^{244}Cm – COMMENTS ON EVALUATION OF DECAY DATA

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This evaluation was completed in December 2004 and corrected in February 2005. The literature available by January 2005 was included.

1. DECAY SCHEME

The decay scheme is based on the evaluation of 2004Ch64. It can be considered as basically completed though some weak gamma transitions were not observed in ^{244}Cm alpha decay. These transitions have been included in the decay scheme from data on the ^{240}Np β^--decay and the ^{240}Am electron capture.

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)	a-activity relative to ^{242}Cm
1954St33	Stevens et al.	19.2(6)	a-activity relative to ^{242}Cm
1961Cao1	Carnall et al.	17.59(6)	Specific activity
1968Be26	Bentley	18.099(32) [a]	2π a-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 χ^2/ν = 0.25. The smallest experimental uncertainty is 0.032, thus the recommended value of ^{244}Cm half-life is **18.11(3) a**.

The evaluated 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 10^7years)

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]	a/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]	a/SF counting, Si(Au) detector
1993Pa29	Pandey et al.	1.263(5)	a/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 recommended 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 Alpha Transitions

The energies of the alpha transitions have been calculated 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 (x100)
0	0.0	0^+	6561(7) yr	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}

Level number	Energy, keV	Spin and parity	Half-life	Probability of α-transition (x100)
5	597.34(4)	1^-		$5.5(9)\times10^{-5}$
6	648.85(4)	3^-		$4.2(30)\times10^{-6}$ [b]
7	860.71(7).	0^+		$1.49(16)\times10^{-4}$
8	900.32(4)	2^+		$5.0(5)\times10^{-5}$
9	938.06(6)	(1^-)		$4.7(11)\times10^{-6}$ [b]

[a] Energy has been taken from 238U(α, 2n γ)-reaction measurements of 1972Sp06.
[b] Calculated 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 evaluated α-transition probabilities (×100) in the ^{244}Cm decay

	a-particle 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	Evaluated
$a_{0,0}$	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]
$a_{0,1}$	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]
$a_{0,2}$	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]
$a_{0,3}$	5515	-	0.0036 (3)	0.003 (1)	0.0034	-	-	-	0.00342 (9)	0.0038 (5)	-	0.012 (1)	0.00352(18) [e]
$a_{0,4}$	5315		~1.5 $\times10^{-4}$		~4 $\times10^{-5}$								4×10^{-5} [f]
$a_{0,5}$	5215	-	1.5 $\times10^{-4}$	-	1 $\times10^{-4}$	-	-	-	4.2(9) $\times10^{-5}$	-	-	-	$5.5(9)\times10^{-5}$ [g]
$a_{0,7}$	4960	-	1.55(16) $\times10^{-4}$	-	3 $\times10^{-4}$	-	-	-	1.42(16) $\times10^{-4}$	-	-		$1.49(16)\times10^{-4}$ [h]
$a_{0,8}$	4920	-	5.0(5) $\times10^{-5}$	-	1.3 $\times10^{-4}$	-	-	-	4.9(8) $\times10^{-5}$	-	-	-	$5.0(5)\times10^{-5}$ [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] Calculated from the relation $P(a_{0,1}) = 100 - P(a_{0,0})$ 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 $a_{0,2}$ 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] Calculated 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 $5.2(7)\times10^{-5}$, calculated from P(γ+ce)-probability balance at the 900-keV level (“8”). The uncertainty is the smallest experimental one.

2.2. Gamma-Ray Transitions and Internal Conversion Coefficients

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-($\gamma_{1,0}$), 98.9- ($\gamma_{2,1}$), 152.6-($\gamma_{3,2}$), 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-($\gamma_{7,0}$) E0 transition its P(ce) value has been obtained from the (α–ce)-coincidence measurement of 1963Bj03: P(ce $\gamma_{7,0}$) + P(ce $\gamma_{7,1}$) = $9.5(20)\times10^{-6}$ 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 from tables of 1978Band and 1993Ba60 using the computer program “ICC99v3.a”. 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 Janßen).

