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Evaluated Decay Data for ^{246}Cm

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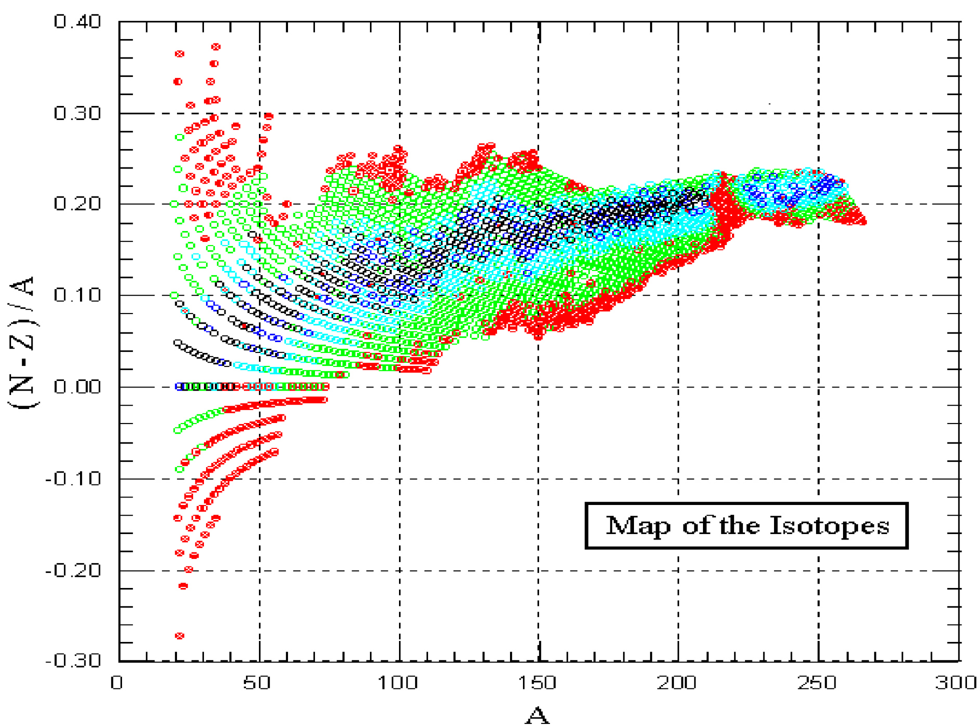

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by
Filip G. Kondev
Nuclear Engineering Division, Argonne National Laboratory

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Dr. Filip G. Kondev
Nuclear Data Program
Nuclear Engineering Division
Building 208/C-162
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439, USA

Tel: +1(630)252-4484
Fax: +1(630)252-4978
E-mail: kondev@anl.gov

ANL/NDM-164

Evaluated Decay Data for ^{246}Cm *

Filip G. Kondev #,

Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, U.S.A.

Abstract

Evaluated decay data for the ^{246}Cm nuclide are presented, including recommended values for the half-life, α− and γ−ray emission energies and probabilities. Data on X-ray radiations, Auger and conversion electron energies and emission probabilities are also tabulated.

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E-mail - kondev@anl.gov.

1. Introduction

The long-lived radionuclide ^{246}Cm is created in the nuclear power cycle by prolonged irradiation of ^{239}Pu. ^{246}Cm forms an important component in the final repository of radioactive waste, and hence the decay properties of this radionuclide, such as half-life and absolute alpha emission probabilities, need to be known with good accuracy. Requirements for improved actinide decay data have been outlined in a recent review by 2001Ni08, and include ^{246}Cm.

The work on evaluation of decay properties of ^{246}Cm was completed in December 2006 with a literature cut off by the same date. The *Saisinuc* software (2002BeXX) and associated supporting programs were used in assembling the data following the established protocol within the Decay Data Evaluation Project (DDEP) collaboration.

2. Decay Scheme

The deformed ^{246}Cm nucleus disintegrates by α emissions and spontaneous fission. The strongest α−decay branch populates the ground state of the daughter nuclide ^{242}Pu, which is also deformed. The level schemes of ^{242}Pu and ^{246}Cm are based on the evaluations of Akovali (2002Ak06) and Artna-Cohen (1998Ar12), respectively. The recent experimental work of Kondev et al. (2007Ko01) reported a weak α−decay branch to the 4^+ level of the ground-state band of ^{242}Pu.

