^{244}Am^{m} - Comments on evaluation of decay data

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Evaluation Procedure

Limitation of Relative Statistical Weight Method (LWM) was applied to average the decay data when appropriate (but see below).

Decay Scheme
A relatively simple decay scheme was constructed from the branching fraction measurements of Fields *et al*. and Gabeskipiya *et al*. (1955Fi36, 1976Ga31) and the gamma-ray studies of Hoff *et al*. (1984Ho02). Only the gamma-ray studies of Hoff *et al*. provide estimates of the gamma-ray emission probabilities and their uncertainties per 100 neutron captures. Thus, no weighted mean data could be derived, and the data of 1984Ho02 were adopted as published.

Nuclear Data

^{244}Am^{m} is an important actinide for high burn-up fuel within the reactor core, and needs to be better characterised for assessments of accelerator-driven systems (ADS) and ^{244}Cm production and decay heat contribution.

Half-life
The recommended half-life has been adopted from two known measurements that did not quantify the uncertainties (1950St61, 1954Gh24). Thus, the assigned uncertainty is a crude estimate of ~ 10 %. This situation is extremely unsatisfactory, and further measurements are required to determine the half-life and uncertainty with much greater confidence.

Half-life measurements.

Reference	Half-life (min)
1950St61	~ 25
1954Gh24	26
Recommended value	26 ± 3

Branching Fractions
Fields *et al.* and Gabeskipiya *et al.* have determined the EC/β⁻ ratio (1955Fi36, 1976Ga31).

Reference	EC/β⁻
1955Fi36	0.000 38 ± 0.000 03*
1976Ga31	0.000 361 ± 0.000 013
Recommended value	0.000 36 ± 0.000 01

* Adjusted from 0.000 39 (3) on consideration of ^{244}Cm half-life (18.11 (3) years).

Recommended EC/β⁻ ratio was used to derive $BF_{\beta-}$ of 0.999 64 (1) and BF_{EC} of 0.000 36 (1).

Gamma Rays

Energies

All gamma-ray transition energies were calculated from the structural details of the proposed decay scheme. The nuclear level energies of 2003Ak04 were adopted, and used to determine the energies and associated uncertainties of the gamma-ray transitions between the various populated-depopulated levels.

Emission Probabilities

Relative emission probabilities and their uncertainties were determined from the studies of Hoff *et al.* (1984Ho02). There are no other known measurements of these important decay characteristics. Under such unsatisfactory circumstances, the data of Hoff *et al.* had to be adopted wholesale, and further measurements are required to confirm the validity of the proposed decay scheme.

Measured gamma-ray emission probabilities per 100 neutron captures.

	E$_\gamma$ (keV)	P_γ	**Multipolarity**
		1984Ho02	
$\gamma_{1,0}$ (Cm)	42.965 (10)	(0.029)*	E2
$\gamma_{6,1}$ (Cm)	941.95 (3)	0.33 (11)	E2
$\gamma_{7,1}$ (Cm)	977.80 (4)	not detected	E0 (+ M1 + E2)
$\gamma_{6,0}$ (Cm)	984.91 (2)	not detected	E0
$\gamma_{10,1}$ (Cm)	1041.22 (3)	0.18 (6)	(M1 + E2)
$\gamma_{11,1}$ (Cm)	1062.95 (3)	0.26 (8)	E1
$\gamma_{10,0}$ (Cm)	1084.181 (14)	0.34 (11)	(E2)
$\gamma_{11,0}$ (Cm)	1105.91 (2)	0.04 (2)	(E1)

* Calculated from experimental electron emission probabilities and theoretical internal conversion coefficients

