# $^{238}$Pu – Comments on evaluation of decay data by V. P. Chechev

This evaluation was done originally in March 2003, corrected in June 2004, and then updated in June 2009 with a literature cut-off by the same date.

## 1. DECAY SCHEME

The decay scheme is based on 2007Br04. Some expected weak gamma-ray transitions were not observed directly in $^{238}$Pu α-decay but have been adopted from decay of $^{234}$Pa and $^{234}$Np.

## 2. NUCLEAR DATA

Q(α) value is from 2003Au03.

The recommended half-life of $^{238}$Pu is based on the experimental results given in Table 1.

Table 1. Experimental values of $^{238}$Pu half-life (in years)

| Reference | Author(s) | Original value [a] | Re-estimated value [a] | Measurement method | Used for final averaging |
|---|---|---|---|---|---|
| 1950Jaffey | Jaffey and Lerner | 89.59 (37) | 89.3 (9) [b] | Direct decay (4 samples) | No |
| 1951Jaffey-1 | Jaffey and Magnusson | 77 | - | Growth of $^{238}$Pu from $^{238}$Np | No |
| 1951Jaffey-2 | Jaffey | 89 (9) | - | Direct decay | No |
| 1951Seaborg | Seaborg et al. | 92 (2) | | Growth of $^{238}$Pu from $^{242}$Cm | No |
| 1954Jo10 | Jones et al. | 89 | | | No |
| 1957Ho71 | Hoffman et al. | 86.41 (30) | 86.4 (5) [b] | Growth of $^{238}$Pu from $^{242}$Cm | No |
| 1965Eichelber | Eichelberger et al. | 87.60 (6) | - | Calorimetry | No |
| 1967Jordan | Jordan | 87.22 (52) | - | Calorimetry | No |
| 1969Benson | Benson | 87.75 (5) | - | Calorimetry | No |
| 1974StYG | Strohm and Jordan | 87.77(3) | - | Calorimetry | Yes |
| 1976Po08 | Polyukhov et al. | 86.98 (20) | 87.0 (7) [c] | Specific activity | Yes |
| 1977Di04 | Diamond et al. | 87.71 (3) | - | Growth of $^{238}$Pu from $^{242}$Cm | Yes |
| 1981Ag06 | Aggarwal et al. | 87.98 (51) | - | Relative activity $^{238}$Pu/$^{239}$Pu | Yes |
| 1981 Sevastyanov | Sevastyanov and Yarina | 86.51 (30) | 86.5 (9) [d] | Direct decay (1 sample) | No |

[a] Uncertainty at the level of 1σ.
[b] Re-estimated in 1977Di06.
[c] Re-estimated by the evaluator using analysis of 1977Di06.
[d] Re-estimated by the evaluator.

By omitting two values reported without uncertainties, the weighted average of the remaining 12 values is 87.73 with an internal uncertainty of 0.019 and $\chi^2/\nu = 2.0$. The average value of 87.73 (3) could be adopted for half-life of $^{238}$Pu. However several calorimetric results obtained in the same laboratory (MLM) may be correlated. In fact, the value 87.77 (3) (1974StYG) comes from the latest calorimetric measurement at this laboratory. Also, the early inaccurate experimental results published in 1950 – 1957 may be omitted, as they were obtained with samples of low isotopic purity. Besides, there are grounds for omitting the result of 1981Sevastyanov (V. D. Sevastyanov and V. P. Jarina, Voprosi Atomnoi Nauki i Tekhniki, seriya Jadernie Konstanti. 5(44)(1981)21), as it was obtained only from one sample using an inaccurate method of direct decay.

Therefore, the four best experimental results obtained by different methods were used for the final statistical analysis. These are 87.77 (3) – 1974StYG; 87.0 (7) – 1976Po08; 87.71 (3) –1977Di04 and 87.98 (51) – 1981Ag06. The weighted average of these data sets is 87.74 with an internal uncertainty of

0.021 and $\chi^2/\nu$ = 1.1. The recommended value of $^{238}$Pu half-life is 87.74 (3) years where the uncertainty is the smallest experimental uncertainty.

