Decay Data Evaluation Project (DDEP): Updated evaluation of the ^{133}Ba, ^{140}Ba, ^{140}La and ^{141}Ce decay characteristics

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Abstract. Within the Decay Data Evaluation Project (DDEP) an updated comprehensive assessment has been made of the decay characteristics of ^{133}Ba, ^{140}Ba, ^{140}La, and ^{141}Ce. Experimental data published up to 2016 along with other information (new compilations, analyses and corrections) were taken into account. Newly evaluated values of the half-lives and a number of other key decay characteristics are presented in this paper for all four radionuclides.

1. Introduction

The Decay Data Evaluation Project (DDEP) is an international collaborative effort aimed at producing high-quality comprehensive nuclear decay data evaluations for important applied radionuclides [1,2], for example, gamma ray standards for detector efficiency calibrations, medical radioisotopes, and essential dosimetry calculations. Such evaluations are based on the comprehensive assembly of all relevant published experimental and theoretical data accumulated up to the present.

The mass region 135 to 141 contains some important applications-oriented calibration standards. Both ^{133}Ba and ^{141}Ce are regularly used as detector efficiency calibrants [3], while ^{140}Ba, ^{140}La are burn-up monitors and constitute evidence of nuclear explosions. The latter are also neutron reaction residuals included in the International Reactor Dosimetry and Fusion File (IRDFF) [4].

Previous DDEP evaluations for ^{133}Ba, ^{140}Ba and ^{140}La decay characteristics were published in Monographie BIPM-5, 2004 [5,6]. Newly recommended half-lives and a limited number of other important decay characteristics for these radionuclides are presented in this paper. While the 2000 DDEP evaluation of ^{141}Ce decay was fairly recently updated by one of the authors in 2012 [8], a newly recommended half-life has arisen from the current exercise and is reported below. The comprehensive decay data evaluations and detailed comments can be found on the DDEP web site maintained by the CEA/LNE-LNHB [7].

2. Background and evaluation methodology

The updated evaluations were obtained using the approaches and methodology adopted by the DDEP working group [2,9]. All experimental data published up to 2016 along with new compilations, analyses and corrections were taken into account in the current evaluations. In particular, as a consequence of a major problem discovered in the NIST ionization chamber used in their radionuclide calibration studies over many years, the NIST corrections to these half-life data in 2014 were taken into account [10].

Statistical processing of published experimental data sets has involved the development and applying of the LWEIGHT computer program, which uses the Limitation of Relative Statistical Weight method (LWM) [11] to obtain well-defined averages throughout the evaluation. The uncertainty assigned to these average values is either greater than or equal to the smallest uncertainty of the values used to calculate the average. This uncertainty of the best result ("smallest experimental uncertainty") reflects the type B standard uncertainty (systematic error of the method) and the recommended uncertainty cannot be less than this value [2,9,12].

Two important compilations that are regularly reviewed and updated lead to the need to correct some of the parameters in decay data evaluations: atomic mass evaluations (AME) [13], and calculations of theoretical internal conversion coefficients (ICCs) by means of the BrIcc computer program [14]. AME leads to updated Q-values and relevant corrections in nuclear transition energy values, while BrIcc calculations have improved the ICCs used in the decay data evaluations.

The evaluated decay characteristics includes: half-life, decay energy, energies and probabilities of beta or electron capture transitions, energies and probabilities of gamma-ray transitions, internal conversion coefficients, energies and absolute emission probabilities of gamma-rays, energies and absolute emission probabilities of X-rays, and energies and absolute emission probabilities of electrons. Newly evaluated values for all these characteristics can be found on the DDEP web site [7], as mentioned above. Our brief review of the updated evaluations focuses on half-lives, decay energies and gamma-ray energies and emission probabilities (intensities).

3. ^{133}Ba

An earlier DDEP evaluation of ^{133}Ba decay data was undertaken by the authors of this paper in 2000 with

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Table 1. ^{133}Cs levels populated in the EC decay of ^{133}Ba and the evaluated intensities of the electron capture transitions.

Level	Level energy, keV	Spin and parity	I(EC), %
0	0	7/2+	<0.0005
1	80.9979 (11)	5/2+	<0.7
2	160.6121 (16)	5/2+	<0.3
3	383.8491 (12)	3/2+	14.5 (5)
4	437.0113 (13)	1/2+	85.4(5)

a minor correction in 2004 [5]. The current evaluation was completed with the same month/year cut-off in the literature, and has now been placed on the DDEP web site [7].

^{133}Ba decays primarily by allowed electron capture branches to the 1/2+ and 3/2+ ^{133}Cs levels at 437.0 and 383.8 keV. Evaluated intensities of the electron capture transitions (I (EC), %) at these levels have been obtained from balances of the gamma-ray transition intensities. Upper limits for other possible electron capture branches to the ^{133}Cs ground state and levels at 81.0 and 160.6 keV have been estimated from log ft systematics (Table 1).

