^{133}Ba - Comments on evaluation of decay data

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The first DDEP evaluation of ^{133}Ba decay data was completed by these authors in January 2004 (2004BeZR). The current updated evaluation was completed in May 2015 with a literature cut-off by the same date. The main changes compared to the initial evaluation are mainly due to new publications: 2012Wa38 (Q-value), 2008Ki07 (theoretical internal conversion coefficients), 2014Manohar (relative gamma and conversion electron probabilities) and 2010Sc08, 2012Fi12, 2014Un01 (half-life measurements and corrections).

1. DECAY SCHEME

^{133}Ba decays primarily by allowed electron capture (ε) branches to the $1/2^+$ and $3/2^+$ ^{133}Cs levels at 437 and 383 keV. As to the intensities of the other possible ε branches to the ^{133}Cs ground state and levels at 81 and 161 keV they can be estimated from log *ft* systematics. From that of 1998Si17, one expects the log *ft* of the unique 2nd forbidden decay to the ground state to be greater than 13.9 which corresponds to a branch of less than 0.0005%. Similarly, the log *ft* of the 2nd forbidden decays to the 81- and 161-keV levels are expected to be greater than 10.6 which corresponds to branches of less than 0.7% and 0.3%, respectively. Our evaluations for each of these branches obtained from the intensity balance at the above levels agree very well with this expectation (see section 2.1). Therefore, all of these unobserved β branches can be assumed as upper limits from the log *ft* systematics.

For comparison see also the evaluations made by Yu. Khazov, A. Rodionov, and F.G. Kondev (2011Kh02), Shaheen Rab (1995Ra12) and A.L. Nichols (1993Nichols) as well as the analyses made by R.B. Firestone (1990Fi03) and F.E. Chukreev (1992Chukreev).

2. NUCLEAR DATA

Q^- value is from 2012 mass evaluation by Wang *et al.* (2012Wa38).

The recommended half-life of ^{133}Ba is based on the experimental results given in Table 1.

Table 1. Experimental values of the ^{133}Ba half-life (in days)

N	Author(s) and year	Reference	$T_{1/2}$ (d)	Method and comments
1	Wyatt *et al.* (1961)	1961Wy01	3908 (73)	γ-ray scintillation spectroscopy and a beta proportional counter;
2	Lagoutine *et al.* (1968)	1968La10	2849 (37)	Ionization chamber, γ-ray scintillation spectroscopy and 4πβ- proportional counter; *omitted* because of the large deviation from the mean value
3	Reynolds *et al.* (1968)	1968Re04	3894 (44)	γ-ray scintillation spectroscopy and a beta proportional counter
4	Walz *et al*. (1970)	1970Wa19	3781 (15)	4πγ ionization chamber; *omitted* as superseded by 12
5	Emery *et al.* (1972)	1972Em01	3981 (37)	γ-ray scintillation spectroscopy and a beta proportional counter; omitted on the Chauvenet's criterion
6	Lloyd *et al.* (1973)	1973Ll01	4127 (260)	*omitted* on the Chauvenet's criterion
7	Hansen *et al.* (1979)	1979HaYC	3850 (55)	Ge(Li), NaI(Tl), Si(Li)
8	Rutledge and Mouchel (1980)	1980RuZY	3785 (27)	4πγ ionization chamber, 4πβ-γ coincidence
9	Houtermans *et al.* (1980)	1980Ho17	3848.0 (11)	4πγ pressurized ionization chamber
10	Hoppes *et al.* (1982)	1982HoZJ	3828 (11)	4πγ ionization chamber; *omitted* as superseded by 19
11	Kits *et al.* (1983)	1983Ki08	3885.9 (43)	4π ionization chamber
12	Walz *et al*. (1983)	1983Wa26	3842 (18)	4πγ ionization chamber
13	Unterweger *et al.*(1992)	1992Un01	3853.6 (36)	4πγ ionization chamber; *omitted* as superseded by 19
14	Martin *et al.* (1979)	1997Ma75	3848.9 (7)	4πγ ionization chamber
15	Unterweger *et al.*(2002)	2002Un02	3854.7 (28)	4πγ ionization chamber; *omitted* as superseded by 19
16	Schrader (2004)	2004Sc04	3840.5 (65)	Ionization chamber; *omitted* as superseded by 17
17	Schrader (2010)	2010Sc08	3840.3 (89)	Ionization-chamber
18	Fitzgerald (2012)	2012Fi12	3854.7 (28)	4πγ ionization chamber; *omitted* as superseded by 19
19	Unterweger and Fitzgerald (2014)	2014Un01	3830 (7)	4πγ ionization chamber
Recommended value (days)			**3849.3 (23)**	**LWM**
Recommended value (years)			**10.539 (6)**	

The values before 1961 were omitted due to their large uncertainties (more than 1 year).

