^{240}Pu – Comments on evaluation of decay data

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This evaluation was done originally in 2004 (2004BeZQ, 2005ChZU) and then updated in June 2009 with a literature cut-off by the same date.

1. DECAY SCHEME

The decay scheme is based on 2006Br20. Some expected weak gamma-ray transitions were not observed directly in ^{240}Pu alpha decay but have been adopted from decay of ^{236}Pa and ^{236}Np and from data on nuclear reactions.

The alpha transitions to ^{236}U highly excited levels with energy of 958.960 and 967 keV were not observed. They are expected from data on level spins and gamma-rays de-excited these levels.

2. NUCLEAR DATA

Q(α) value is from 2003Au03.

The recommended half-life of ^{240}Pu is based on the experimental results given in Table 1. Re-estimated values were used for averaging where necessary.

Table 1. Experimental values of ^{240}Pu half-life (in years)

Reference	Author(s)	Original value	Re-estimated value	Measurement method
1951In03	Inghram et al.	6580 (40)	6500 (45) [b, c]	Mass-Spectrometry
1951We21	Westrum	6300 (600)		a-Particle Counting
1954Farwell	Farwell et al.	6760		a-Particle Counting
1956Bu92	Butler et al.	6600 (100)		a-Particle Counting
1959Dokuchaev	Dokuchaev	6620 (50)	6610 (55) [b]	a-Particle Counting
1968Oe02	Oetting	6524 (10)	6537 (15) [c]	Calorimetry
1978Ja11	Jaffey et al.	6569 (6)	6569 (7) [c]	a-Particle Counting
1984Be19	Beckmann et al.	6574 (6) [a]	6574 (7) [c]	Mass-Spectrometry
1984St06	Steinkruger et al.	6571 (9) [a]		a-Particle Counting
1984Lu04	Lucas and Noyce	6552.2 (20)	6552.2 (66) [c]	a-Particle Counting
1984Ru04	Rudy et al.	6552.4 (17)	6552.4 (66)	Calorimetry
2007Ah05	Ahmad et al.	6545 (19)		Ingrowth of ^{240}Pu in ^{244}Cm source, $^{240}Pu/^{244}Cm$ activity ratio measurement

[a] Quoted uncertainties, corresponding to 95 % confidence level, have been reduced by a factor 2.
[b] Re-estimated in 1978Ja11.
[c] Re-estimated in 1986LoZT.

With omitting the value of 1954Farwell reported without uncertainty the weighted average of the remaining 11 values is 6561 yr with the internal uncertainty 3.1 yr and external uncertainty 3.8 yr.

According to the criterion adopted by the members of the CRP (1986LoZT) a minimum uncertainty of the recommended ^{240}Pu half-life should be attributed as 7 years.

Therefore, the adopted value of the ^{240}Pu half-life is 6561(7) years.

The recommended of ^{240}Pu spontaneous fission half-life is based on the experimental results given in Table 2.

Table 2. Experimental values of ^{240}Pu spontaneous fission half-life (in 10^{11} years)

Reference	Author(s)	Measure-ment value	Measurement method	Used for final averaging
1953Ki72	Kinderman	1.314 (26)	Low geometry a-counting	No
1954Ba14	Barclay et al.	1.225 (30)	Low geometry a-counting	No
1954Ch74	Chamberlain et al.	1.20	Low geometry a-counting	No
1959Mi90	Mikheev et al.	1.20	Low geometry a-counting	No
1962Wa13	Watt et al.	1.340 (15)	Low geometry a-counting	No
1963Ma50	Malkin et al.	1.45 (2)	Low geometry a-counting	No
1967White	White	1.27 (5)	No details available	No
1967Fi13	Fieldhouse et al.	1.176 (25)[a]	SF neutron emission rates	Yes
1979BuZC	Budtz-Jorgensen et al.	1.15 (3)	Fragment spectra, ionization chamber	Yes
1984An25	Androsenko et al.	1.15 (3)	SF neutron emission rates	Yes
1988SeZY	Selickij et al.	1.17 (3)	Fragment detection in 2p geometry	Yes
1989Dy01	Dytlewski et al.	1.12 (2)	Neutron coincidences and low geometry a-counting	Yes
1991Iv01	Ivanov et al.	1.15 (2)	$?_{SF}$ /?a in ^{240}Pu standards	Yes

[a] Re-estimated in 2000Ho27. Original value is 1.170 (25).

