^{137}Cs - Comments on evaluation of decay data

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An evaluation of ^{137}Cs decay data has been performed by Sylvain Leblond during 2021-2023, with a literature cutoff date of January 2023.

Evaluation procedure and convention

The work presented follows mainly the DDEP evaluation procedures, with the associated uncertainty of any recommended value given at one standard deviation. If the authors of any of the references mentioned in this work use a different convention, the uncertainty of the reported measurement is adjusted to one standard deviation for consistency. Additionally, if any reported uncertainty is asymmetric, the value and uncertainty are re-defined symmetrically by means of the method described in [2012Au07].

Given the nature of the ^{137}Cs decay scheme, the determination of most of the transition intensities can be based on a knowledge of one of them and the total internal conversion coefficient of the second excited state of ^{137}Ba. Rather than taking only one route to calculate a consistent decay scheme, I have chosen to use all of the available information by performing a weighted average of different independent methods. Thus, care is required when reading this document, as the recommended emission intensities reported in the table do not necessarily correspond to the evaluated transition intensity obtained independently. For a better understanding, the different methods used to deduce the decay data recommendations are quickly summarized below:

- Q value of the decay is obtained from AME2020
- Energy of ^{137}Ba excited states are recommended from the analysis of published measurements.
- Half-life of ^{137m}Ba and ^{137}Cs are recommended from the analysis of published measurements
- Intensities of beta and gamma emission are deduced from a weighted average of various independent methods (see Section 2.5)
- Conversion coefficients of ^{137}Ba are calculated using BrIcc code
- Mean energy of beta transitions is calculated using BetaShape code
- X-rays intensities are calculated using Emission code

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Foreword

Throughout the document, I have detailed and explained my data evaluations so they can be tracked and assessed by the reader. I believe two decisions made in this work have a huge impact on my recommendations concerning ^{137}Cs β-decay and need to be considered with caution. These important decisions arise from the analysis of three different references:

- **[1978Ch22] and [1983Be18]**. The work of both references is of very high quality and the uncertainty budget estimation is detailed. However, the conversion coefficients deduced in these studies are highly discrepant when compared with other measurements and BrIcc calculations (see Subsection 2.4.2 for more details). As both beta intensity and conversion coefficient are also calculated from the beta spectrum, it is unclear to what extent the other measurements from these references will also be affected by experimental bias. On this matter, I have tried to limit as much as possible the impact of [1978Ch22] and [1983Be18] on the final recommendations. The procedure taken in the analysis for each decay property is detailed in each related section.
- **[1973LeZJ]**: Uncertainties given by the authors may be at the three standard deviation confidence level. However, the situation is not entirely clear: the authors do not mention the convention that they used, and only one sentence gives a hint on the matter at the bottom of page 2 " *[..] et même à celle de H. Hansen [2] qui est égale au tiers de la nôtre…"*, implying that the data in the publication of Hansen *et al.* ([1969Ha05]) are not comparable with the calculation of the latter being "*one third of ours*". The possibility that the results of [1973LeZJ] are given at the three standard deviation confidence level is supported by [1978Ch22] and a previous DDEP evaluation of ^{137m}Ba ([1998HeU0]). Given all this information, I believe that it is necessary to correct the uncertainties reported by [1973LeZJ], and therefore I have performed these corrections in the present work.

1 Decay Scheme

^{137}Cs decays by 100% β^- to the ground state and first two excited levels of ^{137}Ba, with level spins and parities taken from [2007Br23]. Level energies of the $1/2^+$ and the $11/2^-$ states are calculated in the following subsections from measurements of the gamma transition energies to the ^{137}Ba ground state. These results are presented in Table 1, and the detailed analysis for each state can be found below.

Table 1: Properties of ^{137}Ba states populated by the beta decay of ^{137}Cs

Level	Spin-parity	Level energy (keV)
Ground state	$3/2^+$	0
1st excited state	$1/2^+$	283.46 (7)
2nd excited state	$11/2^-$	661.657 (3)

Transition energies are determined from the observed gamma-ray energies and the calculated recoil energies E_R of ^{137}Ba. The mass of the nucleus is taken from [2021Wa16], and the neutron and proton mass from [2020Zy02]. Deduced recoil energies are:

- E_r = 1.70269 (3) eV for the $11/2^- \rightarrow 3/2^+$ gamma emission,
- E_r = 0.31237 (9) eV for the $1/2^+ \rightarrow 3/2^+$ gamma emission.