The values of 1970Wa19, 1982HoZJ, 1992Un01, 2002Un02 and 2012Fi12 were omitted as they were replaced by later results from the same group.

Also the value of 1968La10 was omitted on statistical considerations because of a great contribution into the χ^2 value (27 σ from adopted value).

The uncertainty of 1997Ma75 was increased to 0.98 days to adjust weights according to the Limitation of Relative Statistical Weight method (LWM). In consequence the LWEIGHT program chose the weighted average of 3849.3 days and external uncertainty of 2.3 days. The internal uncertainty is 0.74 d and the smallest experimental uncertainty is 0.7 d. The ratio of the reduced $\chi^2 / (\chi^2)_{crit}$ is 10.0/2.4.

It should be noted that in the weighted average of the two values of 1980Ho17 and 1997Ma75 have altogether 95% of the relative weight. Since these two values agree, any weighted average will be about 3849 days that differs slightly from an unweighted average of about 3853 days.

The recommended value of ^{133}Ba half-life is **3849.3 (23) days**. It can be compared with earlier evaluations of 3849.7 (22) days (2004BeZR) and 3853.7 (40) days (2011Kh02).

2.1. Electron Capture Transitions

The energies of the electron capture, ε, transitions have been calculated from the Q value and the level energies which have been deduced from gamma transition energies (see also 2011Kh02: Adopted Levels, Gammas). The level spins, half-lives and parities of ^{133}Cs (Table 2) are taken from 2011Kh02 (Adopted Levels).

Table 2. ^{133}Cs levels populated in ^{133}Ba ε-decay

Level	Energy (keV)	Spin and parity	Half-life	Pε (%) – obtained from intensity balance	Pε (%) - adopted
0	0	7/2+	stable	0.0000 (5)	< 0.0005
1	80.9979 (11)	5/2+	6.283 (14) ns	0.08 (55)	< 0.7
2	160.6121 (16)	5/2+	172 (4) ps	0.04 (59)	< 0.3
3	383.8491 (12)	3/2+	44 (11) ps	14.46 (51)	14.5 (5)
4	437.0113 (13)	1/2+	≤ 150 ps	85.41 (53)	85.4 (5)

The electron capture probabilities $P\varepsilon_{0,4}$ and $P\varepsilon_{0,3}$ were calculated from the intensity balance for the 437 level and the 384 level, respectively, using the evaluated $P_{\gamma+ce}$ values.

Similarly, the electron capture probabilities $P\varepsilon_{0,2}$ and $P\varepsilon_{0,1}$ are obtained from the intensity balance for 161-keV and 81-keV levels, respectively, as 0.08 (55) and 0.04 (59) per 100 disintegrations. From here the upper limit of 0.63 per 100 disintegrations for each of these transitions agree with theoretical estimations, and the evaluators adopted for their probabilities upper limits of theoretical estimations: $P\varepsilon_{0,2} < 0.3\%$ and $P\varepsilon_{0,1} < 0.7\%$. Similarly, $P\varepsilon_{0,0} < 0.0005$ %.

The P_K, P_L and P_M values for $\varepsilon_{0,4}$ and $\varepsilon_{0,3}$ transitions have been computed using the code LOGFT (http://www.nndc.bnl.gov/logft/).

The available experimental P_K values are presented in **Table 3.**

Table 3. The experimental and adopted P_K values in ^{133}Ba ε-decay.

