^{241}Am - Comments on evaluation of decay data by V. P. Chechev and N. K. Kuzmenko

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1 Decay Scheme

The scheme of ^{241}Am decay is rather complex. It contains more than forty excited levels in ^{237}Np populated by alpha- and gamma-ray transitions (2006Ba41, 1995Ak01). The intense population takes place only for lower levels with the energy less than 230 keV (8 excited levels and ground state in ^{237}Np) and in this part the decay scheme is mainly defined. Nevertheless here there are some gamma-ray transitions scarcely studied and expected but not certainly observed such as 27-keV, 54-keV, 97-keV that leads to not so good intensity balance for some levels. Additional difficulties are due to anomalous internal conversion of the 26-keV and 59-keV gamma ray transitions because of “penetration effects” (1996Jo28, 2008Go10).

For high levels the decay scheme has not been completed yet since many observed gamma-ray transitions were not placed and some expected gamma transitions were not observed. The population of these levels does not exceed 0,1 %.

The unplaced gamma rays carry ≤ 0,6 % of the total intensity of all the gamma rays placed in the decay scheme.

2 Nuclear Data

Q value is from Audi et al. (2003Au03).

The recommended ^{241}Am half-life is based on the experimental results given in Table 1.

Table 1. Experimental values of ^{241}Am half-life (in years).

Reference	Author(s)	Original value	Measurement method
1967Oe01	Oetting and Gunn	432,7 (7)	Calorimetry
1968Br22	Brown and Propst	433 (7)	Specific Activity Determination
1968St02	Stone and Hulet	436,6 (30)	Specific Activity Determination
1972Jo07	Jove and Robert	426,3 (21)	Calorimetry
1974StYG	Strohm and Jordan	432,5 (7)	Calorimetry
1974StYZ		435,0 (7)	Specific Activity Determination
1974Po16	Polyukhov et al.	432,8 (16)	Specific Activity Determination
1975Ra35	Ramthun and Muller	432,0 (2)	Calorimetry

The values before 1967 have been omitted due to their large systematic uncertainties (those values lead to the ^{241}Am half-life of 458 years).

The eight values were used for statistical processing. The uncertainty of 1975Ra35 was increased to 0,38 a to adjust weights according to the LRSW method.

Statistical processing of the final data set with the reduced χ^2 of 3,58 gives the unweighted mean of

432,6 (11) years and of 432,6 with an internal uncertainty of 0,27 and an external uncertainty of 0,51.

The LWEIGHT computer program has used the weighted mean and expanded the uncertainty to 0,6 so range includes the most precise value of 432,0 (1975Ra35). Therefore, the recommended value of ^{241}Am half-life is 432,6 (6) years.

The value of 1,2 (3) 10^{14} years has been adopted for ^{241}Am spontaneous fission half-life as recommended in 2000Ho27.

2.1 α Transitions

The energies of the alpha transitions have been deduced from the Q value and ^{237}Np level energies given in Table 2 from 2006Ba41 where they were deduced from a least-squares fit to gamma ray energies.

Table 2. ^{237}Np levels populated in ^{241}Am α-decay.

Level number	Energy, keV	Spin and parity	Half-life	Probability of α-transition (×100)
0	0,0	$5/2^+$	2,144 (7) 10^6 yr	0,38 (1)
1	33,19629 (22)	$7/2^+$	54 (24) ps	0,23 (1)
2	59,54092 (10)	$5/2^-$	67 (2) ns	84,45 (10)
3	75,899 (5)	$9/2^+$	~ 56 ps	< 0,04
4	102,959 (3)	$7/2^-$	80 (40) ps	13,23 (10)
5	129,99 (3)	$11/2^+$		~ 0,01
6	158,497 (11)	$9/2^-$		1,66 (3)
7	191,53 (6)	$13/2^+$		
8	225,957 (16)	$11/2^-$		0,014 (3)
9	267,556 (17)	$3/2^-$	5,2 (2) ns	5 10^{-4}
10	281,356 (20)	$1/2^-$		
11	305,05 (3)	$13/2^-$		0,0022 (3)
12	316,8 (2) ?			
13	324,420 (23)	$(7/2^-)$		0,0013
14	332,376 (16)	$1/2^+$	≤ 1 ns	
15	359,7 (1)	$(5/2^-)$		6 10^{-4}
16	368,602 (20)	$5/2^+$		9 10^{-4}
17	370,928 (23)	$3/2^+$		3 10^{-4}
18	395,53 (4)	$15/2^-$		7 10^{-4}
19	418,2 (1) ?			
20	434,12 (5)	$(11/2^-)$		4 10^{-4}
21	444,78 (10) ?			
22	452,545 (22)	$9/2^+$		~ 4 10^{-4}
23	459,693 (24)	$7/2^+$		~ 4 10^{-4}
24	486,21 (9)	$(9/2^-)$		1,1 10^{-4}
25	497,01 (5)	$17/2^-$		
26	514,19 (4)	$(3/2^-)$		
27	546,12 (6)	$(5/2^-)$		1 10^{-4}
28	590,09 (4)	$(7/2^-)$		
29	592,33 (7)	$13/2^+$		
30	597,99 (9)	$11/2^+$		
31	646,03 (17)	$(9/2^-)$		
32	666,19 (10)	$(5/2^+, 7/2^-)$		
33	721,961 (13)	$5/2^-$		7 10^{-4}