3. Nuclear Data

Q(α) value is obtained from the adopted α0,0 energy (see section 3.1 for details) and by taking into account the relevant recoil energy. This value differs from that of 5475.1 (9) keV (2003Au03), deduced as a weighted mean of Q(α)=5475.2 (10) keV and 5474.9 (20) keV, which were determined from the α0,0 energies of 1984Sh31 and 1966Ba07, respectively. It should be noted that no uncertainty to the $E_{\alpha 0,0}$ value was reported in the original publication of 1966Ba07, but it was assigned by 2003Au03.

The experimental data on α/SF and $T_{1/2\ SF}$, together with results from the earlier evaluation of Holden (2000Ho27), are presented in Table1. The %α and %SF values were deduced using α/SF=3823 (10), a weighted mean of 3822 (10) (1969Me01) and 3833 (32) (1971Ma32):

$$\%SF = \frac{1}{1+\alpha/SF}\times 100\text{, with }\%\alpha = 100 - \%SF \qquad (1)$$

The recommended partial SF half-life of $T_{1/2\ SF}$=1.81 (2) 10^7 *a* was determined as a weighted mean of 1.80 (1) 10^7 *a* (1969Me01) and 1.85 (2) 10^7 *a* (1971Ma32).

The experimental data for the partial α−decay half-life of ^{246}Cm are presented in Table 2. Since in all cases, except 1971Mc19, relative methods were used to deduce $T_{1/2\ \alpha}$, the values reported in the original publications were corrected using the most recently adopted $T_{1/2\ \alpha}$ of the reference nuclides ^{244}Cm and ^{250}Cf, as summarized in Table 2. Results from the early work of 1954Fr19, 1955Br02, 1956Bu91 and 1961Ca01 are inaccurate and discrepant (with half-life values spanning between 2300 (460) *a* and 9311 (623) *a*), and hence, these data were excluded from the present analysis. Although the remaining five $T_{1/2\ \alpha}$ values have better accuracy, these data are also discrepant. For example, while the data of 1969Me01, 1971Mc19 and 2007Ko01 give a weighted mean of $T_{1/2\ \alpha}$=4701 (17) *a*, the results of 1971Ma32 and 1977Po20 are clustered around the weighted mean value of $T_{1/2\ \alpha}$=4825 (19) *a*. In the present work, detailed evaluations of $T_{1/2\ \alpha}$ were carried out using specially developed techniques that deal with discrepant data (see references 1992Ra08, 1994Ka08 and 2004MaXX for example) and the results are presented in Table 3. The weighted mean (WM) value (external uncertainty) is $T_{1/2\ \alpha}$=4756 (32) *a*, but χ^2_ν =6.16 (where $\chi^2_\nu = \chi^2/N\text{-}1$) is larger than the critical value of $\chi^2_{\nu\ cryt}$=3.32 (99% confidence level) because the data are discrepant. The Limitation of Relative Statistical Weight (LRSW) method adopts $T_{1/2\ \alpha}$=4756 (67) *a*, which is the WM value, but the uncertainty is extended in order to include “the most precise” value of 4823 (20) *a* (1971Ma32) (uncertainty of 0.41%). It should be noted, however, that the determined by the LRSW method “the most precise” value is as accurate as that of 4714 (22) *a* (1969Me01) (uncertainty of 0.47%). Hence, if the value from 1969Me01 is adopted as “the most precise” one, then the LRSW would give $T_{1/2\ \alpha}$=4756 (42) *a*. In the LRSW case, χ^2_ν is also larger than $\chi^2_{\nu\ cryt}$. The Normalized Residual Method (NRM) evaluates a value of $T_{1/2\ \alpha}$=4723 (27) *a,* while the Rajeval method (RM) adopts

$T_{1/2\ \alpha}$=4713 (17) *a*. In both cases χ^2_ν is smaller than $\chi^2_{\nu\ cryt}$. The NRM value is recommended in the present evaluation since the relative statistical weights of the uncertainties (note that only the uncertainty reported in 1971Ma32 has been adjusted by the this method) are less than 50%, while the RM value (uncertainties of 1971Ma32, 1971Mc19 and 1977Po20 were adjusted by this method) is biased towards that of $T_{1/2\ \alpha}$=4714 (22) *a* (1969Me01) (with a relative statistical weight of 62%).