	$P_K(\varepsilon_{0,4})$	$P_K(\varepsilon_{0,3})$
1968Na16	0.68 (5)	
1972Sc08	0.72 (4)	0.80 (7)
1974Da09	0.76 (6)	0.87 (14)
1975Ni07	0.75 (10)	
1983Si17	0.75 (4)	0.80 (4)
1983Si22	0.71 (11)	0.79 (5)
1988BeYQ	0.78 (4)	
1990Da11	0.76 (4)	
1990Bh01	0.730 (12)	0.81 (3)
1992Sa28	0.65 (3)	0.74 (4)
adopted	**0.671 (5)**	**0.7727 (9)**

Most of these values were obtained in 1974-1990 using the method of the X-, gamma-ray sum peak measurements. The measurement results exceed the adopted theoretical P_K values for the allowed $\varepsilon_{0,4}$, $\varepsilon_{0,3}$ - transitions and depend on conversion coefficients α_K and fluorescence yields ω_K used in those works.

2.2. Gamma Transitions and Internal Conversion Coefficients

The evaluated energies of gamma transitions are the energies of gamma rays with adding the recoil energy.

The multipolarities and mixing ratios δ are taken from the adopted data in the ENSDF evaluation (2011Kh02). Gamma-ray transition probabilities P(γ+ce) except for the γ-ray of 81 keV ($\gamma_{1,0}$) have been deduced from their gamma-ray emission probabilities and the total ICC(s). The adopted ICC(s) are obtained from the theoretical values by using the adopted mixing ratios δ and the BrIcc computer program (http://bricc.anu.edu.au), accepting the "frozen orbital (no hole)" approximation (2008Ki07).

P(γ+ce) of the of 81 keV γ-ray transition ($\gamma_{1,0}$) was calculated in order to reach the ground state gamma-ray transition intensity balance:

P(γ+ce) (γ_{81}) = 100% – P(γ+ce) (γ_{161}) – P(γ+ce) (γ383) = 90.05 (6) %.

3. ATOMIC DATA

The atomic data (fluorescence yields, X-ray energies and relative probabilities, and Auger electron energies and relative probabilities) have been deduced using the SAISINUC software.

4. ELECTRON EMISSIONS

The energies of the conversion electrons were obtained from the gamma-ray transition energies and the electron binding energies. The absolute emission probabilities of the conversion electrons were deduced using recommended Pγ and ICC values. The absolute emission probabilities of K and L Auger electrons were calculated using the EMISSION computer program.

5. PHOTON EMISSIONS

5.1. X-ray Emissions

The X-ray energies are based on the wavelengths in the compilation of 1967Be65 (Bearden).

The absolute emission probabilities of Cs KX- and LX- rays were calculated using the EMISSION computer program.

The measured values of the total absolute emission probability of KX-rays (P_{XK}×100) are given below in comparison with the calculated (adopted) value:

1972Sc08	1977Sc31	1989Egorov	**Adopted**
123.1 (17)	117.4 (22)	119.7 (11)	**118.9 (13)**

5.2 Gamma-Ray Emissions

The γ-ray energies are taken from the evaluation 2000He14 where the values are deduced on the revised energy scale. For the γ-ray of 81 keV see also the measurement of 1991We08.

The γ-ray absolute emission probabilities have been computed using the evaluated γ-ray relative emission probabilities and the absolute emission probability of the 356-keV γ-ray of 0.6205 (19) measured in 1980Chauvenet, 1983Ch11. This experimental value for the most intensive γ-ray in the decay of ^{133}Ba was obtained as a result of the international intercomparison ICRM-S-6 (1980Chauvenet). It is more preferable for normalizing of gamma-ray absolute emission probabilities than having been obtained from the ground state intensity balance 0.613 (34) – because of big uncertainties in multipolarity admixtures (and thus in ICC) as well as possible ambiguity in determination of some spins (see 1992Chukreev).

At the same time the relative gamma ray emission probabilities from ICRM-S-6 measured at the fifteen laboratories are used below in Table 1 equally with other measurements for averaging all the available data. The measurements of ICRM-S-6 have been lettered CRP and deduced from absolute emission probabilities published in 1980Chauvenet excluding an activity uncertainties ~ 0.2%.

Table 5. The experimental and adopted relative gamma ray emission probabilities.