1.1 ^{137}Ba $11/2^-$ second excited state

As a consequence of the high gamma-ray emission probability and the favorable decay branching ratio, the transitions from this state have been intensively studied using beta decay measurements. Some measurements were also performed with neutron scattering (such as [1995Bo03]), but they are not included in this work as their uncertainties are significantly larger. The list of the references used for this work is presented in Table 2.

[1952Mu45] and [1968GeZV] have both been discarded since they do not provide enough details on their measurements and/or the associated uncertainties. The value from [1971He20] has been superseded by [2000He14] (even though the measurements are different and independent, they were both performed by Helmer). As a consequence, only three references are considered for the evaluation. This dataset is consistent (χ^2 = 1.20 / χ^2_{crit} = 4.60) and Lweight recommends a transition energy of E_{662} = 661.6566 (26) keV as the weighted average. The value of [1967Za04] has almost no influence in this weighted average (0.2% of the total weight), while the rest of the weight is split between the two remaining references (with a 70/30 ratio). On the one hand, [2000He14] is impressive work with a detailed uncertainty budget estimate, whereas [1976Bo16] contains much less detail regarding quantification of the uncertainty such as to imply some degree of underestimation. As removing [1976Bo16] from the dataset would mean relying on only one measurement [2000He14], I have decided to keep both references in this evaluation. However, I have extended the uncertainty of the weighted average to that of the most precise measurement (0.003 keV).

Table 2: References for the energy of the 11/2 state of ^{137}Ba

Reference	Transition energy (keV)	Uncertainty (keV)	Comments
1952Mu45	661.60	0.14	Discarded due to an absence of detail in the uncertainty estimation
1960Gr38	661.60	0.08	Superseded by 1968GeZV
1967Za04	661.59	0.08	
1968GeZV	661.634	0.012	Discarded due to an absence of detail in the uncertainty estimation
1969GuZV	661.622	0.01	Discarded due to an absence of detail in the uncertainty estimation
1971He20	661.640	0.019	Superseded by 2000He14
1976Bo16	661.651	0.005	
2000He14	661.659	0.003	

Therefore, I recommend **E_{662} = 661.657 (3) keV** for the energy of the 11/2$^-$ excited state of ^{137}Ba, which is very close and consistent with the value adopted in two previous evaluations, deviating by only a few eV (Table 3).

Table 3: Recommended energy for the 11/2$^-$ state of ^{137}Ba

Reference	11/2$^-$ level energy (keV)
2006HeZT	661.659 (3)
2007Br23	661.659 (3)
This work	661.657 (3)

1.2 ^{137}Ba 1/2$^+$ first excited state

Contrary to the previous case, the branching ratio to the first excited state is much less favorable, and thus fewer measurements of this transition have been performed by means of beta decay. Therefore, I have included the data from neutron scattering experiments in the list of references to be considered (Table 4).

Among the seven references considered for this work, two of them ([1973Ke22] and [1996Bi23]) have been discarded due to uncertainty budgets that are inadequately described. Measurements of [1984BoZR] has been superseded by [1995Bo03]. The dataset of three remaining references exhibits reasonable consistency (χ^2 = 1.62 / χ^2_{crit} = 4.60), and Lweight recommends a weighted-average E_{283} = 283.493 (34) keV identified with the internal uncertainty component.

Table 4: References for the energy of the ^{137}Ba 1/2$^+$ state

Reference	Transitions energy (keV)	Uncertainty (keV)	Comments
1973Ke22 / 1973Ke07	279.2	0.6	Discarded due to an absence of detail in the uncertainty estimation
1984BoZR	283.46	0.06	Superseded by 1995Bo03
1995Bo03	283.39	0.07	
1996Bi23	283.4		Discarded due to the absence of an uncertainty estimation
1997Wa37	283.53	0.04	
2007Se05	283.4	0.2	

A limit was placed on the influence of the most accurate measurement with respect to the final recommendation: the uncertainty of [1997Wa37] was increased to 0.066 keV to give a weighting of 50%, and an overall weighted average of E_{283} = 283.461 (46) keV. I have increased the uncertainty to match the most precise measurement and obtain a final recommendation of **E_{283} = 283.46 (7) keV**, which is slightly below the previous evaluations within DDEP and ENSDF (Table 5).

Table 5: Recommended energy for the 1/2$^+$ state of ^{137}Ba

Reference	11/2$^-$ level energy (keV)
2006HeZT	283.5 (1)
2007Br23	283.54 (4)
This work	283.46 (7)

The small discrepancy observed with respect to [2007Br23] arises from the limited dataset considered for the ENSDF evaluation: only [1997Wa37] was taken into account.

