spectrometers.

Table 6. Experimental [a] and evaluated α-particle energies in the decay of ^{244}Cm (keV).

	1960 As11	1963 Dz07	1966 Ba07	1971 Gr17	1992 Fr04	1998 Ga19	Recommended
$\alpha_{0,0}$	5805	5805 (3)	5805 (1)	5804.77 (5)	5803.6 (22)	-	5804.77 (5)
$\alpha_{0,1}$	5763	5762	5763 (1)	5762.16 (3)	-	-	5762.65 (5)
$\alpha_{0,2}$	5666	5665	5664 (3)	-	-	5664 (2)	5665.41 (5)
$\alpha_{0,3}$	5514	5514	5513 (3)	-	-	5515 (3)	5515.29 (6)
$\alpha_{0,4}$	5316	-	5313	-	-	-	5315.3
$\alpha_{0,5}$	5215	-	5215 (3)	-	-	-	5217.24 (7)
$\alpha_{0,7}$	4956	-	4960 (3)	-	-	-	4958.20 (9)
$\alpha_{0,8}$	4916	-	4920 (3)	-	-	-	4919.24 (7)

[a] Authors' values have been adjusted for changes in calibration energies (see 1991Ry01).

5 Electron emissions

The energies of conversion electrons have been obtained from gamma transition energies and relevant electron binding energies. The emission probabilities of conversion electrons have been deduced from the evaluated P(γ) and ICC values.

The absolute emission probabilities of K and L Auger electrons have been calculated using the EMISSION computer program (2000Schönfeld).

6 Photon emissions

6.1 X-ray emissions

The absolute emission probabilities of U KX- and U LX-rays in decay of ^{242}Pu have been calculated using the EMISSION computer program (2000Schönfeld).

The calculated total absolute emission probability of LX-rays P(XL)= 8.92 (23) % agrees with the experimental value of 8.77 (6) % from 1995Jo23.

In 1990Po14 the relative LX-ray emission probabilities in ^{244}Cm α-decay were measured:
[5.3 (8) : Ll; 72 (7) : Lα; 100: Lηβ; 22.4 (23) : Lγ].

These values agree with the recommended ones with the exception of the (Lα/Lηβ)-ratio.

6.2 Gamma-ray emissions

6.2.1. Gamma-ray energies

The energies of the 43-keV ($\gamma_{1,0}$), 99-keV ($\gamma_{2,1}$), and 153-keV ($\gamma_{3,2}$) gamma rays are from ^{244}Cm α-decay (1972Sc01). Other, less accurate measurements of ^{244}Cm α-decay (1956Sm18), ^{240}Np β^{-}-decay (1981Hs02) and ^{240}Am ε-decay (1972Ah07) agree with data from 1972Sc01.

The energies of remaining gamma rays have been obtained from the adopted ^{240}Pu level energies. In Table 7 the recommended gamma ray energies are compared with the available experimental data.

Table 7. Experimental and recommended gamma-ray energies (keV).

	1967Lederer (1978LeZA)	1972Ah07	1972Sc01	1981Hs02	Recommended
$\gamma_{1,0}$		42.9 (1)	42.824 (8)	-	42.824 (8)
$\gamma_{2,1}$	-	98.9 (1)	98.860 (13)	-	98.860 (13)
$\gamma_{3,2}$	-	-	152.630 (20)	-	152.630 (20)
$\gamma_{8,6}$	251.20 (20)	-	-	251.5 (1)	251.47 (6)
$\gamma_{7,5}$	263.34 (15)	-	-	263.4 (1)	263.37 (8)
$\gamma_{8,5}$	302.99 (15)	-	-	303.0 (1)	302.98 (6)
$\gamma_{6,2}$	506.9 (3)	-	-	507.2 (1)	507.16 (5)
$\gamma_{5,1}$	554.5 (2)	-	-	554.6 (1)	554.52 (4)
$\gamma_{5,0}$	597,2 (2)	-	-	597.4 (1)	597.34 (4)
$\gamma_{6,1}$	605.8 (2)	-	-	606.1 (1)	606.03 (4)
$\gamma_{8,2}$	758.6 (2)	-	-	758.6 (1)	758.63 (5)
$\gamma_{7,1}$	817.8 (2)	-	-	817.9 (1)	817.89 (7)
$\gamma_{8,1}$	857.5 (2)	-	-	857.5 (1)	857.50 (4)
$\gamma_{9,1}$	894.7 (5)	-	-	895.3 (1)	895.24 (6)
$\gamma_{8,0}$	900.1 (5)	-	-	900.3 (1)	900.32 (4)
$\gamma_{9,0}$	937.6 (10)	-	-	938.0 (1)	938.06 (6)

6.2.2. Gamma-Ray Emission Probabilities

The absolute emission probabilities for gamma rays of 43-keV ($\gamma_{1,0}$), 99-keV ($\gamma_{2,1}$), 153-keV ($\gamma_{3,2}$) and 202-keV ($\gamma_{4,3}$) have been deduced from intensity balances, using the experimental α-particle probabilities. The relative emission probabilities for the first three gamma rays were measured in 1972Sc01 as [100 - $\gamma_{1,0}$, 6.7 (7) - $\gamma_{2,1}$,and 4.1 (1) - $\gamma_{3,2}$]. The measured $P(\gamma_{2,1})/P(\gamma_{1,0})\times100$ ratio disagrees with the evaluated 5.3 (4), and the measured $P(\gamma_{3,2})/P(\gamma_{1,0})\times100$ ratio agrees with the evaluated 3.95 (23).

The recommended relative emission probabilities of gamma rays with energies greater than 150-keV, obtained by averaging the experimental data from 1967Lederer (1978LeZA) and 1969Sc18 (1970Sc39), are given in Table 8.