3.1 Alpha Transitions

The ^{242}Pu level energies were deduced by a least-square fit to the adopted γ–ray energies (see section 3.2 and Table 7 for details) using the computer program *GTOL* from the *ENSDF* evaluation package. The α0,0 energy was taken from the evaluation of Rytz (1991Ry01), while the α0,1 and α0,2 energies were obtained from the adopted $E_{\alpha 0,0}$= 5387.5 (9) keV, the 2^+ and 4^+ level energies of ^{242}Pu, respectively, and by taking into account the relevant recoil energies.

The experimental values for the α–transition probabilities of ^{246}Cm are presented in Table 5. It should be noted that uncertainties were not reported in the work of 1963Be48 and 1966Ba07, but these were estimated by Rytz (1991Ry01). Table 6 contains the evaluated $P_{\alpha 0,0}$ values using two different data sets, one that excludes values reported without uncertainty in the original publications (“limited data”) and the second that includes all experimental values with uncertainties estimated by Rytz (1991Ry01) in cases where those were missing in the original publications (“all data”). The evaluated values deduced using both data sets are consisted and the WM value from the so-called “all data” set is recommended (χ^2_ν=1.69 is smaller than the critical value of $\chi^2_{\nu\ cryt}$=3.32 (99% confidence level)). The recommended $P_{\alpha 0,2}$ value was deduced using the branching ratios of 2007Ko01 and the adopted here $P_{\alpha 0,0}$=79.17 (22)%. The $P_{\alpha 0,1}$ value was determined as:

$$P_{\alpha 0,1} = 100 - P_{\alpha 0,0} - P_{\alpha 0,2} \qquad (2)$$

The α–decay hindrance factors were calculated using the computer program *ALPHAD* from the *ENSDF* evaluation package with r_0=1.4954 (10) *fm.*

3.2 Gamma-Ray Transitions and Electron Internal Conversion Coefficients

The energy of the $2^+ \rightarrow 0^+$ ground state band γ–ray transition of ^{242}Pu was taken from 1972Sc01. The $4^+ \rightarrow 2^+$ γ–ray transition was not observed in the α–decay of ^{246}Cm and its energy was taken from the Coulomb excitation data of 1983Sp03 (note that the uncertainty in this value comes from the work of 1971EiZS). Gamma–ray transition multipolarities were taken from the *ENSDF* evaluation of 1998Ar12. Since absolute γ–ray emission probabilities were not measured directly for any of the γ–ray transitions that follow α–decay of ^{246}Cm, the absolute transition probabilities, $P_{\gamma+ce}$, were deduced from the relative α–transition probabilities, presented in Table 5, after a correction for the α–decay branching was applied:

$$P_{\gamma+ce}(\gamma_{2,0}) = \frac{\%\alpha}{100} \times P_{\alpha 0,2} \text{ and } P_{\gamma+ce}(\gamma_{1,0}) = \frac{\%\alpha}{100} \times (P_{\alpha 0,1} + P_{\alpha 0,2}) \quad (3)$$

The electron internal conversion coefficients were calculated by a program supplied with the Saisinuc software (2002BeXX) that uses interpolated values of Band et al (2002Ba85) with the hole being taken into account.

4. Atomic Data

The Atomic data (Fluorescence yields, X-Ray energies and Relative probabilities, and Auger electrons energies and Relative probabilities) were provided by the *Saisinuc* software (2002BeXX). Details regarding the origin of these data can be found in 1996Sc06, 1998ScZM, 1999ScZX, 2000ScXX and 2003DeXX.

5. Alpha Emissions

Details are given is section 2.1. The number of alphas per 100 disintegrations was obtained by multiplying the corresponding α–transition probabilities that are presented in Table 5 by the α–decay branching ratio of 0.9997385 (7).

6. Photon Emissions

6.1 X-Ray Emissions

The X-ray emissions per 100 disintegrations were calculated using the computer program *EMISSION* (2000ScXX).