2 Nuclear Data

2.1 Half-life

The ^{137}Cs half-life is used in a wide range of applications, and is considered to be well known. This parameter has been intensively studied over a period of more than 70 years. A total of 72 references have been identified with this work, spanning from 1948 to 2020. Among these 72 references, 16 are previous evaluations attesting to the interest directed towards this specific radioisotope. Given the large number of references, this evaluation of the half-life is divided into three sections: the first two sections deal with the selection and analysis of the references, while the last section is dedicated to the determination of a recommended value and its uncertainty.

2.1.1 Literature overview

All the references identified on the ^{137}Cs half-life are listed in the Table 6, while previous evaluations are displayed in Table 7. The unit chosen to quantify the half-life is "year" for all references, whereby if a publication reports a value in "days", that half-life has been recalculated by adopting a definitive conversion factor of 1 year = 365.242198 days.

Table 6: All references for ^{137}Cs decay half-life

Reference	Half-life (years)	Uncertainty (years)	Detection method	Comments
1948Gr01	33	-	Direct counting (IC)	Discarded: no uncertainty
1948To02	33	-	Specific activity	Discarded: no uncertainty
1950Ag01	37	-	Specific activity	Discarded: no uncertainty
1951GlZY	33	3	Specific activity	
1953Wi09	33	2	Mass spectrometry (^{137}Cs/^{133}Cs)	Superseded by 1955Wi21
1954MeU0	26	1	Mass spectrometry	Discarded: could not be found (reported by 1965MaZR)
1955Br06	29.94*	0.35*	Specific activity	
1955Wi21	26.6	0.4	Specific activity	
1958MoZY	29.2*	1.5*	Specific activity	Superseded by 1964Co35
1960BuU0	27	-	Mass spectrometry	Discarded: no uncertainty + could not be found (reported by 1962Ri12)
1960GlU0	32.6	1.6	Mass spectrometry	Discarded: private communication (reported by 1961Fa03)
1960RiU0	28.4	1.4	Specific activity (γ)	Superseded by 1973Di01
1961Fa03	30.4	0.4	Mass spectrometry (^{137}Ba)	
1961Gl08	29	1	Specific activity	
1962BuU0	30.1	0.7	Mass spectrometry (^{137}Cs/^{133}Cs)	
1962CoU0	29.40	0.18	-	Discarded: could not be found (reported by 1988RaZL). Superseded by 1964Co35
1962Fl09	30.1	0.7	Specific activity (liquid scintillation)	
1962Ri12	29.2	0.3	Mass spectrometry (^{137}Ba)	Superseded by 1973Di01
1963Di12	30.35	0.38	Mass spectrometry (^{137}Cs/^{135}Cs)	Superseded by 1973Di01

1963Go03	29.68	0.05	Direct counting IC	
1963Ri02	29.2	0.3	Mass spectrometry (^{137}Ba)	Superseded by 1973Di01
1964Co35	29.40	0.18	Mass spectrometry (^{137}Cs/^{135}Cs)	
1964ReZX	30.7	0.3#	Direct counting IC	Superseded by 1972Em01
1965Fl01	30.9	0.7	Specific activity	Superseded by 1965Fl01 (IC 2π)
1965Fl01	29.9	0.5	Direct counting (IC 2π)	
1965Gi06	30.55	1.55	Mass spectrometry (^{137}Cs/^{135}Cs)	Superseded by 1972Em01
1965Gi06	29.78	0.14	Mass spectrometry (^{137}Ba)	Superseded by 1972Em01
1965Gi06	30.72	0.12	Specific activity	Superseded by 1972Em01
1965Le25	30.55	2.03#	Mass spectrometry (^{137}Cs/^{135}Cs)	Superseded by 1972Em01
1965Le25	29.78	0.32#	Mass spectrometry (^{137}Ba)	Superseded by 1972Em01
1965Le25	30.72	0.125#	Specific activity (γ)	Superseded by 1972Em01
1965ReU0	30.6	0.35#	Direct counting (IC)	Superseded by 1972Em01
1966Re13	30.2	0.3	Direct counting (IC)	Superseded by 1972Em01
1967Di06	30.25	0.07	-	Discarded: private communication (reported by 1975He03)
1968An01	29.76	0.13	-	Discarded: could not be found (reported by 1975He03)
1968Re04	30.23	0.16	Direct counting (IC)	Superseded by 1972Em01
1970Ha32	30.64	0.43	Direct counting (IC)	
1970Wa19	29.901	0.045	Direct counting (IC)	Superseded by 2010Sc08
1972Em01	30.18	0.1	Direct counting (IC)	
1973Co39	30.44	0.05	Direct counting (γ)	
1973Di01	30.174	0.011#	Mass spectrometry (^{137}Cs/^{135}Cs)	
1978Gr08	29.86	0.27	Specific activity (liquid scintillation)	
1980Ho17	30.142	0.030	Direct counting (IC)	
1980RuZX	28.61	0.40	Direct counting (IC)	Superseded by 1990Ma15
1982HoZJ	30.68	0.04	Direct counting (IC)	Superseded by 2020UnU0