3.1. Half-life

We updated the 2004 DDEP half-life evaluation of ^{133}Ba on the basis of enforced adjustment to earlier NIST and PTB measurements in previous years [10,15] (see comments for ^{133}Ba on the DDEP web site [7]). A final set of ten selected experimental values were analysed by LWEIGHT to determine a weighted average half-life of 3849.3 d with an external uncertainty of 2.3 d (reduced-$\chi^2/(\chi^2)_{crit}$ is 10.0/2.4). Thus, the recommended ^{133}Ba half-life value is 3849.3 (23) days, or 10.539 (6) years, which is virtually unchanged from the previous value of 10.540 (6) years [5] and differs from the recommended ENSDF value of 10.551 (11) years [16].

3.2. Gamma-ray transitions and emissions

ICCs adopted for gamma-ray transitions in ^{133}Ba decay were obtained by means of the BrIcc computer program [14] using the multipolarities and mixing ratios δ from an ENSDF evaluation [16].

The absolute gamma-ray intensities (Iγ, %) listed in Table 2 have been calculated from the relative emission intensities of each gamma-ray evaluated from experimental data sets for (number of values from 21 to 37) and a normalisation factor of 0.6205 (19) adopted from the absolute emission probability of the 356-keV γ-ray which resulted from an international intercomparison ICRM – S – 6 [17].

4. ^{140}Ba and ^{140}La

Initial evaluations of ^{140}Ba and ^{140}La decay data were performed by R.G. Helmer in 2003 [6], and have been replaced with the results of our recent evaluations to be found on the DDEP web site [7]. We have followed Helmer's approach in the evaluation of the gamma ray energies and emission probabilities while updating the ICC and other decay characteristics as a consequence of the new information published in refs [10,13,14].

Table 2. Evaluated gamma-ray energies and absolute intensities in the EC decay of ^{133}Ba.

Gamma ray	Energy, keV	Iγ, % - 2004 [5]	Iγ, % - 2016 [7]
$\gamma_{4,3}$(Cs)	53.1622 (6)	2.14 (3)	2.14 (6)
$\gamma_{2,1}$(Cs)	79.6142 (12)	2.65 (5)	2.63 (19)
$\gamma_{1,0}$(Cs)	80.9979 (11)	32.9 (3)	33.3 (3)
$\gamma_{2,0}$(Cs)	160.6121 (16)	0.638 (4)	0.638 (6)
$\gamma_{3,2}$(Cs)	223.2368 (13)	0.453 (3)	0.450 (5)
$\gamma_{4,2}$(Cs)	276.3989 (12)	7.16 (5)	7.13 (6)
$\gamma_{3,1}$(Cs)	302.8508 (5)	18.34 (13)	18.31 (11)
$\gamma_{4,1}$(Cs)	356.0129 (7)	62.05 (19)	62.05 (19)
$\gamma_{3,0}$(Cs)	383.8485 (12)	8.94 (6)	8.94 (6)

Table 3. ^{140}La levels populated in the β^- decay of ^{140}Ba and the evaluated intensities of the beta transitions.

Level	Level energy, keV	Spin, parity	E(β), keV	I(β), %
0	0	3−	1048 (8)	≤ 0.00001
1	29.9641 (6)	2−	1018 (8)	25.6 (42)
2	43.884 (18)	1−	1004 (8)	35.6 (31)
3	63.1790 (7)	4−	985 (8)	<10^{-8}
4	162.659 (2)	2−	885 (8)	4.14 (31)
5	467.63 (3)	1−	580 (8)	9.71 (12)
6	581.106 (18)	0−	467 (8)	24.94 (50)

Both ^{140}Ba and ^{140}La decay by β^- emission: ^{140}Ba populates five ^{140}La excited levels (Table 3), while ^{140}La decays to 18 excited levels of ^{140}Ce [7]. Evaluated intensities of all of these beta transitions have been obtained from the depopulation-population balances of the gamma-ray transition intensities.

4.1. Half-lives

No new ^{140}Ba and ^{140}La half-life measurements have been published during the intervening period of 2004–2014. The evaluated half-life values of ^{140}Ba (12.753 (5) days) and ^{140}La (40.286 (5) hours) were obtained by statistical processing sets of selected measurements, including the NIST values adjusted in 2014 [10]. Uncertainties in the evaluated and recommended half-lives were assigned on the basis of the smallest experimental uncertainty in the original data sets [9]. More detailed information is given in the comments for ^{140}Ba and ^{140}La on the DDEP web site [7] and Ref. [12].