Early measurement values have been omitted from averaging according to analysis of Holden and Hoffman (2000Ho27). The weighted average of 6 selected values is 1.15 with the internal uncertainty 0.010 and external uncertainty 0.0087.

The recommended value of the ^{240}Pu spontaneous fission is 1.15 (2)·10^{11} years where the uncertainty is the smallest quoted uncertainty.

2.1 Alpha Transitions

The energies of the alpha transitions have been obtained from the Q value and the level energies given in Table 3 from 2006Br20.

Table 3. ^{236}U levels populated in ^{240}Pu α-decay

Level number	Energy, keV	Spin and parity	Half-life	Probability of α-transition (x100)
0	0,0	0^+	2.343 (6)·10^7 yr	72.74 (18)
1	45.2440 (20)	2^+	234 (6) ps	27.16 (19)
2	149.477 (6)	4^+	124 (7) ps	0.0863 (18)
3	309.785 (7)	6^+	58 (3) ps	0.001082 (18)
4	522.25 (5)	8^+	24 (2) ps	4.7 (5)·10^{-5}
5	687.59 (4)	1^-	3.78 (9) ns	1.93 (4)·10^{-5}
6	744.18 (7)	3^-	< 0.1 ns	
7	919.14 (17)	0^+		≈ 6.5·10^{-7}
8	957.90 (17)	(2^+)		< 1.7·10^{-7}
9	960.3 (3)	(2^+)		< 1.3·10^{-7}
10	966.62 (9)	1^-		< 1·10^{-7}

The probabilities of the most intense transitions $\alpha_{0,0}$ and $\alpha_{0,1}$ have been obtained by averaging experimental data (Table 4). The probabilities of all the remaining α-transitions have been deduced from the P(γ+ce) balances at relevant levels in ^{236}U. The $\alpha_{0,6}$-transition probability of 1.3 (7) 10^{-8} % has been taken from 2006Br20.

Table 4. Experimental and recommended values of α-transition probabilities (×100) in ^{240}Pu decay

	a-particle energy keV	1956 Ko67	1956 Go43	1952 As28 1957 As83	1969 Le05	1977 Ba69	1984 Ah06	1990 An33	1992 Bl13	1994 Ra27	1994 Sa63	1996 Vi07	2004 Si03	Recommended
$a_{0,0}$	5168	75.5	75.5	76		73.51 (36)	72.8 (1)	73.0 (5)	72.55 (20)	73.1 (1)	72.5 (11)	74 (2)	72.56 (6)	72.74 (18) [a]
$a_{0,1}$	5124	24.4	24.5	24		26.39 (21)	27.1 (1)	27.0 (5)	27.35 (10)	26.8 (1)	27.5 (11)	26 (2)	27.35 (7)	27.16 (19) [b]
$a_{0,2}$	5021	0.091 (6)	0.085 (15)	0.1		0.096 (5)	0.090 (5)		0.10 (2)					0.0863 (18) [c]
$a_{0,3}$	4864	0.0032 (1)				0.001								0.001082 (18) [c]
$a_{0,4}$	4655													4.7 (5)·10^{-5} [c]
$a_{0,5}$	4492				2.1(4) 10^{-5}									1.93 (4)·10^{-5} [c]

[a] LWEIGHT computer program has increased the uncertainty of 2004Si03 to 0.0649 and recommended a weighted average (72.74) with the expanded uncertainty of 0.18 so range includes the most precise value of 72.56.
[b] LWEIGHT computer program has recommended a weighted average (27.16) with the expanded uncertainty of 0.19 so range includes the most precise value of 27.35.
[c] Deduced from (γ+ce)-intensity balance at relevant levels.