Level number	Energy, keV	Spin and parity	Half-life	Probability of α-transition (×100)
34	755,685 (19)	$7/2^-$		$8{,}6\ 10^{-5}$
35	770,57 (5)			
36	799,82 (4)	$9/2^-$		$4\ (3)\ 10^{-5}$
37	805,77 (12)	$(7/2^+, 9/2^+)$		
38	853,36 (15)	$11/2^-$		
39	861,65 (19)	$(5/2^+, 7/2)$		
40	920,88 (20)			
41	946 (2)			
42	962 (3) ?			
43	1014 (3) ?			

The probabilities of the alpha transitions $\alpha_{0,0}$, $\alpha_{0,1}$, $\alpha_{0,2}$, $\alpha_{0,4}$ and $\alpha_{0,6}$ have been obtained by averaging experimental values from the spectrometric measurements carried out for the last twenty five years (Table 3). Earlier measurements for these alpha transitions see in 2006Ba41.

Table 3. Experimental and recommended probabilities (%) of the most intense alpha transitions.

	α-particle energy, keV	1984Ah06 1993Ahmad	1987Bo25	1994Bl12	1996 Bueno	1996 Sanchez	1998Ya17	Recommended
$\alpha_{0,0}$	5544	0,36 (1)	0,34 (5)	0,36 (5)	0,5 (2)	0,36 (3)	0,394 (9)	0,38 (1)
$\alpha_{0,1}$	5511	0,23 (1)	0,22 (3)	0,22 (6)	-	0,28 (3)	0,224 (7)	0,23 (1)
$\alpha_{0,2}$	5486	84,6 (2) [a]	84,7 (9)	84,69 (28)	84,5 (8)	84,5 (3)	84,30 (7)	84,45 (10)
$\alpha_{0,4}$	5443	13,1 (1) [a]	13,0 (3)	13,08 (24)	12,5 (3)	13,2 (3)	13,40 (8)	13,23 (10)
$\alpha_{0,6}$	5388	1,65 (8)	1,6 (1)	1,66 (6)	1,6 (2)	1,65 (7)	1,67 (2)	1,66 (3)

[a] The $\alpha_{0,2}$ and $\alpha_{0,4}$ probabilities from 1984Ah06 were superseded by the same author in 1993Ahmad. The latter values are given in Table 3.

The probabilities of the alpha transitions $\alpha_{0,3}$, $\alpha_{0,5}$, $\alpha_{0,9}$, $\alpha_{0,13}$, $\alpha_{0,15}$, $\alpha_{0,33}$ have been adopted from the magnetic spectrometer measurements of 1964Ba26. The probabilities of the $\alpha_{0,8}$ and $\alpha_{0,11}$ transitions have been obtained from measurements of 1955Go57, 1964Ba26 and 1965Mi06. The probabilities of the $\alpha_{0,34}$ and $\alpha_{0,36}$ transitions have been deduced from the intensity balance of gamma transitions.

2.2 γ Transitions

The recommended energies of the gamma-ray transitions are virtually the same as the gamma-ray energies because nuclear recoil is negligible for ^{237}Np.

The gamma-ray transition probabilities have been deduced from their gamma-ray emission probabilities and the evaluated total ICC's.

ICC's for the intense E1 anomalously converted gamma-ray transitions $\gamma_{2,1}$ (26,3 keV) and $\gamma_{2,0}$ (59,5 keV) have been obtained from a joint analysis of the gamma ray and L-, M- conversion electron probabilities measured in ^{241}Am α decay and ^{237}U β^-decay (1996Jo28, 2006Ba41). Experimental conversion electron data are given in 1959Sa10, 1964Wo03, 1966Ko06, 1966Le13, 1966Ya05, and 1998Ko61. For discussion of anomalous electric dipole gamma-ray transitions see 1960As02, 1966Ya05, 1967Pa23, 1970Gr36, 1996Jo28, and 2008Go10. In 2008Go10 an assessment of ICCs for a number of such transitions was made. In particular, the total ICCs for gamma-ray transitions $\gamma_{2,1}$ (26,3 keV) and $\gamma_{2,0}$ (59,5 keV) in ^{237}Np have been assessed as 7,9 (8) and 0,99 (9), respectively.