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 adopted values of U KX-ray energies are compared with experimental values.

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

	1980Di13	1982Ba56	Adopted
$K\alpha_2$	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

	1980Di13	1982Ba56	Adopted
$K\beta_1$	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. ALPHA 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 calculated from Q_α and ^{240}Pu level energies, taking into account the relevant recoil energies.

In Table 6 the calculated (evaluated) 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	Evaluated
$\alpha_{0,0}$	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 deduced 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 total absolute emission probability of K Auger electrons has been deduced using the evaluated emission probability of K–conversion electrons P(ceK) = 0.000205(10) % and the adopted K-fluorescence yield (ω_K) given in section 3. The total absolute emission probability of L Auger electrons has been deduced using the evaluated total (L1 + L2 + L3) absolute emission probability of L–conversion electrons P(ceL) = 17.0(6) % and the adopted ϖ_L given in section 3.

6. PHOTON EMISSIONS

6.1. X-Ray Emissions

The absolute emission probabilities of Pu KX-rays have been deduced using the adopted value of ω_K(Pu), the evaluated absolute emission probability of K conversion electrons (see above) and relative intensities of KX-ray components from 1999Schönfeld.

The absolute emission probabilities of LX-rays in the ^{244}Cm α-decay are from the accurate measurements of 1995Jo23. The absolute LX-ray emission probabilities (per 100 disintegrations) calculated with the program EMISSION [0.219(8)-Ll; 3.41(11)-La; 0.092(4)-Lη, 4.19(14)-Lβ; 0.97(4)-Lγ], as well as the total P(XL) = 8.9(4)%, agree with the adopted experimental values from 1995Jo23.

In 1990Po14 the relative LX-ray emission probabilities in ^{244}Cm α-decay were measured: [5.3(8)-Ll; 72(7)-La; 100-L$\eta\beta$; 22.4(23)-Lγ]. These values agree with the recommended ones with the exception of the (La/L$\eta\beta$)-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 calculated from the adopted level energies. In Table 7 the evaluated (recommended and calculated) 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-($\gamma_{1,0}$), 99-($\gamma_{2,1}$), 153-($\gamma_{3,2}$), 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-keVgamma rays from the decay of ^{244}Cm

	Energy, keV	1967Lederer 1978LeZA	1969Sc18 1970Sc39	Evaluated
$\gamma_{3,2}$	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 153keV) and P(γ 555keV).

[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 555keV) in Table 8 and a normalization factor obtained from decay scheme.

The absolute gamma-ray emission probability $P^{(1)}(\gamma\,555keV) = 9.1(11)\times10^{-5}$ 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 $P(\alpha_{0,7}) = 1.49(16)\times10^{-4}$ per 100 disintegrations, deduced from the experimental data of 1960As11 and 1997Ka59:

$P(\gamma\,555keV) = [P(\alpha_{0,7}) - P(ce\,861keV)] / [P'(\gamma\,263keV)\times(1+\alpha_T^{263}) + P'(\gamma\,818keV)\times(1+\alpha_T^{818}]$, where P'(γ) is a gamma-ray emission probability relative to that of the 555-keV transition (i.e., P(γ)/P(γ 555keV)).

Another way of calculating a normalization factor is by using the relative gamma-ray emission probability P(γ 153keV)/P(γ 555keV) = 12.4(15) measured in1969Sc18 (1970Sc39) and the absolute probability P(γ 153keV) calculated from the intensity balance for the level 294-keV level (“3”):
$P^{(2)}$(γ 555keV) = 8.2(11)×10^{-5} per 100 disintegrations.

The average of the two P(γ 555keV) values, 8.7(11)×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 895keV)/P(γ 289keV) = 3.6(15) and P(γ 895keV)/P(γ 341keV) = 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 calculated 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.

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