4.2. Gamma-ray transitions and emissions

ICCs for the gamma-ray transitions in the β^- decays of ^{140}Ba and ^{140}La were obtained via the BrIcc program [14] in an identical manner to the ^{133}Ba decay data evaluation.

Absolute gamma-ray intensities (Iγ, %) in ^{140}Ba and ^{140}La β^- decays (Tables 4 and 5) have been determined from the evaluated relative gamma-ray intensities and scaling factors calculated from gamma-ray transition probability balances to the ground states of ^{140}La and ^{140}Ce, respectively (Tables 4 and 5). This particular approach proved to be highly appropriate and valid because of the negligible amount of direct β^- decay to the two ground states [7].

The small differences between the 2004 and 2016 evaluations of the gamma-ray emission probabilities and

Table 4. Evaluated gamma-ray energies and absolute intensities in the β^- decay of ^{140}Ba.

Gamma ray	Energy, keV	Iγ, % - 2004 [5]	Iγ, % - 2016 [7]
$\gamma_{2,1}$(La)	13.880 (18)	1.15 (3)	1.16 (4)
$\gamma_{1,0}$(La)	29.9641 (6)	14.32 (25)	14.4 (4)
$\gamma_{4,0}$(La)	162.6591 (19)	6.26 (9)	6.49 (27)
$\gamma_{5,4}$(La)	304.971 (30)	4.30 (4)	4.33 (9)
$\gamma_{5,2}$(La)	423.79 (4)	3.11 (3)	3.13 (6)
$\gamma_{5,1}$(La)	437.666 (30)	1.927(19)	1.94 (4)
$\gamma_{6,2}$(La)	537.261 (25)	24.39 (22)	24.6 (5)

Table 5. Evaluated energies and absolute intensities of the most intense gamma rays in the β^- decay of ^{140}La.

Gamma-ray energy, keV	Iγ, % - 2004 [5]	Iγ, % - 2015 [7]
328.761 (4)	20.8 (3)	20.8 (3)
432.513 (8)	2.995 (16)	3.00 (3)
487.022 (6)	46.1 (4)	46.1 (5)
751.653 (7)	4.392 (24)	4.39 (5)
815.781 (6)	23.72 (12)	23.72 (20)
867.839 (16)	5.58 (3)	5.58 (7)
919.533 (10)	2.730 (23)	2.73 (3)
925.198 (7)	7.04 (4)	7.04 (7)
1596.203 (13)	95.428 (25)	95.40 (5)
2521.390 (14)	3.412 (24)	3.41 (5)

their uncertainties are primarily caused by the adoption of more realistic ICCs in the current work as derived by means of BrIcc.

5. ^{141}Ce

The initial DDEP evaluation of ^{141}Ce decay data was made by Schönfeld in 1999 [18] and updated in Ref. [8]. As in [8], we obtained a recommended value for the absolute intensity of the single gamma ray in the decay of ^{141}Ce with energy 145.4433 (14) keV by determining the weighted average of four published experimental values, but with an uncertainty equal to the smallest experimental uncertainty of the measurements: 48.29 (30)%.

The evaluated value of the ^{141}Ce half-life has been obtained in this work taking into account the new published experimental values [10,19]. Of the eight measurement results taken for analysis (in days): 32.5 (2) [20], 32.6 (2) [21], 32.45 (13) [22], 32.501 (13) [23], 32.50 (3) [24], 32.51 (10) [25], 32.56 (5) [19] and 32.51 (5) [10], the LWEIGHT program identified one outlier (32.6 (2) [21]). The remaining set of seven values was adopted to deduce a weighted average of 32.504 d with an internal uncertainty of 0.011 d ($\chi^2/(\chi^2_{\mathrm{crit}}) = 0.25/2.80$). The smallest experimental uncertainty is 0.013 d.

Therefore, the newly recommended half-life for ^{141}Ce is 32.504 (13) d, and can be compared with the two earlier DDEP evaluations of 32.508 (13) days [18] and 32.503 (11) days [8].

6. Energy conservation

The reliability of the evaluated data was checked for each nuclide by comparison of the total average emission energies $\langle E \rangle$ per disintegration as calculated from the

Table 6. Comparison of the total average emission energies $< E >$ with the Q values [13].

Nuclide	$<$E$>$, keV	Q, keV
^{133}Ba	516.8 (36)	517.3 (10)
^{140}Ba	1040 (60)	1048 (8)
^{140}La	3763 (10)	3760.9 (18)
^{141}Ce	580.5 (33)	580.4 (11)

current evaluated data with Q values from mass tables [13] (Table 6). The good agreement of the $\langle E \rangle$ value with the Q value for each nuclide confirms the consistency of the adopted decay scheme and reliability of the evaluated emission energies and intensities [26].

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