The evaluated spontaneous fission half-life of $^{238}$Pu has been based on the experimental results given in Table 2. The weighted average of 5 selected values (with reported uncertainties) is 4.74 with an internal uncertainty 0.081 and $\chi^2/\nu$ = 0.72.

The recommended value of $^{238}$Pu spontaneous fission is 4.74 (12)·$10^{10}$ years where the uncertainty is the smallest experimental uncertainty.

Table 2. Experimental values of $^{238}$Pu spontaneous fission half-life (in $10^{10}$ years)

| Reference | Author(s) | Original value [a] | Re-estimated value [a] | Measurement method | Used for final averaging |
|---|---|---|---|---|---|
| 1949Jaffey | Jaffey and Hirsch | 4.9 (4) | 4.7 (6) [b] | Ioniz. chamber | Yes |
| 1952Se67 | Segre | 2.6 | 3.9 [b] | Ioniz. chamber | No |
| 1961Dr04 | Druin et al. | 5.0 (6) | 5.1 (6) [b] | Photoemulsion | Yes |
| 1972Ha11 | Hastings and Strohm | 4.77 (14) | - | Si(Au) | Yes |
| 1975GaZX | Gay and Sher | 4.63 (12) | - | Fission fragm. coincid. in mica | Yes |
| 1988SeZY | Selitsky et al. | 5.01 (21) | - | 2π ioniz. chamber | Yes |

[a] Uncertainty at the level of 1σ.
[b] Adjusted in 1972Ha11 to $^{238}$Pu half-life of 87.77 yr. See also 2000Ho27.

### 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 2007Br04.

Table 3. $^{234}$U levels populated in $^{238}$Pu α decay

| Level number | Energy, keV | Spin and parity | Half-life | Probability of α-transition (x100) |
|---|---|---|---|---|
| 0 | 0,0 | 0+ | 2.455 (6) $10^5$ yr | 71.04 (6) |
| 1 | 43.4981 (10) | 2+ | 0.252 (7) ns | 28.85 (6) |
| 2 | 143.352 (4) | 4+ | | 0.104 (3) |
| 3 | 296.072 (4) | 6+ | | 0.00292 (4) |
| 4 | 497.04 (3) | 8+ | | 6.80 (23)·$10^{-6}$ |
| 5 | 786.288 (16) | 1- | | 8.21 (16)·$10^{-6}$ |
| 6 | 809.907 (18) | 0+ | < 0.1 ns | 1.0·$10^{-4}$ |
| 7 | 849.266 (18) | 3- | | 7.5 (22)·$10^{-8}$ |
| 8 | 851.74 (3) | 2+ | > 1.74 ps | 8.1·$10^{-6}$ |
| 9 | 926.720 (15) | 2+ | 1.38 (17) ps | 1.30 (5)·$10^{-6}$ |
| 10 | 947.64 (6) | 4+ | | 2.3·$10^{-7}$ |
| 11 | 989.430 (13) | 2- | 0.76 (4) ns | 1.50 (15)·$10^{-7}$ |
| 12 | 1023.77 (3) | 4+ | | ~ 2.0·$10^{-7}$ |
| 13 | 1044.536 (23) | 0+ | | 1.17(7)·$10^{-6}$ |
| 14 | 1085.26 (4) | 2+ | | ~ 1.2·$10^{-6}$ |

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 $^{234}$U.