2.2. Gamma Transitions and Internal Conversion Coefficients

The recommended energies of gamma-ray transitions are virtually the same as the gamma-ray energies because nuclear recoil is negligible for ^{234}U.

The gamma-ray transition probabilities have been deduced from the gamma-ray emission probabilities and total internal conversion coefficients (ICCs). The ICCs have been interpolated using the BrIcc package with the so called "*Frozen Orbital*" approximation (2008Ki07). The uncertainties in the ICCs for pure multipolarities have been taken as 2 %. The multipolarities have been taken from 2006Br20.

The experimental values of ICC have been adopted for the E1 anomalously converted gamma-ray transitions $\gamma_{5,1}$ (642.4 keV) and $\gamma_{5,0}$ (687.6 keV).

3. ATOMIC DATA

3.1. Fluorescence yields

The fluorescence yield data are from 1996Sc06 (Schönfeld and Janßen).

3.2. X-Rays

The energies of U LX-rays taken from the SAISINUC software supporting programs agree with the measurements of 1994Le28 and 1994Le37 where the fine structure of LX-radiation was measured in decays of ^{239}Pu and ^{240}Pu. Other measurements of U LX-rays can be found in 1983Ah02, 1984Bo41, 1992Ba08 and 1995Jo23.

The U KX-ray energies have been taken from 1999Schönfeld where the calculated values based on X-ray wavelengths from 1967Be65 (Bearden). In Table 5 the adopted values of U KX-ray energies are compared with experimental values.

The relative KX-ray emission probabilities have been taken from 1999Schönfeld.

Table 5. Experimental and recommended (calculated) values of U KX-ray energies (keV)

	1976GuZN	1982Ba56	1983Ah02	Adopted
$K\alpha_2$	94.655 (5)	94.656 (2)	94.67 (2)	94.666
$K\alpha_1$	98.442 (5)	98.435 (2)	98.45 (2)	98.440
$K\beta_3$	110.42	110.416 (3)	110.42 (3)	110.421
$K\beta_1$	111.30	111.300 (2)	111.31 (2)	111.298
$K\beta_5$	-	111.868 (5) - $K\beta_5''$ 112/043 (5) - $K\beta_5'$	112.01 (5)	111.964
$K\beta_{2,4}$	114.54	-	114.50 (3)	114.46
$KO_{2,3}$	115.40	-	115.40 (5)	115.377

3.3. Auger Electrons

The energies of Auger electrons are from the SAISINUC software supporting programs.

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

4. ALPHA EMISSIONS

The energy of alpha particles corresponding to the alpha transition to a ground state of ^{236}U, $E(\alpha_{0,0})$, has been adopted from the absolute measurement of 1972Go33 taking into account the correction of − 0.17 keV recommended by A.Rytz in 1991Ry01.

The energies of all other alpha particles have been deduced from Q(α), $E(\alpha_{0,0})$ and the level energies taking into account the ^{236}U recoil energies.

In Table 6 the deduced (recommended) values of α-particle energies are compared with the experimental results.

Table 6. Experimental and recommended α-particle energies in decay of ^{240}Pu, keV

	Measured [a]						Recommended
	1956 Ko67	1956 Go43	1952As28 1957As83	1962 Le11	1972 Go33	1977 Ba69	
$\alpha_{0,0}$	5166	5165	5168 (4)	5167.7 (7)	5168.13 (15) [b]	5168.13 (15) [b]	5168.13 (15) [b]
$\alpha_{0,1}$	5122	5121	5123 (5)	5123.3 (7)	5123.26 (23)	5123.45 (25)	5123.6 (2)
$\alpha_{0,2}$	5021 (2)	5020	5019			5021.3 (5)	5021.1 (2)
$\alpha_{0,3}$	4858 (5)	4856				4863.4 (5)	4863.5 (2)

[a] Original values have been adjusted taking into account changes in calibration energies as suggested in 1991Ry01.
[b] Absolute measurement; the value was adopted as recommended in 1991Ry01 and used in 2003Au03 for obtaining Q(α).