1982RuZV	29.23	0.38	Direct counting (IC)	Superseded by 1990Ma15
1983Wa26	29.90	0.04	Direct counting (IC)	Superseded by 2010Sc08
1987MaU0	29.936	0.016	Direct counting (IC)	Superseded by 1990Ma15
1990Ma15	30.029	0.012	Direct counting (IC)	
1992Go24	29.955	0.019	Direct counting (IC)	Superseded by 2016Ju05
1992Un01	30.16	0.05	Direct counting (IC)	Superseded by 2020UnU0
1999Po34	29.80	0.12	Direct counting (γ)	
2002Un02	30.167	0.026	Direct counting (IC)	Superseded by 2020UnU0
2004Sc04	30.03	0.05	Direct counting (IC)	Superseded by 2010Sc08
2010Sc08	30.057	0.041	Direct counting (IC)	
2012Be08	29.96	0.08	Direct counting (γ)	
2014Un01	29.843	0.032	Direct counting (IC)	Superseded by 2020UnU0
2016Ju05	29.994	0.029	Direct counting (IC)	
2020UnU0	29.884	0.151	Direct counting (IC)	

[*] Original uncertainty was asymmetric, and has been re-defined symmetrically.

[#] Uncertainty in the reference is originally given with more than 65% CL, and has been updated.

Table 7: All half-life recommendations for ^{137}Cs β^- decay

Reference	Half-life (years)	Uncertainty (years)
1965MaZR	30.76	0.5
1975He03	30.034	0.1
1984ScU0	30	0.2
1985HoU0	30.1	-
1986BrZQ	30	0.2
1986ScU0	30.002	0.20
1988RaZL	30.11	0.08
1989ScU0	30.25	0.11
1990ChYZ	30.2	-
1990Wo04	30.25	0.11
1992Ra08	30.114	0.030
1994Ka08	30.076	0.033
2002He06	30.08	0.08
2006HeZT	30.05	0.08
2007Br23	30.08	0.09

It is worth mentioning that, at the time of this work, they are two unanalyzed/unpublished datasets that are relevant to the half-life evaluation of ^{137}Cs (both mentioned in [2016Po08]):

- PTB measurements are a continuation of their studies published in [2010Sc08]. A private communication with Kossert and Nähle has confirmed that this work is on-going and yet to be analyzed in order to provide a more precise measurement by means of a refined data-analysis code. Publication is expected in a few years.
- Decay rate of ^{137}Cs was studied at the Canadian National Council (NRC) laboratory from 1995 to 2009 by means of three ionization chambers. A private communication with Galea has confirmed that this dataset has yet to be analyzed.

2.1.2 Literature selection

As a starting point, a first subset of references for further consideration has been extracted from Table 6, based on DDEP guidelines concerning uncertainties and the presence of superseding measurements. A few cases of such superseding studies are considered below:

- USSR publications [1961Gl08], [1962BuU0] and [1962Fl09] exhibit no clear affiliation, and thus create difficulties regarding any possible correlation between these measurements. Since all three sets of measurements are based on different detection methods, I have assumed that they were independent of each other. [1999Po34] performed more than 35 years after 1961/62 is believed to be independent from the three earlier studies.
- Two Swiss measurements have been performed in Lausanne separated by 14 years ([1992Go24] and [2016Ju05]). A private communication with Juget has confirmed that his work included the dataset from [1992Go24], and therefore only [2016Ju05] has been considered further in this evaluation effort.
- More than one method of detection is used in several references to determine the half-life of ^{137}Cs (for example, [1965Fl01]). Even though these various detection methods might appear to be independent, only the most precise of the methods adopted was retained.

The remaining references that match all of the criteria are listed in Table 7. This dataset is highly discrepant (χ^2 = 11.001 / χ^2_{crit} = 2.00). The unweighted average is $T_{1/2}$ = 30.02 (4) years, and the weighted average is $T_{1/2}$ = 30.089 $(24)_{ext}$ $(7)_{int}$ years whereby 42% of the total weighting is identified with [1973Di01].