Table 4. Experimental and recommended values of α-transition probabilities (×100) in the decay of $^{238}$Pu

| | Energy keV | 1954 As07 | 1957 Ko33 | 1970 Ba72 | 1971 So15 | 1984 Ah06 | 1984 Bo41 | 1984 Burns | 1987 Bo25 | 1998 Ya17 | Recommended |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\alpha_{0,0}$ | 5499 | 72 [a] | 71.1 (12) | 72.2 [a] | 70.7 (2) | 70.9 (1) | 70.91 (10) | 71.11 (4) | 71.3 (6) | 71.14 (10) | 71.04 (6) [b] |
| $\alpha_{0,1}$ | 5456 | 28 [a] | 28.7 (12) | 27.8 [a] | 29.3 (2) | 29.0 (1) | 28.98 (10) | 28.78 (4) | 28.6 (4) | 28.74 (10) | 28.85 (6) [b] |
| $\alpha_{0,2}$ | 5358 | | 0.13 (1) | 0.068 [a] | 0.1 [a] | 0.106 (3) | 0.105 (5) | 0.1002 (17) | | 0.114 (10) | 0.104 (3) [c] |
| $\alpha_{0,3}$ | 5208 | | 0.005 (1) | 0.0018 [a] | | 0.036 (5) | 0.0030 (1) | | | | 0.00292 (4) [d,e] |
| $\alpha_{0,4}$ | 5010 | | | $\sim 4 \cdot 10^{-6}$ | | | | | | | $6.80\ (23) \cdot 10^{-6}$ [e] |
| $\alpha_{0,5}$ | 4726 | | | $2.2 \cdot 10^{-5}$ | | | | | | | $8.21\ (16)\ 10^{-6}$ [e] |
| $\alpha_{0,6}$ | 4703 | | | $5 \cdot 10^{-5}$ | | | | | | | $1.0 \cdot 10^{-4}$ [e,f] |
| $\alpha_{0,7}$ | 4664 | | | | | | | | | | $7.5\ (22) \cdot 10^{-8}$ [e] |
| $\alpha_{0,8}$ | 4662 | | | $< 2 \cdot 10^{-5}$ | | | | | | | $8.1 \cdot 10^{-6}$ [e] |
| $\alpha_{0,9}$ | 4588 | | | $(1.2 \cdot 10^{-5})$ | | | | | | | $1.30\ (5) \cdot 10^{-6}$ [e] |

[a] Omitted from averaging because no uncertainty was reported.
[b] Weighted average of 7 experimental values; uncertainty is external.
[c] Weighted average of 5 experimental values (with quoted uncertainties) is 0.104 (3); the value deduced from P(γ+ce) balance is 0.1030 (24); the recommended value is 0.104 (3).
[d] Agrees well with the experimental value from 1984Bo41
[e] Evaluated from P(γ+ce) balance.
[f] Value of $1.2\ (4) \cdot 10^{-4}$ was obtained by α–γ and α-ce coincidences in 1963Bj03.

### 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.

Gamma-ray transition probabilities [P(γ+ce)] 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 emission probabilities of E0- and (E0+E2)- transitions have been obtained by using experimental conversion electron intensities from $^{234}$Pa and $^{234}$Np decays (see 2007Br04) and data from $^{238}$Pu α-decay of 1963Bj03, 1964Le17, 1964Le22.

## 3. ATOMIC DATA

### 3.1. Fluorescence yields

Fluorescence yield data are from 1996Sc06 (Schönfeld and Janβen).

### 3.2. X Radiations

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

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

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

| | 1976GuZN | 1982Ba56 | 1983Ah02 | Recommended |
|---|---|---|---|---|
| $K\alpha_2$ | 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 [a] | 110.416 (3) | 110.42 (3) | 110.421 |
| $K\beta_1$ | 111.30 [a] | 111.300 (2) | 111.31 (2) | 111.298 |
| $K\beta_5$ | - | 111.868 (5)- $K\beta_5''$<br>112.043 (5)- $K\beta_5'$ | 112.01 (5) | 111.964 |
| $K\beta_{2,4}$ | 114.54 [a] | - | 114.50 (3) | 114.46 |
| $KO_{2,3}$ | 115.40 [a] | - | 115.40 (5) | 115.377 |

The energies of U LX-rays taken from the SAISINUC software supporting programs agree with the measurements of 1994Le37 where the fine structure of LX-radiation was measured in decays of $^{239}$Pu and $^{240}$Pu.