It should be noted that Sibbens and Romme (2004Si03) measured (using a 50 mm^2 high-resolution planar silicon detector) the energies of ^{240}Pu alpha particles relatively to reference peaks of ^{238}Pu and ^{239}Pu for a ^{238,239,240}Pu mixture. They obtained $E(a_{0,0})$ = 5168.54 (14) keV and $E(a_{0,1})$ = 5124.10 (15) keV discrepant with other published data.

5. ELECTRON EMISSIONS

The energies of the conversion electrons have been obtained from the gamma transition energies and the atomic-electron binding energies.

The emission probabilities of conversion electrons have been deduced from the evaluated P(γ) and ICC values. The experimental spectrum of the conversion electrons in decay of ^{240}Pu is given in 1958Sa21.

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

The total absolute emission probability of L Auger electrons has been deduced using the adopted total absolute emission probability of U LX–rays and fluorescence yield ϖ_L = 0.500 (19).

6. PHOTON EMISSIONS

6.1. X-Ray Emissions

The absolute emission probabilities of U LX–rays have been obtained as weighted averages of measurement results from 1994Le28 and 1994Le37. The uncertainties are the smallest quoted uncertainties.

The total absolute emission probability of U LX–rays P(XL) = 10.34 (15) %, adopted from measurements of 1994Le28, 1994Le37, agrees well with the value of P(XL) = 10.14 (23) %, calculated with using the EMISSION computer program (2000Schönfeld). The measurement result of 1970Swinth (11.5 (3) %) disagrees with the adopted and calculated values.

The absolute KX –ray emission probabilities have been calculated using the EMISSION computer program (2000Schönfeld).

6.2. Gamma-Ray Emissions

The energies of gamma-rays have been adopted from 2006Br20 based on the available experimental data from ^{240}Pu α-decay (Table 7) and data from decay of ^{236}Pa and ^{236}Np.

Table 7. Measured in ^{240}Pu α-decay [a] and recommended values of gamma-ray energies (keV)

	1969Le05	1971GuZY	1972Sc01	1974HeYW	1975OtZX	1976GuZN	1981He16	Recommended
$\gamma_{1,0}$		45.235 (20)	45.242 (6)			45.232 (5)	45.244 (3)	45.2440 (20)
$\gamma_{2,1}$		104.233 (10)	104.233 (5)	104.15 (2)		104.244 (5)	104.234 (6)	104.233 (5)
$\gamma_{3,2}$		160.35 (50)	160.310 (8)	160.27 (2)	160.312 (10)	160.280 (15)	160.308 (3)	160.308 (3)
$\gamma_{4,3}$			212.4 (1)		212.48 (5)			212.46 (5)
$\gamma_{5,2}$	538.05 (30)				538.09 (15)			538.10 (10)
$\gamma_{5,1}$	642.43 (10)			642.48 (15)	642.33 (10)	642.48		642.34 (5)
$\gamma_{5,0}$	687.77 (15)			688.01 (15)	687.57 (10)	687.7		687.56 (10)
$\gamma_{7,1}$	873.91 (20)				873.92 (15)			874.0 (2)

[a]. Other much more inaccurate measurements results see in 1958Sa21, 1959Tr37 and 1972CiZS.

The experimental and recommended gamma-ray emission probabilities for γ-rays with energy less than 200 keV are given in Table 8. The recommended P(γ) values have been obtained by averaging several experimental results (except for $P(\gamma_{1,0})$ that calculated from intensity balance).