Table 8: Refined set of references for ^{137}Cs half-life

Reference	Half-life (years)	Uncertainty (years)	Detection method	Comments
1951GlZY	33	3	Specific activity	Discarded
1955Br06	29.94*	0.35*	Specific activity	Discarded
1955Wi21	26.6	0.4	Specific activity	Discarded
1961Fa03	30.4	0.4	Mass spectrometry (^{137}Ba)	Discarded
1961Gl08	29	1	Specific activity	Discarded
1962BuU0	30.1	0.7	Mass spectrometry ($^{137}Cs/^{133}Cs$)	Discarded
1962Fl09	30.1	0.7	Specific activity (LS)	Discarded
1963Go03	29.68	0.05	Direct counting (IC)	Discarded
1964Co35	29.4	0.18	Mass spectrometry ($^{137}Cs/^{135}Cs$)	Discarded
1965Fl01	29.9	0.5	Direct counting (2π IC)	Discarded
1970Ha32	30.64	0.43	Direct counting (IC)	Discarded
1972Em01	30.18	0.1	Direct counting (IC)	Discarded
1973Co39	30.44	0.05	Direct counting (γ)	Discarded
1973Di01	30.174	0.011#	Mass spectrometry ($^{137}Cs/^{135}Cs$)	
1978Gr08	29.86	0.27	Specific activity (LS)	Discarded
1980Ho17	30.142	0.030	Direct counting (IC)	Discarded
1990Ma15	30.029	0.012	Direct counting (IC)	
1999Po34	29.80	1.2	Direct counting (γ)	Discarded
2010Sc08	30.057	0.041	Direct counting (IC)	
2012Be08	29.96	0.08	Direct counting (γ)	
2016Ju05	29.994	0.029	Direct counting (IC)	
2020UnU0	29.88	0.15	Direct counting (IC)	

* Original uncertainty was asymmetric, and has been re-defined symmetrically.

All the measurements of Table 7 are represented as a function of their publication dates in Figure 1. These measurements are displayed with different symbols and colors in order to distinguish the various detection methods.

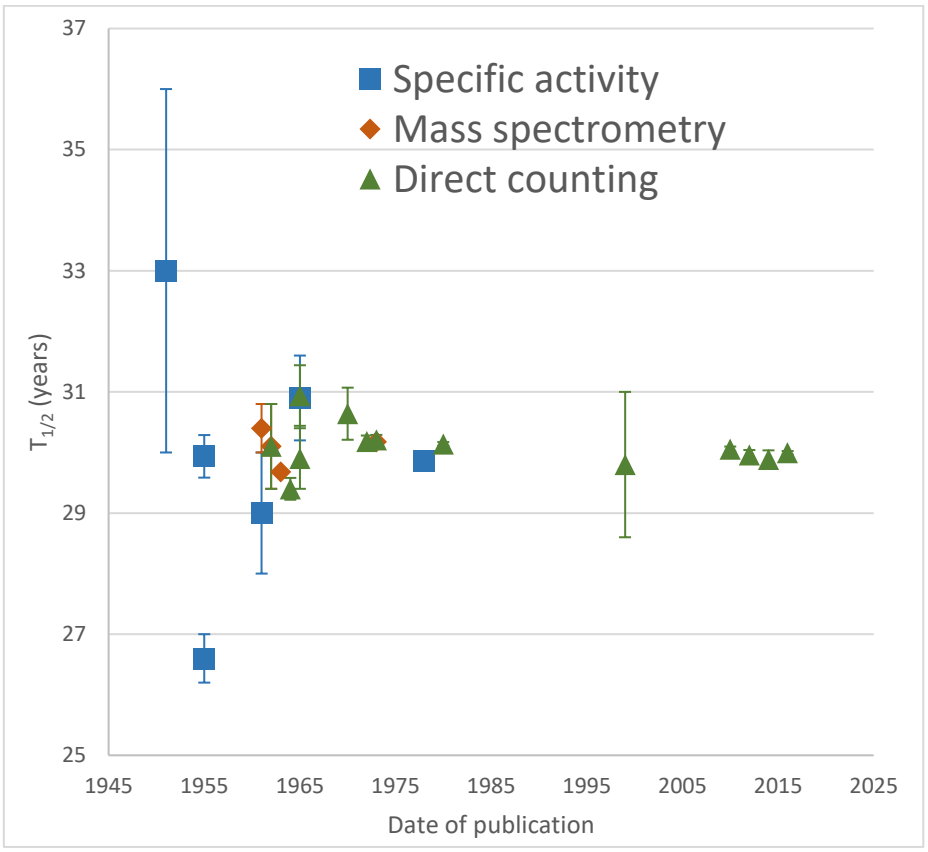

Figure 1: Experimental measurements of ^{137}Cs half-life as a function of publication date from the first set of data in Table 7.