ICC's for other gamma transitions have been interpolated using the BrIcc computer program, version v2.2a, data set BriccFO (2008Ki07). Multipolarities of the gamma-ray transitions and E2/M1 mixing ratios have been adopted from 2006Ba41 based on the measurements of 1959Sa10, 1964Wo03, 1966Ko06, 1966Ya05, 1998Ko61.

The E2 admixture of 16,6 (25) % for M1+E2 gamma-ray transition $\gamma_{4,2}$(43,4-keV) has been obtained by averaging the four measurement results from 1964Wo03 (17,6 (19) %), 1966Ko06 (13 (2) %), 1966Ya05 (11 (4) %), and 1998Ko61 (21,2 (22) %).

3 Atomic Data

The atomic data (fluorescence yields, X-ray energies and relative probabilities, and Auger electrons energies and relative probabilities) were deduced by using the Saisinuc software (2002Be). The fluorescence yield ϖ_M is from 1989Hubbell.

The XL -ray energies are taken from 2001Sc08.

The XK -ray energies are taken from 1999Schönfeld. Below these calculated (adopted) values are compared with the experimental results of 1982Ba56 and 1983Ah02:

	Calculated (1999Schönfeld)	Measured in 1982Ba56	Measured in 1983Ah02
$K\alpha_2$	97,069	97,069 (3)	97,08 (2)
$K\alpha_1$	101,059	101,057 (3)	101,07 (2)
$K\beta_3$	113,303	113,308 (4)	113,30 (2)
$K\beta_1$	114,234	114,244 (3)	114,24 (2)
$K\beta_5$	114,912	-	114,95 (2)
$K\beta_2$	117,463		}
$K\beta_4$	117,876		} 117,51 (3)
$KO_{2,3}$	118,429	-	118,45 (5)

4 α Emissions

The recommended energies of alpha particles have been deduced from the energies of alpha transitions taking info account the recoil energies for ^{237}Np.

The experimental values of the alpha particle energies from spectrometric measurements are given in 1971Gr17, 1968Ba25, 1968Ka09, 1965Mi06, 1964Ba26, 1962Le11, 1957Ro20, 1955Go57 (see also 2006Ba41). Most of them have lesser accuracy in comparison with the recommended values.

5 Electron emissions

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

The emission probabilities of the conversion electrons have been deduced using the evaluated P_γ and ICC values. The total absolute emission probabilities of K and L Auger electrons have been calculated using the EMISSION computer program.

6 Photon emissions

6.1 X-ray emissions

The total absolute emission probability of Np MX - rays is the experimental result of 1971Ka48.

The recommended absolute emission probabilities of Np LX - rays have been obtained by averaging of experimental results (per 100 disintegrations) shown in Table 4.

Table 4. Experimental and recommended absolute Np LX-ray emission probabilities (%) [a].

	1971 Ge11	1971 Wa28	1974 Ca16	1976 GuZN	1980 Cohen	1988 Co07	1992 Bl07	1994 Le37	2008 Le07	**Recommended**	2001Sc08 (calculated)
Ll	0,81 (7)	0,87 (6)	0,86 (2)	0,806 (40)	0,87 (3)	0,83 (3)	0,837 (10)	0,864 (12)	0,837 (9)	**0,844 (9)** [b]	0,842 (27)
$L\alpha$	12,6 (9)	13,5 (12)	13,20 (25)	13,2 (7)	13,2 (3)	12,7 (4)	13,01 (10)	13,03 (13)	13,00 (12)	**13,02 (10)** [b]	13,3 (4)
$L\eta$	} 19,1 (14)	19,1 (14)	19,25 (40)	19,2 (10)	19,78 (36)	0,368 (5)	0,377 (15)	0,369 (12)	0,404 (5)	**0,384 (20)** [c]	0,383 (16)
$L\beta$						18,3 (6)	18,61 (15)	18,39 (19)	18,65 (13)	**18,58 (13)** [b]	20,0 (6)
$L\gamma$	4,75 (35)	4,75 (35)	4,85 (15)	4,94 (25)	4,96 (20)	4,8 (2)	4,815 (38)	4,74 (8)	4,84 (3)	**4,83 (3)** [b]	5,17 (14)

[a] In addition to given references the value of 19,46 (16) for $L\eta$+$L\beta$ was obtained in 1974Ga40.
[b] The smallest uncertainty of the experimental results.
[c] The LWEIGHT computer program has used the weighted mean of 0,3843 and expanded the uncertainty so range includes the most precise value of 2008Le07.