6.2 Gamma-Ray Emissions

The number of γ rays per 100 disintegrations was obtained from the $P_{\gamma+ce}(\gamma_{i,k})$ values, described in section 2.2, and the total electron internal conversion coefficients, $\alpha_T(\gamma_{i,k})$ that are presented in Table 7:

$$P_\gamma(\gamma_{i,k}) = \frac{P_{\gamma+ce}(\gamma_{i,k})}{1+\alpha_T(\gamma_{i,k})} \qquad (4)$$

7. Electron Emissions

The energies of the conversion electrons have been calculated from the γ–ray transition energies presented in Table 7 and the corresponding electron shell binding energies (1977La19). The number of conversion electrons of type x=T,L,M,N and O, where T stands for total, L for L-shell electrons, etc., per 100 disintegrations have been determined from the evaluated numbers of photons per 100 disintegrations, $P_\gamma(\gamma_{i,k})$, and the corresponding electron internal conversion coefficients, $\alpha_x(\gamma_{i,k})$

$$ec_{i,kx} = P_\gamma(\gamma_{i,k}) \times \alpha_x(\gamma_{i,k}) \qquad (5)$$

The number of L Auger electrons per 100 disintegrations was obtained from the computer program *EMISSION* (2000ScXX).

8. Acknowledgment

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Table 1. Experimental and evaluated data for the α/SF ratio and the SF half-life of ^{246}Cm

Author	α/SF	$T_{1/2\ SF}$, x10^7a	Method	Used in the evaluation
1956Fi11	2740 (140)	>1.24	From α/SF	No
1956FrXX		2.0(8)	relative to ^{246}Pu weight and the α−counting technique	No
1965Me02	0.139 (9)10^6 [a)]	1.66(10)	relative to ^{244}Cm α−decay data [b)]	No
1969Me01	3822 (10)	1.80 (1)	From α/SF	Yes
1971Ma32	3833 (32)	1.85 (2)	From α/SF	Yes
2000Ho27		1.81 (2)	Evaluated value	No

[a)] Net (^{246}Cm fissions)/(^{244}Cm α−disintegrations).
[b)] Using $T_{1/2,\alpha}$ (^{244}Cm)=18.11 (7) *a*, mole ratio ($^{244}Cm/^{246}Cm$)=7.82 (9) and (^{246}Cm fissions)/(^{244}Cm α−disintegrations) =0.139 (9)10^6.

Table 2. Experimental data for the partial α−decay half-life of ^{246}Cm

Author	Method [a)]	$T_{1/2\ \alpha}$, a [b)]	$T_{1/2\ \alpha}$, a [c)]	$T_{1/2\ \alpha}$, a [d)]	Used in the evaluation
1954Fr19	RSA to ^{244}Cm	4000 (600)	18.44 (5)	3928 (589)	No
1955Br02	IA to ^{246}Pu	2300 (460)			No
1956Bu91	IA to ^{250}Cf	6620 (320)	9.3 (9)	9311 (623)	No
1961Ca01	RSA to ^{244}Cm	5480 (170)	17.59 (6)	5642 (175)	No
1969Me01	RSA to ^{244}Cm	4711 (22)	18.099 (15)	4714 (22)	Yes
1971Mc19	ASA	4654 (40)			Yes
1971Ma32	RSA to ^{244}Cm	4820 (20)	18.099 (15)	4823 (20)	Yes
1977Po20	RSA to ^{244}Cm	4852 (76)	18.099 (15)	4855 (76)	Yes
2007Ko01	IA to ^{250}Cf	4706 (40)	13.08 (9)		Yes

[a)]RSA-relative specific activity method; ASA – absolute specific activity method; IA in-growth activity method.
[b)] Value reported in the original publication.
[c)] Half-life value for the reference ^{244}Cm or ^{250}Cf nuclide used in the original publication.
d) Corrected ^{246}Cm half-life values using $T_{1/2}$(^{244}Cm)=18.11 (3) *a* (2005ChXX) and $T_{1/2}$(^{250}Cf)=13.08 (9) *a* (2001Ak11))

Table 3. Evaluated values of the half-life of ^{246}Cm.