Strict evaluation/selection has been performed to refine this dataset, based on a critical analysis of the different experimental studies. The rejected references are listed below, with additional comments on their analyses:

- **1951GlZY, 1955Wi21, 1961Fa03, 1961Gl08, 1962BuU0, 1964Co35, 1965Fl01, 1972Em01, 1980Ho17, 1999Po34:** All of these references were discarded as a consequence of a lack of information on the experimental conditions of the measurements, or inadequacies in the estimation of the associated uncertainty.
- **1955Br06:** Efforts were made to detail the various sources of uncertainties in this specific activity measurement. However, the estimation of the efficiency of the 4π counter was judged to be questionable (see [1990Wo04] for more details). Absorption in the source film was deduced by extrapolation to zero thickness by a linear function, which is also of doubtful merit. The decay scheme of ^{137m}Ba used for the correction of the counting rate was also inaccurate, and would need to be revised to current recommendations. Furthermore, the counting rate is affected by a similar lack of knowledge of the decay scheme.
- **1962Fl09** Specific activity measurements were performed using a liquid scintillation counter. The efficiency of the counter was quoted to be "93%" without any details or uncertainty assigned to this value. Apparently, the self-absorption and absorption within the scintillator were not taken into account in the estimation of the uncertainty.

The absolute activity was determined by extrapolation of the spectrum, but no further explanation was given (especially regarding the uncertainty). Furthermore, no information was provided regarding the shape of the assumed beta spectrum. Finally, the measured activity was not constant over the measurement time of the experiment. The authors attribute this phenomenon to the solution being in contact with the surface of the cuvette. However, another feasible explanation would be the inability to maintain the homogeneity and stability of the solution over the course of the experiment.

- **1963Go03** ^{137}Cs activity was measured by an ionization chamber with a radium source as a reference over a period of three years. Contamination by Cs-134 was estimated by gamma-ray spectroscopy, and was also monitored over the same three years. This contamination was estimated by two methods that were consistent at only the ±10% level, but this observation was apparently not taken into account at a later stage in the data analysis. [1990Wo04] also highlights that the contamination might have not been estimated properly.
- **1970Ha32** There are very few details of the experimental setup or analysis procedure. The stability of the chamber was monitored by means of a ^{99}Tc standard over the measurement period, and exhibited a 2.5% decline which was attributed without any evidence to a loss or diffusion of technetium. During the same period of time, the chamber was disassembled on several occasions to change the wires and high voltage, which may also have caused the drop in efficiency.
- **1973Co39** A source of ^{137}Cs was used both to verify the stability of the detector and to measure the half-life by means of gamma-ray spectroscopy over a nine-year period. This procedure is unusual, and the author does not mention any other stability check. Shielding around the detector was replaced during the measurement period, and data analysis shows clear deviation after this change indicating the presence of systematic bias in the measurements. The existence of some degree of bias was acknowledged, but the impact was not estimated. Finally, [1990Wo04] has pointed out that the procedure of excluding the value outside ±3σ should be viewed as debatable.
- **1978Gr08** The half-life of ^{137}Cs was determined by means of the specific activity method with a liquid scintillator. Compared with other articles in which the specific activity method had been adopted, extensive efforts were made by the authors to assess and quantify the possible bias to their measurements. The half-life was calculated as the unweighted average of ten measurements with an uncertainty based on the standard deviation of the dataset. However, the systematic uncertainty was estimated with insufficient detail, and the authors acknowledged that their resulting value was subjective.

Three other references also gave rise to some concern regarding the quality of their reported results:

- **1973Di01** Half-life determinations of ^{134}Cs and ^{137}Cs have been performed by mass spectrometry over a period of 10 years. Experimental biases over the measurement period were estimated using the ^{135}Cs/^{133}Cs ratio. However, this method assumes implicitly that the biases are the same for the ratio considered, and this hypothesis is not debated in the reference. Daughter ^{137}Ba is likely to be a contaminant in the ^{137}Cs measurement, since only very high-resolution spectrometers can separate the two isobaric isotopes. The authors addressed this issue by discussing the temperature of the

filament, concluding that there was no contamination, but without giving any quantitative estimate. Finally, they discussed the global uncertainty budget of the experiment, and concluded that the 99% confidence level was suitable for their estimation. Woods has undertaken an in-depth review and points out some limitations regarding the estimation of the uncertainties. A difficult reference to assess, the same experimental setup and estimation method was also adopted to measure the ^{134}Cs half-life with good precision to give a value very close to existing DDEP recommendations.