The experimental results of 1993Lépy (per 100 disintegrations) are quoted in 2001Sc08: Ll - 0,875 (18), $L\alpha$ - 13,10 (21), $L\eta$ - 0,354 (8), $L\beta$ - 18,5 (4), $L\gamma$ - 4,84 (8). These results were superseded in 1994Le37 and were not used by the evaluators for statistical processing.

The evaluated total absolute emission probability of LX - rays P(XL) = 37,66 (17) % can be compared with the value of 36,8 (21) % calculated using the EMISSION computer program.

The absolute emission probabilities of Np XK -rays have been calculated using the EMISSION computer program. The recommended value of the total absolute emission probability P(XK) = 0,003 82 (10) % can be compared with measurements of 1976GuZN which give P(XK) = 0,004 01 (10) %.

Below the experimental data of 1976GuZN are compared with the calculated values of absolute emission probability for KX-ray components:

	1976GuZN (measured) [a]	Recommended (calculated)
$K\alpha_2$	0,001 18 (4)	0,001 134 (30)
$K\alpha_1$	0,001 89 (6)	0,001 81 (5)
$K\beta_1'$	7,1 (3) 10^{-4}	6,58 (21) 10^{-4}
$K\beta_2'$	2,29 (15) 10^{-4}	2,26 (8) 10^{-4}

[a] The uncertainties quoted in 1976GuZN have been increased by 2 % to allow for the uncertainty of the detector calibration.

6.2 Gamma-ray emissions

6.2.1 Gamma-ray energies

The gamma ray energies have been taken mainly from 2006Ba41 (see also the evaluation of 1988ChZL). Some gamma ray energies have been deduced directly from the adopted ^{237}Np level energies.

The recommended gamma ray energy values are based on measurements of 1955Da02, 1959Sa10, 1964Wo03, 1966Ko06, 1966Ya05, 1968Je01, 1968Ka09, 1970Ne11, 1976GuZN, 1978Ge06, 1978Ge17, 1978Ov01, 1979Ar11, 1984Ov02, and 1998Ab43.

The energies of gamma rays $\gamma_{2,1}$ (26,3 keV) and $\gamma_{2,0}$ (59,5 keV) have been adopted from 2000He14. The energy of gamma ray $\gamma_{1,0}$ (33,2 keV) has been deduced as the difference of $E\gamma_{2,0}$ - $E\gamma_{2,1}$. The energies of gamma rays $\gamma_{3,1}$ (42,7 keV), $\gamma_{4,2}$ (43,4 keV), and $\gamma_{8,4}$ (123,0 keV) have been taken from 1998Ko61. The gamma ray with energy of 32,183 keV has been adopted from 1976GuZN and was not reported by others.

The energies of gamma rays $\gamma_{27,26}$ (31,9 keV), $\gamma_{17,14}$ (38,5 keV), $\gamma_{14,10}$ (51,0 keV), $\gamma_{5,3}$ (54,1 keV), $\gamma_{13,9}$ (56,9 keV), $\gamma_{7,5}$ (61,6 keV), $\gamma_{14,9}$ (64,8 keV), $\gamma_{36,33}$ (77,9 keV), $\gamma_{11,8}$ (79,0 keV), $\gamma_{15,9}$ (92,4 keV) and $\gamma_{5,1}$ (96,8 keV) have been deduced from the adopted ^{237}Np level energies. These gamma ray transitions were not observed in the ^{241}Am α-decay; they are expected from the decay scheme (see 2006Ba41).

The gamma rays $\gamma_{20,11}$ (129,1 keV), $\gamma_{23,13}$ (135,3 keV), $\gamma_{30,23}$ (138,3 keV) and unplaced in decay scheme gamma rays with energies of 128,05 keV and 136,7 keV have been adopted from 1979Ar11 and were not observed by others.

Many unplaced gamma rays are reported only in 1998Ab43.

6.2.2 Gamma-ray emission probabilities

The recommended absolute emission probabilities (Pγ) of the most intense gamma rays $\gamma_{1,0}$ (26,3 keV), $\gamma_{2,1}$(33,2 keV), $\gamma_{4,2}$ (43,4 keV) and $\gamma_{2,0}$(59,5 keV) have been deduced from the available experimental data (Table 5).