	γ53	γ80	γ81	γ161	γ223	γ276	γ303	γ356	γ383
1967Bl15	3.8 (8)	3.8 (4)	53 (4)	1.1 (3)	0.7 (3)	11.0 (7)†	30 (2)	100	14.5 (1)
1968Al16	3.3 (5)	-	-	1.20 (6)†	0.74 (6)	12.0 (4)†	30.6 (9)†	100	14.2 (5)
1968Bo04	4.2 (2)†	4.0 (4)	58.2 (15)	1.07 (5)	0.78 (6)	11.8 (3)	29.8 (8)	100	14.3 (10)
1968Do10	3.2 (4)	5.5 (7)†	52 (7)	0.99 (10)	0.72 (8)	11.6 (8)	29.4 (2)	100	14.3 (10)
1968No01	3.78 (9)	4.9 (6)	60 (7)	1.21 (5)†	0.80 (3)†	11.61 (17)	29.75 (29)	100	14.18 (26)
1969Gu15	2.91 (5)	4.54 (7)	53.7 (17)	1.13 (15)	-	11.2 (3)	29.3 (5)	100	14.03 (26)†
1972Sc08	3.54 (5)	3.9 (2)	52.6 (10)	1.16 (5)	0.74 (4)	11.4 (3)	30.2 (6)	100	14.4 (3)
1973In06	-	-	-	0.98 (7)	0.76 (5)	11.6 (5)	29.6 (11)	100	14.9 (6)†
1973Legrand	-	3.7 (4)	56 (6)	1.4 (2)†	0.66 (2)†	11.35 (25)	29.4 (6)	100	14.3 (3)
1973Mc18	-	-	-	-	-	11.43 (23)	29.3 (6)	100	14.5 (3)
1977Ge12	3.0 (4)	5.6 (15)†	52 (4)	1.12 (8)	0.85 (7)†	11.7 (8)	29.87 (21)	100	14.4 (11)
1977Sc31	3.49 (8)	4.29 (12)	55.8 (16)	0.97 (3)	0.73 (3)	11.41 (16)	29.4 (3)	100	14.33 (21)
1978He21	3.54 (18)	3.1 (3)†	49.2 (26)	1.08 (4)	0.745 (25)	11.7 (4)	29.8 (4)	100	14.36 (20)
1978Vylov	3.57 (12)	4.16 (18)	54.6 (17)	0.98 (8)	0.71 (4)	11.4 (3)	28.8 (8)†	100	14.3 (5)
1980Ro22	-	-	-	1.03 (7)	0.72 (5)	11.69 (16)	29.9 (4)	100	14.79 (27)†
1983Yo03	-	-	-	1.035 (28)	0.756 (16)	11.57 (7)	29.55 (18)	100	14.36 (9)
1987Lakshmi	2.96 (9)	4.67 (14)	55.3 (16)	-	-	-	-	100	-
1989Da11	3.6 (5)	3.7 (5)	52.3 (7)	1.032 (10)	0.713 (8)	11.51 (8)	29.51 (23)	100	13.99 (9)†
1990Me15	3.48 (7)	3.77 (9)	51.2 (4)	1.05 (3)	0.71 (2)	11.3 (2)	29.2 (3)	100	14.5 (2)
1998Hw07	-	-	-	0.950 (18)	0.715 (10)	11.64 (13)	29.31 (40)	100	14.52 (17)
CRP-1	-	-	-	1.11 (9)	0.85 (5)†	11.7 (4)	29.9 (11)	100	14.5 (5)
CRP-2	3.56 (14)	-	53.1 (19)	0.99 (4)	0.729 (28)	11.7 (3)	30.1 (9)	100	14.4 (5)
CRP-3	3.53 (8)	4.20 (12)	54.8 (12)	1.031 (24)	0.69 (3)	11.51 (14)	29.5 (3)	100	14.37 (16)
CRP-4	3.53 (7)	4.18 (11)	54.6 (12)	1.037 (20)	0.730 (22)	11.48 (14)	29.5 (4)	100	14.41 (16)
CRP-5	3.9 (7)	4.00 (15)	51.5 (19)	1.020 (27)	0.728 (22)	11.5 (3)	29.5 (9)	100	14.2 (5)
CRP-6	3.45 (8)	4.73 (12)	57.6 (14)	1.020 (25)	0.728 (18)	11.68 (28)	29.7 (7)	100	14.5 (4)
CRP-7	3.56 (8)	4.73 (12)	58.9 (15)	1.070 (27)	0.738 (18)	11.50 (28)	29.6 (7)	100	14.3 (4)
CRP-8	-	-	-	-	-	11.22 (27)	29.3 (6)	100	14.53 (28)
CRP-9	-	-	-	-	-	11.22 (24)	29.3 (5)	100	14.26 (25)
CRP-10	-	-	-	-	-	11.48 (25)	29.3 (5)	100	14.20 (22)
CRP-11	-	-	-	-	-	11.57 (19)	29.4 (4)	100	14.34 (26)
CRP-12	3.69 (18)	4.37 (16)	55.3 (18)	1.050 (19)	0.741 (15)	11.53 (16)	29.5 (4)	100	14.36 (20)
CRP-13	2.92 (16)	-	-	-	0.75 (3)	11.9 (4)	30.2 (11)	100	14.6 (5)
CRP-14	3.53 (8)	4.39 (11)	55.9 (12)	1.015 (20)	0.735 (10)	11.61 (13)	29.6 (4)	100	14.34 (18)