Method/Author [a)]	**Evaluated $T_{1/2}$, a**	**χ^2/N-1**
UWM	4750 (38)	6.21
WM (external)	4756 (32)	6.16
LRSW	4756 (67)	6.16
NRM	4723 (27)	2.78
RM	4713 (17)	1.24
1989Ho24	4760 (40)	7.48
1998Ar12	4760 (40) [b)]	

[a)] UWM – Unweighted Mean; WM – Weighted Mean; LRSW – Limitation of Relative Statistical Weight; NRM – Normalized Residual; RM – Rajeval.
[b)] Value adopted from 1989Ho24

Table 4. Experimental and evaluated values of the α–particle energies in decay of ^{246}Cm

Authors	**$E_{\alpha 0,0}$, keV**	**$E_{\alpha 0,1}$, keV**	**$E_{\alpha 0,2}$, keV**	**Comment** [a)]
1963Be48	5387	5345		MS
1963Dz07	5387 (4)	5345 (4)		MS
1966Ba07	5385	5342		MS
1984Sh31	5386.5 (10)	5343.5 (10)		MS
2007Ko01	5386 (3)	5342 (3)	5242 (3)	SD
1991Ry01	5387.5 (9)	5342.7 (9)		evaluated
Adopted	**5387.5 (9)**	**5343.7 (9)**	**5242.5 (10)**	**Evaluated**

a) MS – magnetic α–spectrometer; SD – semiconductor detector

Table 5. Experimental and evaluated α–transition probabilities in decay of ^{246}Cm.

Authors	**$P_{\alpha 0,0}$, %**	**$P_{\alpha 0,1}$, %**	**$P_{\alpha 0,2}$, %**	**Comment [a)]**
1963Be48	78	22		MS
1963Dz07	78 (5)	22 (5)		MS
1966Ba07	79	21		MS
1984Sh31	82.2 (12)	17.8 (12)		MS
2007Ko01	79.08 (22)	20.9 (4)	0.020 (2)	SD
1991Ry01	80.7 (11) [b)]	19.3 (11) [b)]		evaluated
Adopted	**79.17 (22)**	**20.81 (22)**	**0.020 (2)**	**Evaluated**

a) MS – magnetic α–spectrometer; SD – semiconductor detector

b) Rytz (1991Ry01) assigned uncertainties to the original 1963Be48 and 1966Ba07 values as follow: $P_{\alpha 0,0}$=78 (3) and $P_{\alpha 0,1}$=22 (3) (1963Be48) and $P_{\alpha 0,0}$=79 (2) and $P_{\alpha 0,1}$=21 (2) (1966Ba07).

Table 6. Evaluated $P_{\alpha 0,0}$ values in the α–decay of ^{246}Cm

Method/Author [a)]	**"limited data"**		**"all data"**	
	$P_{\alpha 0,0}$, keV	**χ^2/N-1**	**$P_{\alpha 0,0}$, keV**	**χ^2/N-1**
UWM	79.8 (13)		79.26 (78)	
WM	79.18 (22)	3.30	79.17 (22)	1.69
LRSW	79.18 (22)	3.30	79.17 (22)	1.69
NRM	79.15 (22)	2.31	79.17 (22)	1.69
RM	79.10 (22)		79.10 (22)	
1991Ry01			80.7 (11)	

a) UWM – Unweighted Mean; WM – Weighted Mean; LRSW – Limitation of Relative Statistical Weight; NRM – Normalized Residual; RM – Rajeval.

Table 7. Energies, multipolarities and electron internal conversion coefficients for γ–ray transitions following α–decay of ^{246}Cm

	Energy, keV	Multi-polarity	α_K	α_L	α_M	α_N	α_O	α_T
$\gamma_{1,0}$	44.545 (9)	E2	-	542 (16)	152 (5)	41.6 (12)	9.8 (3)	746 (22)
$\gamma_{2,1}$	102.8 (1)	E2	-	10.1 (3)	2.82 (8)	0.775 (23)	0.183 (5)	13.9 (4)

Appendix

Recommended Decay Data for ^{246}Cm

1. DECAY SCHEME

^{246}Cm disintegrates by α emissions (99.97385 %) and spontaneous fission (0.02615 %).The strongest α−decay branch of 79.17 (22) % populates the ^{242}Pu ground state, while the first (44.545 keV) and the second (147.35 keV) excited states of ^{242}Pu are populated with intensities of 20.81 % and 0.020 %, respectively.