Table 5. Experimental and recommended values of the most intense gamma rays in ^{241}Am α-decay.

Reference	P$\gamma_{1,0}$ (26,3 keV) ×100	P$\gamma_{2,1}$ (33,2 keV) ×100	P$\gamma_{4,2}$ (43,4 keV) ×100	P$\gamma_{2,0}$ (59,5 keV) ×100
1952Be24	2,8 (3)			40,0 (15)
1957Ma17	2,5 (2)		0,073 (7)	35,9 (6)
1964Mc12				34,6 (7)
1965Mi06				38,0 (6)
1969Pe17				35,3 (6)
1971Ge11	2,23 (18)	0,104 (11)	0,057 (18)	
1974Ca16	2,4 (1)			
1975Le09				36,3(4)
1976GuZN	2,45 (5)			
1976Pl05				35,5 (3)
1978Ge06	2,54 (26)	0,106 (11)	0,073 (7)	
1983Ah02		0,125 (8)		
1983De11	2,41 (5)			
1983Hu04				35,82 (17) [d]
1984Ov02		0,12 (1)	0,066 (5)	
1987De22				36,36 (17)
1992Bl07	2,395 (19)	0,1233 (28)	0,0654 (29)	36,03 (25)
1992Ma16				35,6 (2)
2005Iw01	2,06 (3)			35,87 (17)
Recommended	**2,31 (8)** [a]	**0,1215 (28)** [b]	**0,0669 (29)** [c]	**35,92 (17)** [e]

[a] The LWEIGHT computer program has used the weighted mean of 2,31 and expanded the uncertainty so range includes the most precise value of 1992Bl07.
[b] The LWEIGHT computer program has used the weighted mean of 0,12148 and external uncertainty of 0,0028. The smallest value of experimental uncertainties is also 0,0028.
[c] The LWEIGHT computer program has used the weighted mean of 0,0669 and internal uncertainty of 0,0022. The smallest value of experimental uncertainties is 0,0029.
[d] Uncertainty quoted by authors (0,12) has been increased to 0,17 by the evaluators to include possible systematic errors in correction factors to 59,5-keV-peak counting rate.

[e] The LWEIGHT computer program has identified one by one the three outliers of 1952Be24, 1965Mi06 and 1964Mc12 and used the weighted mean of 35,92 (8). The smallest value of experimental uncertainties of 0,17 has been adopted as the uncertainty.

The absolute emission probabilities of gamma rays $\gamma_{3,1}$ (42,7 keV), $\gamma_{6,4}$ (55,6 keV), γ(57,8 keV), $\gamma_{8,6}$ (67,5 keV), and $\gamma_{4,1}$ (69,8 keV) have been adopted from the measurements of 1978Ge06.

The absolute emission probabilities of gamma rays $\gamma_{6,2}$ (99,0 keV), $\gamma_{4,0}$ (103,0 keV), $\gamma_{8,4}$ (123,0 keV), and $\gamma_{6,1}$ (125,3 keV) have been adopted from the measurements of 1976GuZN.

The remaining weak gamma ray emission probabilities ($P\gamma < 10^{-5}$) have been adopted from the evaluations of 2006Ba41 and 1988ChZL, based mainly on the measurements of 1976GuZN and 1978Ge17 with Ge(Li) detectors, and (for gamma rays with energy more than 200 keV) from the measurements of 1998Ab43 with 40 % HPGe detector and intense purified sources. The uncertainties quoted in 1998Ab43 have been increased by 1 % to allow for the uncertainty of the detector calibration.

Other measurements of Pγ are given in 19840v02, 1983Hu04, 1983De11, 1983Ah02, 1979Ce04, 1978Ge06, 1976Pl05, 1975Le09, 1974Ca16, 1974HeYW, 1971Ge11, 1971Cl03, 1967Gu08, 1967Br26, 1966Ko06, 1965Mc12, 1965Be38, 1957Ro20, 1957Ma17, 1956Ho38, 1955Tu13, 1955Ja01, 1955Da02, 1955Ba31, and 1952Be24.

The gamma ray emission probabilities quoted in 1976GuZN and also in 19840v02, 1978Ge06, 1974Ca16, 1971Ge11, 1967Gu08 have been normalized to Pγ (59,54 keV) = 0,3592. The gamma ray emission probabilities from 1971Cl03, 1978Ge17 have been normalized to Pγ (208,00 keV) = $7{,}86\ 10^{-6}$.

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 ^{241}Am 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, 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 ^{241}Am decay data evaluation we have Q(M) = 5637,82 (12) keV and Q(eff) = 5638 (8) keV, i.e. consistency is better than 0,15 %.

8 References

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