	γ53	γ80	γ81	γ161	γ223	γ276	γ303	γ356	γ383
CRP-15	3.36 (18)	-	-	1.05 (4)	0.758 (28)	11.7 (5)	29.6 (10)	100	14.3 (4)
CRP-16	3.26 (17)	-	-	1.05 (4)	0.764 (26)	11.7 (4)	29.7 (6)	100	14.3 (3)
CRP-19	3.53 (5)	-	-	1.063 (17)	0.725 (17)	11.61 (12)	29.7 (3)	100	14.53 (13)
CRP-20	3.53 (6)	4.05 (8)	55.1 (9)	1.05 (5)	0.72 (4)	11.49 (21)	29.4 (6)	100	14.51 (22)
CRP-21	3.62 (6)	4.15 (12)	55.8 (9)	1.039 (15)	0.705 (11)	11.57 (17)	29.5 (4)	100	14.40 (20)
2014Manohar††	3.505 (50)	4.05 (7)	52.44 (98)	0.94 (3)	0.72 (2)	11.21 (7)	29.17 (18)	100	14.39 (9)
Number of input values	28	21	25	30	29	37	37		35
Reduced χ^2	7.0/1.7	5.6/1.9	4.0/1.8	1.9/1.7	0.8/1.7	0.9/1.6	0.4/1.6		0.2/1.6
Weighted average	3.454	4.241	53.36	1.029	0.725	11.497	29.51		14.40
Internal uncertainty	0.016	0.027	0.23	0.0047	0.0035	0.028	0.061		0.034
External uncertainty	0.042	0.064	0.45	0.0066	0.0030	0.026	0.038		0.015
Adopted value (LWM)	**3.45 (9)**	**4.24 (30)**	**53.7 (5)** †††	**1.029 (10)**	**0.725 (8)**	**11.49 (7)**	**29.51 (18)**	**100**	**14.40 (9)**

† Omitted as outliers

†† None quantitative estimates of uncertainty *components* (uncertainty budget) are given in 2014Manohar for measured relative gamma-ray intensities. These uncertainties seem to be too underestimated. The reviewers adopted for them the smallest uncertainties from all previous measurements for each corresponding gamma-ray.

††† Adopted value has been changed slightly from the weighted average for a precise ground state intensity balance to get. Such a small change only for one gamma-ray supports the adopted experimental value of 62.05 (19) % for the 356 keV γ-ray absolute emission probability and confirms the decay scheme. The adopted uncertainty of 0.5 is external.

In addition, in 1996Mi26 a special precise measurements of the absolute emission probabilities only for the two weak 161 and 223 keV gamma-rays were made by using a 4πβ(ppc)-γ(HPGe) coincidence system. The adopted relative emission probabilities of these gamma-rays (1.029 (10) and 0.725 (8)) can be compared with relative emission probabilities (1.028 (8) and 0.730 (5), respectively) calculated from the absolute values (0.6383 (38) % and 0.4530 (31) %, respectively) from 1996Mi26.

6. ENERGY CONSERVATION

The total average energy of 516.8 (36) keV, for one disintegration, calculated from the current evaluated data corresponds well to the available energy of 517.3 (10) keV (Q^+) from the mass tables (2012Wa38) confirming the consistency of the decay scheme and the reliability of this evaluation.

7. REFERENCES

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