### 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 from 1996Sc06.

## 4. ALPHA EMISSIONS

The energy of alpha particles corresponding to the alpha transition to the ground state of $^{234}$U, $E(\alpha_{0,0})$, has been adopted from the absolute measurement of 1971Gr17 with a correction of – 0.18 keV recommended by A. Rytz in 1991Ry01 because of changes in calibrations energies.

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

In Table 6 the deduced (recommended) values of α-particle energies are compared with the experimental results obtained by using magnetic and semiconductor spectrometry.

Table 6. Experimental and recommended values of α-particle energies (keV) in decay of $^{238}$Pu.

| | Measured [a] | | | | | | Recommended |
|---|---|---|---|---|---|---|---|
| | 1954As07 | 1957Ko33 | 1962Le11 | 1968Ba25 | 1970Ba72 | 1971Gr17 | |
| $\alpha_{0,0}$ | 5499 | 5497.7 (10) | 5499.2 (8) | 5499.2 (10) | 5499.2 (8) [c] | 5499.03 (20) [b] | 5499.03 (20) [b] |
| $\alpha_{0,1}$ | 5456 | 5454.7 (10) | 5456.3 (8) | 5456.1 (10) | 5456.1 | 5456.3 (4) | 5456.3 (2) |
| $\alpha_{0,2}$ | 5358 | 5358.6 (10) | 5362 (1) | | 5357.7 | | 5358.1 (2) |
| $\alpha_{0,3}$ | | 5215 (5) | | | 5205.6 | | 5208.0 (2) |
| $\alpha_{0,4}$ | | | | | ≈5015 | | 5010.4 (2) |
| $\alpha_{0,5}$ | | | | | 4724 | | 4726.0 (2) |
| $\alpha_{0,6}$ | | | | | 4704 | | 4702.8 (2) |
| $\alpha_{0,7}$ | | | | | - | | 4664.1 (2) |
| $\alpha_{0,8}$ | | | | | 4661 | | 4661.7 (2) |
| $\alpha_{0,9}$ | | | | | ≈4590 | | 4587.9 (2) |

[a] Original values have been adjusted for changes in calibration energies as suggested in 1991Ry01.
[b] Absolute measurement; this value is recommended in 1991Ry01 and used in 2003Au03 for obtaining $Q(\alpha)$.
[c] Value is from 1962Le11; adopted in 1970Ba72 as calibration energy.

## 5. ELECTRON EMISSIONS

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

The emission probabilities of conversion electrons have been deduced from the evaluated P(γ) and ICC values. Below the experimental L1:L2:L3 conversion electron sub-shell intensities from 1969Am02 are compared with theoretical values for the most intense E2 transition of $\gamma_{1,0}$ (43.498 keV).

| Theoretical | Measured |
|---|---|
| 3.85 (11) : 113 (3) : 100 | 3.99 (22) : 114.7 (20) : 100 |

The total absolute emission probabilities of K Auger electrons have been deduced using the evaluated total P(XK) and the adopted fluorescence yield $\omega_K$.

The total absolute emission probability of L Auger electrons have been deduced using the total evaluated P(XL) and the adopted fluorescence yield $\varpi_L$.

## 6. PHOTON EMISSIONS

### 6.1. X-Ray Emissions

6.1.1. M X-Rays

The total absolute emission probability of MX–rays is based on the measurement (1990Po14) of the relative emission probability P(MX)/P(LX) = 0.194 (24).

6.1.2. L X-Rays

The calculation of the total absolute emission probability of LX-rays [P(XL)], using the EMISSION computer program (2000Schönfeld), gives P(XL) = 10.55 (25) %. The available experimental results for P(XL) are discrepant: 13 % - 1954As07; 10.6 (3) % - 1964Ha14; 12.83 (14) % - 1968By01; 9.2 (1) % - 1968Salgueiro; 11.2 (4) % - 1968Swinth; 11.4 (3) % - 1971Swinth; 14.18 (11) % - 1976Va23; 11.38 (10) % - 1977Bemis; 11.55 (18) % - 1984Bo41; 10.62 (32) % - 1984DrZX and 1984BaYT; 10.63 (8) % - 1995Jo23.