- **2012Be08** ^{137}Cs half-life was measured by means of gamma-ray spectroscopy. While the setup, acquisition and analysis are described in depth, information on the uncertainty associated with the half-life is rather sparse. Claims of equipment stability seem to be based on monitoring the width of the 662-keV gamma line, which is judged to be questionable. The primary objective of this study was to investigate the correlation of the ^{137}Cs decay rate with the variation of sun-to-earth distance and impact of solar flares - no evidence was found for this behavior over 5100 hours of study, which also indicates the high stability of the measurement procedure.
- **2020UnU0** This *corrigendum* further corrects many half-life data published in a series of previous papers ending with [2014Un01] for measurements performed with an ionization chamber at NIST [2002Un02]. These corrections account for a previously unforeseen collapse in the positioning of the source holder that had only recently been discovered [2012Un01]. Corrections have been performed by adopting a quadratic function to interpolate the position of the source within the detector. Questions remain as to the level of precision of these corrections and the calculation of the associated uncertainty.

2.1.3 Data analysis

Six references remain acceptable after the above selection process (Table 9). Three of them are judged to be robust enough for immediate inclusion in the evaluation, along with the retention of three others to be discussed further.

Table 9: Final set of references considered for ^{137}Cs half-life measurements

Reference	Half-life (years)	Uncertainty (years)	Detection method	Comments
1973Di01	30.174	0.011	Mass spectrometry (^{137}Cs/^{135}Cs)	Doubts
1990Ma15	30.029	0.012	Direct counting (IC)	
2010Sc08	30.057	0.041	Direct counting (IC)	
2012Be08	29.96	0.08	Direct counting (γ)	Doubts
2016Ju05	29.994	0.029	Direct counting (IC)	
2020UnU0	29.88	0.15	Direct counting (IC)	Doubts

The complete dataset in Table 9 is inconsistent (χ^2 = 19.94 / χ^2_{crit} = 3.02), with an unweighted-average $T_{1/2}$ = 30.016 (40) years and weighted-average $T_{1/2}$ = 30.096 $(34)_{ext}$ $(8)_{int}$ years. Approximately 48% of the total weighting is identified with [1973Di01], and 40% with [1990Ma15].

When the dataset is restricted to the three most robust measurements, much greater consistency is achieved ($\chi^2 = 0.92$ / $\chi^2_{crit} = 4.61$), with an unweighted-average $T_{1/2} = 30.027\ (18)$ years and weighted-average $T_{1/2} = 30.026\ (10)_{ext}\ (11)_{int}$ years. Approximately 78% of the total weighting is identified with [1990Ma15] which had been assigned a relatively low uncertainty. The Lweight algorithm converges to a final Cs-137 half-life value of $T_{1/2} = 30.026\ (11)$ years.

Inconsistency within the complete dataset in Table 9 is mainly caused by [1973Di01]. This measured value deviates the most from the average (0.5% deviation), while being the most precise datum. Under these circumstances, this particular measurement has been removed from further consideration. The resulting dataset of five measurements is consistent ($\chi^2 = 0.86$ / $\chi^2_{crit} = 3.32$), with an unweighted-average $T_{1/2} = 29.984\ (30)$ years and weighted-average $T_{1/2} = 30.024\ (11)_{ext}\ (10)_{int}$ years. Approximately 78% of the total weighted-average is now associated with [1990Ma15], and the Lweight algorithm converges to a final Cs-137 half-life value of $T_{1/2} = 30.024\ (11)$ years. Regarding the other two doubtful references, their inclusion in the evaluation does not significantly affect the result: the weightings are only 1.7% for [2012Be08] and 0.5% for [2020UnU0].

Finally, it is important to consider the uncertainty estimate in [1990Ma15]. As mentioned previously, the relatively low uncertainty that has been assigned by the authors represents 78% of the total weighting within the final weighted average. Both [2010Sc08] and [2016Ju05] have more than double the uncertainty of [1990Ma15], while all of them employ a similar detection technique. Although [1990Ma15] involves a longer measurement time, the statistical component of the uncertainty is not dominant in any of the three studies. Therefore, the overall uncertainty of [1990Ma15] has been increased from 0.012 to 0.022 years in order justifiably to limit the impact of this reference on the final recommendation of $T_{1/2} = 30.018\ (16)$ years, or $T_{1/2} = 30.018\ (22)$ years if the uncertainty is limited to the lowest experimental uncertainty. A half-life of **$T_{1/2}$ = 30.018 (22) years** is recommended, and has been compared with previous evaluations in Table 10.