Vandenbosch *et al.* have measured the ^{243}Am*(n,γ)* cross-section ratio for ^{244}Am^{m} and ^{244}Am production (1964Va04), and this value has been used to convert the P_γ per 100 neutron captures to P_γ per 100 disintegrations of ^{244}Am^{m}:

$$\frac{\sigma(^{243}Am(n,\gamma)^{244}Am^{m})}{\sigma(^{243}Am(n,\gamma)^{244}Am)} = 18.6(19)$$

$$^{244}Am^{m} = 18.6(19)\times{}^{244}Am \qquad (1)$$

Consider *(n,γ)* reaction to produce ^{244}Am, and expressing the generation of ^{244}Am and ^{244}Am^{m} in the following manner:

$$\sum(^{244}Am + {}^{244}Am^{m}) = 100\% \qquad (2)$$

Substituting Eqn. (1) in (2):

$$^{244}Am = 100/19.6(19) = (5.1\pm 0.5)\%$$

$$\text{and} \quad {}^{244}Am^{m} \quad = \quad (94.9 \pm 0.5)\%$$

Absolute Pγ per 100 disintegrations of ^{244}Am^{m} were obtained by multiplying the Pγ per 100 neutron capture data of Hoff *et al.* by a factor of 1/0.949 (5).

There is considerable ambivalence in the quantification of the transition probabilities of the E0 977.80- and 984.91-keV gammas that cannot be satisfactorily resolved on the basis of the available measurements. While Hoff *et al.* found no evidence for any gamma-ray emissions with these particular energies (1984Ho02), von Egidy *et al.* observed a 977.92-keV gamma ray in their neutron capture studies with the following emission probability ratio (1984Vo07):

$$\frac{P_{\gamma}(977.92\,keV)}{P_{\gamma}(1084.18\,keV)} \quad = \quad \frac{0.12(4)}{0.52(16)}\,.$$

Substituting $P_{\gamma}(1084.18\,keV) = 0.36(12)$ in this equation from the β^{-} decay of ^{244}Am^{m},

$$P_{\gamma}(977.92\,keV) \quad = \quad \frac{0.12(4)}{0.52(16)} \times 0.36(12) \quad = \quad 0.083(28),$$

with the recommended uncertainty reflecting only the uncertainty in $P_{\gamma}(1084.18\,keV)$. This value is in good agreement with equivalent calculations involving the 1041.22- and 1062.95-keV gamma rays (0.084 (27) and 0.081 (24), respectively) that were also observed by von Egidy *et al* (1984Vo07).

Gamma-ray emissions: recommended energies, absolute emission probabilities, multipolarities and theoretical internal conversion coefficients (frozen orbital approximation).

E_{γ} (keV)	P_{γ}^{abs}	Multipolarity	α_K	α_L	α_{M+}	α_{tot}	
42.965 (10)	0.030 (9)*	E2	-	760 (11)	290 (4)	1050 (15)	β^{-}
941.95 (3)	0.35 (12)	E2	0.011 20 (16)	0.003 18 (5)	0.001 09	0.015 47 (22)	β^{-}
977.80 (4)	-	E0 (+ M1 + E2)	-	-	-	-	β^{-}
984.91 (2)	-	E0	-	-	-	-	β^{-}
1041.22 (3)	0.19 (6)	(M1 + E2)	-	-	-	-	β^{-}
1062.95 (3)	0.27 (8)	anomalous E1‡	0.09 (3)	0.015 (4)	0.005	0.11 (3)	β^{-}
1084.181 (14)	0.36 (12)	anomalous (E2)‡	0.030 (8)	0.008 (2)	0.003	0.041 (11)	β^{-}
1105.91 (2)	0.04 (2)	anomalous (E1)‡	0.14 (3)	0.024 (6)	0.006	0.17 (4)	β^{-}

* Uncertainty of 30 % assigned on the basis of TP(total) of 30 (9), as defined by Hoff *et al*. (1984Ho02).

‡ Anomalous internal conversion coefficients derived from the measurements of Hoff *et al.* (1984Ho02), with the components adjusted to match theoretical data on a relative basis.

Hoff *et al.* used a beta spectrometer to study the conversion electrons and determine the internal conversion coefficients of the various gamma transitions (1984Ho02). Total transition probabilities per 100 neutron captures were also derived by Hoff *et al*. for the two E0 gamma transitions: 977.80-keV TP_{γ} per 100 disintegrations of ^{244}Am^{m} approximated to 0.08 (2), and 984.91-keV TP_{γ} per 100 disintegrations of ^{244}Am^{m} approximated to 1.0 (1). Anomalous internal conversion coefficients were observed for the 1062.95-, 1084.181- and 1105.91-keV gamma rays.