The result of the most accurate and latest measurement (1995Jo23) agrees well with the calculated values and with the value from 1984DrZX where the fine structure of LX-radiation was measured. The value from 1995Jo23 has been adopted as the recommended absolute emission probability of U LX–rays from decay of $^{238}$Pu: P(XL) = 10.63 (8) %.

For the evaluation of emission probabilities of the LX-ray components Ll, Lα, Lβη, Lγ the measured values given in Table 7 were renormalized by the evaluator to the adopted value P(XL) = 10.63 (8) % and then averaged. In Table 8 the evaluated emission probabilities are compared with values calculated in 1995Jo23 from alpha-branching ratios, theoretical ICC and theoretical atomic branching ratios.

Table 7. Experimental absolute emission probabilities of U LX-rays from α decay of $^{238}$Pu

| | 1976Va23 | 1977Bemis | 1984Bo41 | 1995Jo23 |
|---|---|---|---|---|
| Ll | - | 0.26 (1) | 0.260 (7) | 0.231 (3) |
| Lα | 5.05 (6) | 4.15 (7) | 4.06 (6) | 3.81 (3) |
| Lβη | 7.41 (9) | 5.61 (7) | 5.85 (9) | 5.31 (4) |
| Lγ | 1.48 (2) | 1.36 (2) | 1.38 (2) | 1.29 (1) |

Table 8. Renormalized experimental, evaluated, and calculated absolute emission probabilities of U LX-rays from α decay of $^{238}$Pu

| | 1976Va23 (measured) | 1977Bemis (measured) | 1984Bo41 (measured) | 1995Jo23 (measured) | Adopted (averaged) | Calculated (1995Jo23) | Calculated (EMISSION code) |
|---|---|---|---|---|---|---|---|
| Ll | - | 0.24 (1) | 0.239 (7) | 0.231 (3) | 0.235 (4) [b] | 0.234 | 0.232 (8) |
| Lα | 3.77 (5) | 3.88 (7) | 3.74 (6) | 3.81 (3) | 3.80 (3) [c] | 3.78 | 3.73 (12) |
| Lβη | 5.53 (7) [a] | 5.24 (7) | 5.38 (8) | 5.31 (4) | 5.31 (4) [c] | 5.42 | 5.23 (16) |
| Lγ | 1.10 (2) [a] | 1.27 (2) | 1.27 (2) | 1.29 (1) | 1.28 (1) [c] | 1.26 | 1.23 (4) |

[a] Omitted from averaging based on statistical considerations.
[b] Weighted average; uncertainty is internal.
[c] Weighted average; uncertainty is the smallest experimental one.

6.1.3. KX-Rays

The absolute X-ray emission probability of U K$\alpha_2$ with energy 98.44 keV (P(K$\alpha_2$)) has been adopted from 1976GuZN. The absolute emission probabilities of all other X-rays have been deduced from their relative emission probabilities using the adopted P(K$\alpha_2$) = 1.69 (4)$\cdot 10^{-4}$ %. (The uncertainty of this value includes an additional 2 % detector efficiency uncertainty).

The total absolute KX-ray emission probability P(XK) = 3.56 (11)$\cdot 10^{-4}$ %, obtained using P(K$\alpha_2$) and the ratio of P(XK) / P(K$\alpha_2$), exceeds the value calculated from $\omega_K$ and the total emission probability of K–conversion electrons $P^{(ce)}$(XK) = 2.6$\cdot 10^{-4}$ %. This disagreement may be due to an inaccurate estimation of K-conversion electron intensities from E0 and (E0 + E2) transitions in decay of $^{238}$Pu.