2. NUCLEAR DATA

%α (^{246}Cm): 99.97385 (7) %

%SF (^{246}Cm): 0.02615 (7) %

Q_α(^{246}Cm): 5476.7 (9) keV

$T_{1/2\ \alpha}$(^{246}Cm): 4723 (27) *a*

$T_{1/2\ SF}$(^{246}Cm): 1.81 (2)10^7 *a*

2.1. AlphaTransitions

	Level Energy, keV	Energy of α−particles, keV	Emission Probability ×100	Hindrance Factor
$\alpha_{0,0}$	0.0	5387.5 (9)	79.17(22)	1.00
$\alpha_{0,1}$	44.545 (9)	5343.7 (9)	20.81(22)	2.05
$\alpha_{0,2}$	147.35 (10)	5242.5 (10)	0.020(2)	500

2.2. Gamma Transitions and Internal Conversion Coefficients

	Energy, keV	Pγ+ce ×100	Multi-polarity	α_K	α_L	α_M	α_N	α_O	α_T
$\gamma_{1,0}$ (Pb)	44.545 (9)	20.82 (22)	E2	-	542 (16)	152 (5)	41.6 (12)	9.8 (3)	746 (22)
$\gamma_{2,1}$ (Pb)	102.8 (1)	0.020 (2)	E2	-	10.1 (3)	2.82 (8)	0.775 (23)	0.183 (5)	13.9 (4)

3. ATOMIC DATA Pu (Z=94)

3.1 Fluorescence yields

ω_K : 0.971 (4)
ϖ_L : 0.521 (20)
n_{KL} : 0.790 (5)

3.2 X-Ray Radiations

		Energy, keV	Relative probability
X_K(Pu)			
$K\alpha_2$	(Pu)	99.525	63.17
$K\alpha_1$	(Pu)	103.734	100
$K\beta_3$	(Pu)	116.244	}
$K\beta_1$	(Pu)	117.228	}36.7
$K\beta_5$	(Pu)	117.918	}
$K\beta_2$	(Pu)	120.54	}
$K\beta_4$	(Pu)	120.969	}12.7
$KO_{2,3}$	(Pu)	121.543	}
X_L(Pu)			
Ll	(Pu)	12.1246	
$L\alpha$	(Pu)	14.0834 – 14.2791	
$L\eta$	(Pu)	16.334	
$L\beta$	(Pu)	16.4987 – 19.331	
$L\gamma$	(Pu)	20.7081 – 21.9844	

3.3. Auger Electrons

		Energy keV	Relative probability
e_{AK}(Pu)			
KLL	(Pu)	72.263 – 85.357	100
KLX	(Pu)	92.607 – 103.729	60.6
KXY	(Pu)	109.93 – 121.78	9.18
e_{AL}(Pu)		0.4 – 22.995	

4. α Emissions

	Energy of α-particles keV	Number of alphas per 100 disintegrations
$\alpha_{0,0}$	5387.5 (9)	79.15 (22)
$\alpha_{0,1}$	5343.7 (9)	20.80 (22)
$\alpha_{0,2}$	5242.5 (10)	0.020 (2)

5. Photon Emissions

5.1. X-Ray Emissions

	Energy keV	Number of photons per 100 disintegrations
X_L (Pu)	12.1246 – 21.9844	7.95 (20)
Ll (Pu)	12.1246	0.195 (7)
Lα (Pu)	14.0834 – 14.2791	3.03 (9)
Lη (Pu)	16.334	0.082 (4)
Lβ (Pu)	16.4987 – 19.331	3.76 (12)
Lγ (Pu)	20.7081 – 21.9844	0.87 (3)

5.2 Gamma-Ray Emissions

		Energy, keV	Number of photons per 100 disintegrations
$\gamma_{1,0}$	(Pu)	44.545 (8)	0.0279 (8)
$\gamma_{2,1}$	(Pu)	102.8 (1)	0.00134 (14)