Table 8. Experimental and recommended emission probabilities of gamma-rays in ^{240}Pu decay with energy less than 200 keV (per 10^4 α-decays)

	Energy (keV)	1971 GuZY	1972 Sc01	1975 OtZX	1976 GuZN	1976 Um01	1981 He16	1981 Morel	1994 Ba91	Recommended
$\gamma_{1,0}$	45.24	4.50 (10) [a]	4.50 [b]		4.53 (9) [d]	4.61 (14) [e]	4.35 (9)			4.62 (9) [f]
$\gamma_{2,1}$	104.23	0.700 (14) [a]	0.91 (5) [c]	0.70 [b]	0.698 (14) [d]		0.718 (7)			0.714 (7) [g]
$\gamma_{3,2}$	160.31	0.0420 (8) [a]	0.049 (12) [c]	0.0408 (10)	0.0402 (8) [d]		0.0402 (4)	0.0402 (7)	0.04065 (17)	0.04045 (22) [h]

[a] Omitted from averaging as the results of 1971GuZY were superseded in 1976GuZN.
[b] Omitted from averaging as an uncertainty is not quoted.
[c] Omitted on statistical considerations (using Chauvenet's criterion).
[d] The uncertainty quoted in 1976GuZN was re-estimated in 1986LoZT to include a 2 % detector efficiency uncertainty.
[e] The uncertainty quoted in 1976Um01 was re-estimated in 1986LoZT to include a 2 % detector efficiency uncertainty and 1 % from the sample isotopic composition.
[f] Deduced from intensity balance at level 45,24 keV using $P(\alpha_{0,1})$ = 27,16 (19) % and total ICC $a_T(\gamma_{1,0})$ = 589 (12). The recommended value agrees with the measurement of 1976Um01and differs from the measurement result of 1981He16.
[g] Weighted average of 1976GuZN and 1981He16; the uncertainty is the smallest quoted uncertainty.
[h] LWEIGHT computer program identified an outlier (1972Sc01). With the five remained experimental values for processing the program increased the uncertainty of 1994Ba91 to 0.00030 and recommended a weighted average; the uncertainty is internal.

The emission probabilities of $\gamma_{4,3}$(212 keV) and $\gamma_{5,2}$(538 keV) have been adopted from absolute measurements of 1975OtZX. The emission probabilities of $?_{5,1}$(642 keV) and $?_{5,0}$(687 keV) have been obtained by averaging experimental data (Table 9).

Table 9. Experimental and recommended emission probabilities of gamma-rays de-exciting the ^{236}U level with energy of 687.6 keV in ^{240}Pu decay (per 10^8 a-decays)

	Energy, keV	1969Le05	1971GuZY	1975OtZX	1975Dr05	1976GuZN	Recommended
$\gamma_{5,2}$	538.1	≈ 0.23 [a]		0.147 (12)			0.147 (12)
$\gamma_{5,1}$	642.4	14.5 [a]	14.5 (5) [b]	12.6 (4)	13 (1)	12.45 (30)	12.6 (3) [c]
$\gamma_{5,0}$	687.6	3.77 (11)	3.70 (15) [b]	3.30 (13)		3.55 (9)	3.56 (9) [c]

[a] Omitted from averaging as an uncertainty is not quoted.
[b] Omitted from averaging as the results of 1971GuZY were superseded in 1976GuZN.
[c] Weighted average of 3 experimental values; the uncertainty is the smallest quoted uncertainty.

The emission probability of $\gamma_{7,1}$ (874 keV) has been obtained as a weighted average of measurement results from 1969Le05 and 1975OtZX.

The weak gamma-rays with energy more than 900 keV were reported in 1969Le05 and 1976GuZN. They are expected from the decay scheme but their emission probabilities ($<10^{-7}$ per 100 decays) were determined with a great inaccuracy.

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 ^{240}Pu 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)} × 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 ^{240}Pu decay data evaluation we have Q(M) = 5255.75 (14) keV and Q(eff) = 5255 (9) keV. Thereafter, the percentage deviation is (0.00 ± 0.17) %, i.e. consistency is superior.

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