A combination of the P_γ and P_{total} measurements of Hoff *et al.* and von Egidy *et al.* were adopted (1984Ho02, 1984Vo07), while complete sets of anomalous internal conversion coefficients were determined on the basis of the theoretical data derived from Kibedi *et al.* (2008Ki07) and adjusted in terms of the studies of Hoff *et al.* (1984Ho02). The emission probability of the 42.965-keV gamma ray was estimated by Hoff *et al.* to be 0.029 per 100 neutron captures from P_{total} of 30 (9) and theoretical internal conversion coefficients. This transition probability of 30 (9) was corrected for the ^{244}Am contribution to derive a TP of 31.6 (95) and P_γ(42.96 keV) of 0.030 (9) per 100 disintegrations of ^{244}Am^{m}.

Multipolarities and Internal Conversion Coefficients

The nuclear level scheme specified by Akovali has been used to define the multipolarities of the gamma transitions on the basis of known spins and parities (2003Ak04). Recommended internal conversion coefficients have been determined from the frozen orbital approximation of Kibedi *et al*. (2008Ki07), based on the theoretical model of Band *et al*. (2002Ba85, 2002Ra45). Some of these data were judged to be anomalous from the studies of Hoff *et al.* (1984Ho02), and were adjusted accordingly (ICC data for the 1062.95-, 1084.181- and 1105.91-keV gamma transitions).

Beta Particles

Energies and emission probabilities

The ^{244}Am^{m} nuclear level was estimated to have an energy of (89 ± 2) keV from S(n) of 5366.5 (17) keV (2003Au03) and a gamma-ray energy of 5277.6 (4) keV from the neutron capture state to ^{244}Am^{m} (1984Vo07). Energies of the ^{244}Cm nuclear levels adopted from Akovali (2003Ak04), Q_{β^-} value of (1427.3 ± 1.0) keV from Audi *et al.* (2003Au03), and ^{244}Am^{m} nuclear level energy of (89 ± 2) keV were used to determine the energies and uncertainties of the beta-particle transitions.

Adopted Nuclear Levels of ^{244}Cm: J^π and Origins (2003Ak04).

Nuclear level number	Nuclear level energy (keV)	J^π	Origins
0	0.0	0+	^{244}Bk EC decay, ^{244}Am β⁻ decay, **^{244}Am^{m} β⁻ decay**, ^{248}Cf α decay, Coulomb excitation
1	42.965 ± 0.010	2+	^{244}Am β⁻ decay, **^{244}Am^{m} β⁻ decay**, ^{248}Cf α decay, Coulomb excitation
2	142.348 ± 0.011	4+	^{244}Am β⁻ decay, ^{248}Cf α decay, Coulomb excitation
3	296.211 ± 0.011	6+	^{244}Am β⁻ decay
4	501.786 ± 0.012	8+	^{244}Am β⁻ decay
5	970 ± 4	(2+, 3–)	Coulomb excitation
6	984.914 ± 0.021	0+	**^{244}Am^{m} β⁻ decay**
7	1020.76 ± 0.03	(2+)	**^{244}Am^{m} β⁻ decay**
8	1038 ± 6	(2+, 3–)	Coulomb excitation
9	1040.188 ± 0.012	6+	^{244}Am β⁻ decay
10	1084.181 ± 0.014	1, 2+	**^{244}Am^{m} β⁻ decay**
11	1105.91 ± 0.02	(1, 2–)	**^{244}Am^{m} β⁻ decay**

Beta-particle emission probabilities were determined by balancing the proposed decay scheme through consideration of the βγ-population and γ-depopulation of the nuclear levels of daughter ^{244}Cm. The recommended absolute gamma-ray emission probabilities and theoretical internal conversion coefficients derived from Kibédi *et al.* (2008Ki07) were used in this process, with the theoretical internal conversion coefficients adjusted if identified as anomalous on the basis of the measurements by Hoff *et al*.

Beta-particle Emission Probabilities per 100 Disintegrations of ^{244}Am^{m}.