6. Electron Emissions

		Energy, keV	Number of electrons per 100 disintegrations
e_{AL}	(Pu)	0.4 – 22.995	7.20 (17)
$ec_{1,0\ T}$	(Pu)		20.8 (7)
$ec_{1,0\ L}$	(Pu)	21.441 – 26.488	15.1 (5)
$ec_{1,0\ M}$	(Pu)	38.612 – 40.77	4.22 (13)
$ec_{1,0\ N}$	(Pu)	42.986 – 44.121	1.16 (4)
$ec_{1,0\ O}$	(Pu)	44.2 – 44.538	0.273 (9)
$ec_{2,1\ T}$	(Pu)		0.0186 (20)
$ec_{2,1\ L}$	(Pu)	79.7 – 84.7	0.0135 (14)
$ec_{2,1\ M}$	(Pu)	96.9 – 99.0	0.00379 (4)
$ec_{2,1\ N}$	(Pu)	101.2 – 102.4	0.00104 (11)
$ec_{2,1\ O}$	(Pu)	102.4 – 102.8	0.00025 (3)

7. Main production modes

^{245}Cm(n,γ)
^{250}Cf α−decay

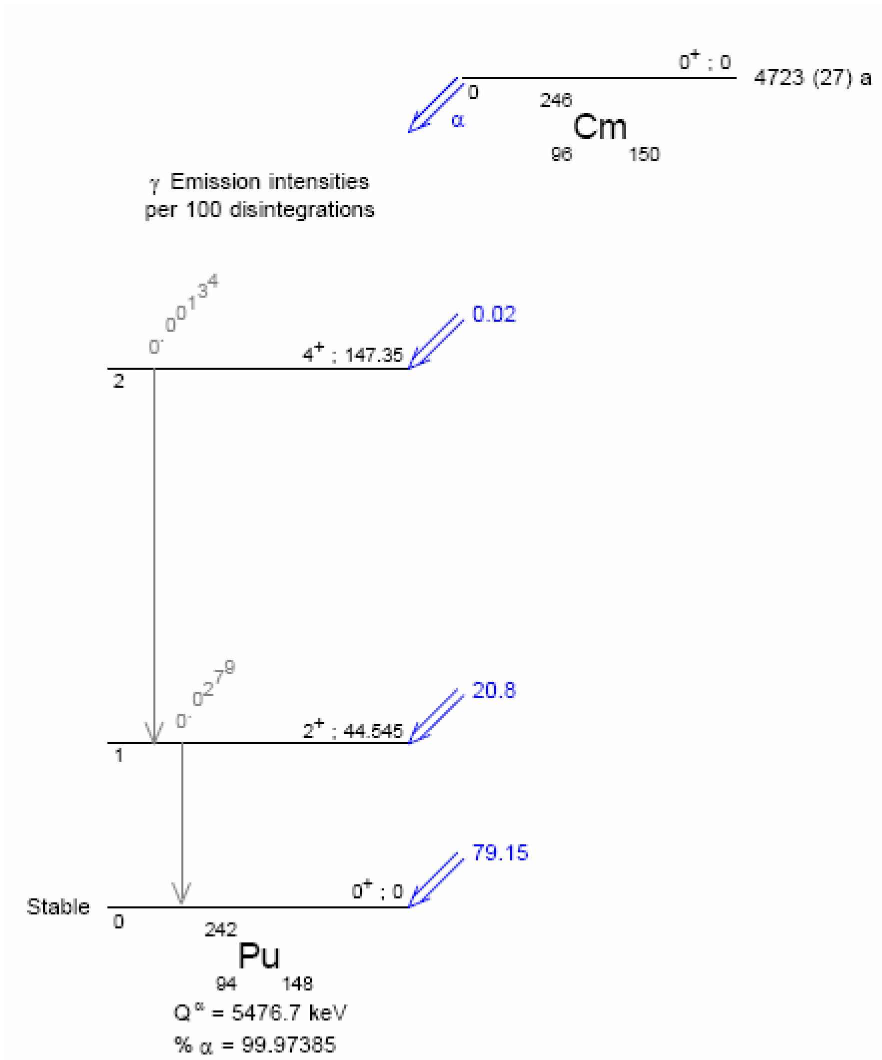

Figure 1. Decay scheme of ^{246}Cm.

Argonne NATIONAL LABORATORY

Nuclear Engineering Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 208
Argonne, IL 60439-4842

www.anl.gov

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