### 6.2. Gamma-Ray Emissions

6.2.1. Gamma-Ray Energies

The energies of prominent gamma-rays $\gamma_{1,0}$(43.5 keV), $\gamma_{2,1}$(99.9 keV) and $\gamma_{3,2}$(152.7 keV) have been taken from 1984He19, with a correction of 5.8 ppm in the gamma-ray energy scale as provided by 2000He14. The energies of gamma-rays $\gamma_{13,5}$(258.2 keV) and $\gamma_{5,1}$(742.8 keV) are from 2000Ni13. The remaining gamma-ray energies have been taken from 2007Br04 based on the measurements of 1969LeZX and also 1954As07, 1955Ch02, 1956Ne17, 1971Cl03, 1971GuZY, 1971Ma68, 1976GuZN, 1984Ov01. Several of gamma-rays were not observed in $^{238}$Pu α-decay and their energies have been taken from the decay of $^{234}$Pa and $^{234}$Np (2007Br04). The experimental and recommended gamma-ray energies are given in Table 9.

Table 9. Experimental and recommended gamma-ray energies (keV) from $^{238}$Pu α decay [a]

| | 1969LeZX | 1971GuZY | 1972Sc01 | 1976GuZN | 1984He19 | Recommended |
|---|---|---|---|---|---|---|
| $\gamma_{1,0}$ | | 43.492 (10) | 43.491 (9) | 43.477 (5) | 43.498 (1) | 43.498 (1) |
| $\gamma_{2,1}$ | 99.84 (4) | 99.871 (10) | 99.85 (1) | 99.864 (5) | 99.853 (3) | 99.852 (3) |
| $\gamma_{3,2}$ | 152.71 (5) | 152.77 (3) | 152.719 (19) | 152.68 (2) | 152.720 (2) | 152.719 (2) |
| $\gamma_{4,3}$ | 200.9 (2) | 200.98 | 201.017 (30) | 200.98 | | 200.97 (3) |
| $\gamma_{14,7}$ | 235.9 (3) | | | | | 235.9 (3) |
| $\gamma_{13,5}$ | 258.3 (2) | 258.23 | | | | 258.227 (3) |
| $\gamma_{14,5}$ | 299.2 (2) | | | | | 299.1 (2) |
| $\gamma_{7,2}$ | 706.1 (3) | 705.6 | | 705.6 | | 705.9 (1) |
| $\gamma_{8,2}$ | 708.4 (2) | 708.4 | | 708.4 | | 708.3 (2) |
| $\gamma_{5,1}$ | 742.77 (10) | 742.82 | | 742.82 | | 742.813 (5) |
| $\gamma_{6,1}$ | 766.39 (10) | 766.41 (2) | | 766.41 | | 766.38 (2) |
| $\gamma_{5,0}$ | 786.30 (10) | 786.30 | | 786.30 | | 786.27 (3) |
| $\gamma_{7,1}$ | 805.8 (3) | 805.42 | | 805.4 | | 805.80 (5) |
| $\gamma_{8,1}$ | 808.25 (15) | 808.23 | | 808.2 | | 808.20 (10) |
| $\gamma_{8,0}$ | 851.70 (10) | 851.73 | | 851.7 | | 851.70 (10) |
| $\gamma_{12,2}$ | 880.5 (3) | | | | | 880.5 (1) |

| | 1969LeZX | 1971GuZY | 1972Sc01 | 1976GuZN | 1984He19 | Recommended |
|---|---|---|---|---|---|---|
| $\gamma_{9,1}$ | 883.23 (10) | 883.21 | | | | 883.24 (4) |
| $\gamma_{10,1}$ | 904.37 (15) | 904.34 | | | | 904.37 (15) |
| $\gamma_{9,0}$ | 926.72 (15) | 926.73 | | | | 926.72 (10) |
| $\gamma_{14,2}$ | 941.9 (2) | 942.02 | | | | 941.94 (10) |
| $\gamma_{11,1}$ | 946.0 (3) | 946.12 | | | | 946.00 (3) |
| $\gamma_{13,1}$ | 1001.03 (15) | 1001.10 | | | | 1001.03 (3) |
| $\gamma_{14,1}$ | 1041.8 (3) | 1041.90 | | | | 1041.7 (2) |
| $\gamma_{14,0}$ | 1085.4 (3) | 1085.40 | | | | 1085.4 (2) |

[a] Other much more inaccurate measurement results can be found in 1954As07, 1955Ch02, 1956Ne17, 1971Cl03 and 1971Ma68. They agree with those given in Table 9.