	^{244}Cm level energy (keV)	**E_β (keV)**	**P_β**	**Transition type**	**log *ft***
$\beta^-_{0,11}$	1105.91 ± 0.02	410 ± 3	0.35 ± 0.09	(1st forbidden non-unique)	6.80
$\beta^-_{0,10}$	1084.181 ± 0.014	432 ± 3	0.56 ± 0.13	(allowed)	6.67
$\beta^-_{0,7}$	1020.76 ± 0.03	496 ± 3	0.08 ± 0.02	(allowed)	7.7
$\beta^-_{0,6}$	984.914 ± 0.021	531 ± 3	1.36 ± 0.16	allowed	6.58
$\beta^-_{0,1}$	42.965 ± 0.010	1473 ± 3	31 ± 9	allowed	6.74
$\beta^-_{0,0}$	0.0	1516 ± 3	67 ± 9	allowed	6.45

Σ 100.35

EC Transition

Energy and transition probability

The EC transition energy was assigned a value of (164 ± 9) keV commensurate with Q_{EC} calculated from Audi *et al.* (2003Au03), while the transition probability was adopted from the recommended BF_{EC} of 0.00036 (1).

EC Transition Probability per 100 Disintegrations of ^{244}Am^{m}.

	E_{EC} (keV)	**P_{EC}**	**Transition type**	**log *ft***	**P_K**	**P_L**	**P_M**
$EC_{0,0}$	164 ± 9	0.036 ± 0.001	allowed	6.37	0.24 (5)	0.53 (4)	0.168 (12)

Atomic Data

K and L X-ray Emission Probabilities per 100 Disintegrations of ^{244}Am^{m}.

			Energy keV	Photons per 100 disint.
XL		(Cm)	12.633 – 23.527	12.3 (27)
	XL_l	(Cm)	12.633	0.43 (8)
	XL_α	(Cm)	14.746 – 14.961	4.6 (11)
	XL_η	(Cm)	17.314	0.13 (4)
	XL_β	(Cm)	17.286 – 19.688	6.0 (14)
	XL_γ	(Cm)	22.735 – 23.527	1.4 (4)
XK_α	$XK_{\alpha2}$	(Cm)	104.590	0.013 (4)
	$XK_{\alpha1}$	(Cm)	109.271	0.020 (6)
$XK'_{\beta1}$	$XK_{\beta3}$	(Cm)	122.304	)
	$XK_{\beta1}$	(Cm)	123.403	) 0.0076 (21)
	$XK''_{\beta5}$	(Cm)	124.124	)
$XK'_{\beta2}$	$XK_{\beta2}$	(Cm)	126.889	)
	$XK_{\beta4}$	(Cm)	127.352	) 0.0027 (8)
	$XKO_{2,3}$	(Cm)	127.970	)

The x-ray and Auger-electron data have been calculated using the evaluated gamma-ray data, and atomic data from 1996Sc06, 1998ScZM and 1999ScZX. Both the x-ray and Auger-electron emission probabilities were determined by means of the EMISSION computer program (version 4.01, 28 January 2003, with the emission.101 database extended to Z = 96 to calculate component L x-ray data of daughter Cm). This program incorporates atomic data from 1996Sc06 and the evaluated gamma-ray data.

Electron energies were determined from electron binding energies tabulated by Larkins (1977La19) and the evaluated gamma-ray energies. Absolute electron emission probabilities were calculated from the evaluated absolute gamma-ray emission probabilities and associated internal conversion coefficients.

Data Consistency

An effective Q-value of 1515.5 (30) keV has been adopted from the atomic mass evaluation of Audi *et al*. (2003Au03) while in the course of formulating the decay scheme of ^{244}Am^{m}. This value has subsequently been compared with the Q-value calculated by summing the contributions of the individual emissions to the ^{244}Am^{m} beta- and EC-decay processes (i.e. β^-, conversion electrons, γ, etc.):

$$\text{calculated Q-value} = \sum (E_i \times P_i) = 1510\ (190)\ \text{keV}$$

Percentage deviation from the effective Q-value of Audi *et al*. is (0 ± 13) %, which supports the derivation of a highly consistent decay scheme with a very large variant.

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