Table 8. Experimental and recommended relative emission probabilities of > 150-keV gamma rays from the decay of ^{244}Cm.

	Energy (keV)	1967Lederer 1978LeZA	1969Sc18 1970Sc39	Recommended
$\gamma_{3,2}$	152.6	-	1240 (150)	1170 (160) [a]
$\gamma_{8,6}$	251.5	14 (3)	12.7 (20)	13.1 (20) [b]
$\gamma_{7,5}$	263.4	73 (5)	68 (6)	71 (5) [b]
$\gamma_{8,5}$	303.0	23 (4)	21.0 (20)	21.4 (20) [b]
$\gamma_{6,2}$	507.2	10 (3)	-	10 (3) [c]
$\gamma_{5,1}$	554.5	100	100	100
$\gamma_{5,0}$	597.3	61 (2)	62 (4)	61 (2) [b]
$\gamma_{6,1}$	606.0	10 (2)	9.1 (11)	9.3 (20) [b]
$\gamma_{8,2}$	758.6	15.6 (8)	18.3 (21)	15.9 (8) [b]
$\gamma_{7,1}$	817.9	75 (4)	91 (8)	78 (4) [b]
$\gamma_{8,1}$	857.5	6.6 (4)	< 7.5	6.6 (4) [c]
$\gamma_{9,1}$	895.2	2.1 (6)	< 1.3	2.1 (6) [c]
$\gamma_{8,0}$	900.3	1.5 (6)	< 0.4	1.5 (6) [c]
$\gamma_{9,0}$	938.1	0.5 (5)	< 0.75	0.5 (5) [c]

[a] Deduced from the evaluated absolute emission probabilities P(γ 153 keV) and P(γ 555 keV).
[b] Weighted average, uncertainty is the smallest experimental value reported.
[c] Adopted from 1967Lederer (1978LeZA).

The deduced absolute emission probabilities of gamma-rays with energies greater than 250 keV are based on our recommended relative gamma-ray emission probabilities P(γ)/P(γ 555 keV) in Table 8 and a normalization factor obtained from decay scheme.

The absolute gamma-ray emission probability $P^{(1)}(\gamma\ 555\ \text{keV}) = 9.1\ (11) \times 10^{-5}$ per 100 disintegrations (used for decay-scheme normalization) has been obtained from the intensity balance at the 861-keV level ("7") using the alpha-transition probability $P(\alpha_{0,7}) = 1.49\ (16) \times 10^{-4}$ per 100 disintegrations, deduced from the experimental data of 1960As11 and 1997Ka59:

$$P(\gamma\ 555\ \text{keV}) = [P(\alpha_{0,7}) - P(\text{ce}\ 861\ \text{keV})]\ /\ [P'(\gamma\ 263\ \text{keV})\times(1+\alpha_T^{263}) + P'(\gamma\ 818\ \text{keV})\times(1+\alpha_T^{818})],$$

where P'(γ) is a gamma-ray emission probability relative to that of the 555-keV transition (i.e., P(γ)/P(γ 555 keV)).

Another way of deducing a normalization factor is by using the relative gamma-ray emission probability P(γ 153 keV)/P(γ 555 keV) = 12.4 (15) measured in 1969Sc18 (1970Sc39) and the absolute probability P(γ 153 keV) obtained from the intensity balance for the level 294-keV level ("3"):

$$P^{(2)}(\gamma\ 555\ \text{keV}) = 8.2\ (11) \times 10^{-5}\ \text{per 100 disintegrations.}$$

The average of the two P(γ 555 keV) values, $8.7\ (11) \times 10^{-5}$ per 100 disintegrations, was used as a normalization factor for calculating absolute emission probabilities of gamma-rays with energy greater than 250 keV.

The absolute emission probabilities for the 289-keV ($\gamma_{9,6}$) and 341-keV ($\gamma_{9,5}$) gamma rays have been deduced using the ratios P(γ 895 keV)/P(γ 289 keV) = 3.6 (15) and P(γ 895 keV)/P(γ 341 keV) = 1.0 (3) measured in ^{240}Np β^--decay (1981Hs02, 2004Ch64).

The absolute emission probability of the 202-keV ($\gamma_{4,3}$) gamma ray has been obtained using the adopted $\alpha_{0,4}$-transition probability. The 202-keV E2-gamma-ray transition was not observed in the ^{244}Cm alpha decay; however, it is expected from theoretical considerations and by analogy with the ^{242}Cm decay scheme.

7 Consistency of recommended data

The most accurate Q value, Q(M), is taken from the atomic mass adjustment table of Audi et al. (2003Au03). Comparison of Q(eff)(deduced as the sum of average energies per disintegration ($\sum E_i \times P_i$) for all emissions accompanying ^{244}Cm α- decay) with the tabulated decay energy Q(M) allows to check a consistency of the recommended decay-scheme parameters obtained in this evaluation.

Here E_i and P_i are the evaluated energies and emission probabilities of the i-th alpha particle, beta particle, gamma ray, X-ray, etc. Consistency (percentage deviation) is determined by $\{[Q(M) - Q(eff))] / Q(M)\} \times 100$. "Percentage deviations above 5 % would be regarded as high and imply a poorly defined decay scheme; a value of less than 5 % indicates the construction of a reasonably consistent decay scheme" (quoted from the article by A.L. Nichols in Appl. Rad. Isotopes 55 (2001) 23-70).

For the above ^{244}Cm decay data evaluation we have Q(M) = 5901.74 (5) keV and Q(eff) = 5903 (33) keV, i.e. consistency of (0.02 ± 0.56) % is not superior, but better than 0.6 %.

8 References

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