### 6.2.2. Gamma-Ray Emission Probabilities

The experimental and recommended absolute gamma-ray emission probabilities P(γ) for prominent γ-rays (with energies < 200 keV) are given in Table 10. The recommended P(γ) values have been obtained by averaging several experimental results. They agree well with the values deduced from intensity balances at relevant $^{234}$U levels using P(α) and total ICCs.

Table 10. Experimental and recommended absolute emission probabilities (per $10^4$ α-decays) for prominent gamma-rays from the decay of $^{238}$Pu

| | $E_\gamma$ (keV) | 1976GuZN | 1976Um01 | 1979 Vaninbroukx | 1984Bo41 | 1984He19 | 1984Ov01 | 1994Ba91 | Recommended (averaged) [a] | Deduced [b] |
|---|---|---|---|---|---|---|---|---|---|---|
| $\gamma_{1,0}$ | 43.5 | 3.93 (8) | 4.11 (8) | 3.93 (12) | 3.96 (10) | 3.82 (8) | | | 3.97 (8) | 4.06 (8) |
| $\gamma_{2,1}$ | 99.8 | 0.724 (14) | | | 0.730 (11) | 0.743 (8) | 0.631 (38) [c] | | 0.735 (8) | 0.741 (25) |
| $\gamma_{3,2}$ | 152.7 | 0.0956 (20) | | | 0.0928 (14) | 0.0936 (10) | 0.086 (4) [c] | 0.0923(7) | 0.0930 (7) | 0.095 (4) |

[a] Weighted averages; uncertainties are the smallest experimental values.
[b] Deduced from P(α) values and total ICCs.
[c] Omitted based on statistical considerations.

The relative emission probabilities of $\gamma_{14,7}$(235.9 keV), $\gamma_{13,8}$(258.2 keV) and $\gamma_{14,5}$(299.1 keV) have been adopted from 1969LeZX. The absolute emission probability of $\gamma_{10,2}$ (804.4 keV) has been deduced using the ratio of P(γ 804.4 keV) / P(γ 904.4 keV) = 1.8 (7) measured in $^{234}$Pa $\beta^-$-decay (2007Br04). P(γ) values for other gamma-rays, which were also not observed in the $^{238}$Pu α-decay, have been deduced from decay of $^{234}$Pa and $^{234}$Np (2007Br04) using experimental relative gamma-ray emission probabilities.

The absolute emission probabilities of all other weak gamma-rays (with energies more than 200 keV) have been deduced from their evaluated relative emission probabilities given in Table 11.

The value P(γ766) = 2.19 (5)·$10^{-7}$ measured in 1976GuZN (the uncertainty includes an additional 2 % detector efficiency uncertainty) was used as a normalization factor. This value agrees well with the value of 2.19 (9)·$10^{-7}$, deduced from the measured in 1979Ce04 P(γ786) = 3.16 (9)·$10^{-8}$ and the relative intensity P(γ786) / P(γ766) = 0.144 (4), as well as with the value of 2.21 (15)·$10^{-7}$ measured in 1984Ov01. The latter value has been obtained by the evaluator from authors' Pγ renormalized to P(γ 152.7-keV) = 9.30 (7)·$10^{-6}$.

Table 11. Experimental and recommended relative emission probabilities of gamma-rays with energy more than 200 keV from decay of $^{238}Pu$

| | | 1969LeZX | 1971GuZY | 1971Ma68 | 1976GuZN | 1979Ce04 | 1984Ov01 | Recommended |
|---|---|---|---|---|---|---|---|---|
| $\gamma_{4,3}$ | 201.0 | 15 (3) | 17.8 (3) | | 18.6 (4) | 17.0 (5) | | 17.9 (4) |
| $\gamma_{14,7}$ | 235.9 | 0.04 (2) | | | | | | 0.04 (2) |
| $\gamma_{13,5}$ | 258.2 | 0.35 (5) | 0.28 (6) | | | | | 0.32 (5) |
| $\gamma_{14,5}$ | 299.1 | 0.20 (5) | | | | | | 0.20 (5) |
| $\gamma_{7,2}$ | 705.9 | 0.42 (6) [a] | 0.225 (23) | | 0.23 (10) | | 0.25 (10) | 0.23 (5) |
| $\gamma_{8,2}$ | 708.3 | 1.15 (9) [a] | 2.24 (23) | 2.5 (6) | 2.29 (23) | 2.5 (6) | 1.7 (3) | 2.22 (14) |
| $\gamma_{5,1}$ | 742.8 | 23.2 (4) | 23.1 (2) | 25.7 (15) | 23.6 (5) | 23.8 (4) | 22.6 (12) | 23.3 (2) |
| $\gamma_{6,1}$ | 766.4 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| $\gamma_{5,0}$ | 786.3 | 14.5 (3) | 14.7 (2) | 14.9 (10) | 15.0 (3) | 14.4 (4) | 13.7 (5) | 14.6 (2) |
| $\gamma_{7,1}$ | 805.8 | 0.56 (6) | 0.56 (6) | | 0.59 (3) | | 0.7 (2) | 0.58 (3) |
| $\gamma_{8,1}$ | 808.2 | 3.40 (8) | 3.57 (10) | 3.2 (5) | 3.65 (13) | 3.52 (18) | 4.0 (4) | 3.50 (8) |
| $\gamma_{8,0}$ | 851.7 | 5.79 (20) | 5.79 (11) | 6.6 (6) | 5.89 (17) | | 4.9 (5) | 5.81 (11) |
| $\gamma_{12,2}$ | 880.5 | 0.7 (2) | | | | | 0.65 (16) | 0.68 (16) |
| $\gamma_{9,1}$ | 883.2 | 3.43 (15) | 2.72 (27) | 3.3 (5) | | 3.54 (25) | 3.2 (6) | 3.30 (17) |
| $\gamma_{10,1}$ | 904.4 | 0.30 (4) | 0.26 (8) | | | | 0.25 (10) | 0.28 (5) |
| $\gamma_{9,0}$ | 926.7 | 2.53 (10) | 2.56 (10) | 2.7 (6) | | 2.58 (13) | 2.4 (3) | 2.55 (10) |
| $\gamma_{14,2}$ | 941.9 | 2.06 (9) | 2.19 (9) | 2.2 (6) | | 2.23 (27) | 1.9 (4) | 2.13 (9) |
| $\gamma_{11,1}$ | 946.0 | 0.40 (6) | 0.43 (9) | | | | | 0.42 (6) |
| $\gamma_{13,1}$ | 1001.0 | 4.39 (14) | 5.42 (33) [a] | 4.0 (7) | | 4.61 (18) | 4.1 (5) | 4.46 (14) |
| $\gamma_{14,1}$ | 1041.7 | 0.84 (7) | 0.95 (10) | 0.7 (3) | | | 1.3 (3) | 0.90 (7) |
| $\gamma_{14,0}$ | 1085.4 | 0.34 (4) | 0.95 (10) [a] | 1.1 (4) [a] | | | 0.5 (2) | 0.35 (4) |

[a] Omitted on the basis of statistical considerations.

## 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 $^{238}$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 $^{238}$Pu decay data evaluation we have Q(M) = 5593.20 (19) keV and Q(eff) = 5593(5) keV. Thereafter, the percentage deviation is (0.00 ± 0.09) %, i.e. consistency is superior.

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