Table 10: Comparison of recommended ^{137}Cs half-life with previous recent evaluations

Evaluation	$T_{1/2}$ (years)
This work	30.018 (22)
Latest DDEP (2002He06)	30.05 (8)
Latest ENSDF (2007Br23)	30.08 (9)

The differences observed in the evaluations arise mainly from the recent measurements of [2010Sc08], [2012Be08], [2016Ju05] as well as the correction reported in [2020UnU0]. They represent 50% of the total weight of this evaluation, after modifying the uncertainty quantified in [1990Ma15].

2.2 Q value

A Q-value of 1175.63 (17) keV for the β^- decay of ^{137}Cs has been taken from [2021Wa16], and remains unchanged from [2003Au03].

2.3 β^- emissions

The maximum energy of each emission is deduced from the Q value and the previously discussed level energies of ^{137}Ba.

Only two β^- transitions have been observed experimentally, and several measurements of the emission intensities have been performed to determine the β^- intensities in both cases. It is worth mentioning that several measurements are not absolute intensity measurements but relative intensity measurements between the two beta branches. Thus the reported beta transition intensities are often correlated between the two branches. As explained previously, the recommended emission intensities are based on a methodology that ensures a coherent decay scheme (see Section 2.5), although the reader can find the evaluation of the measured emission intensities in Subsections 2.3.1 and 2.3.2.

2.3.1 Beta decay from ^{137}Cs ground state to ^{137}Ba 11/2$^-$ state

The β^- emission intensity to the second excited state can be measured directly, or can be deduced from the determination of the total conversion coefficient and absolute gamma-ray emission intensity of the ^{137}Ba (11/2$^-$) → ^{137}Ba (3/2$^+$) transition. Ten publications contain intensity measurements, and are listed in Table 11.

Table 11: References for ^{137}Cs beta decay to ^{137}Ba second excited state

Reference	Emission intensity (%)	Uncertainty (%)	Comments
1957Ri41	95.24	0.33	Discarded - absence of detail concerning the uncertainty
1958Yo01	92.4	0.8	Discarded - absence of detail concerning the uncertainty
1962Da05	93.5	0.2	Discarded - absence of detail concerning the uncertainty
1965Me03	95.2	1.0	
1966Hs02	94.0	0.5	
1973LeZJ	94.7	0.3	
1975Go28	95.5	1.0	
1978Ch22	93.79	0.07	Subsequently discarded due to systematic bias
1978Gr09	93.6	0.5	
1983Be18	94.43	0.07	Subsequently discarded due to systematic bias

Three references have been discarded ([1957Ri41], [1958Yo01] and [1962Da05]) because they do not contain sufficient justification of their declared uncertainty budgets. [1978Ch22] and [1983Be18] have been discarded and superseded by 1975Go28 due to suspicion of the systematic bias in the measurement (see foreword for more details). Three of the five remaining

studies share the same experimental technique based on measurements of the absolute gamma-ray intensity and the total conversion coefficients, whereas [1978Gr09] is based on a direct measurement and [1966Hs02] on the relative ratio of the two branches. This remaining dataset is consistent ($\chi^2 = 1.51$ / $\chi^2_{crit} = 3.32$) with a weighted average of $I_\beta = 94.42\ (22)\%$. Approximately 52% of the total weighting is identified with [1973LeZJ] and 18% on [1978Gr09]. The uncertainty of the average has been extended to match the smallest experimental uncertainty to give a evaluated value of **I_β = 94.4 (3)%**.

2.3.2 Beta decay from ^{137}Cs ground state to ^{137}Ba 3/2$^+$ state

Seven publications are identified with absolute intensity measurements of the β^- decay to the ground state of ^{137}Ba, as listed in Table 12. Three references ([1957Ri41], [1958Yo01] and [1962Da05]) have been discarded because of a lack of experimental details and limited uncertainty budgets. [1978Ch22] work has been superseded by [1983Be18]

The remaining dataset of three references is consistent ($\chi^2 = 1.88$ / $\chi^2_{crit} = 4.60$), even though [1966Hs02] deviates from the other two.. Given the doubts existing on a systematic bias in [1983Be18] (see foreword for more details), the decision was also made to increase its uncertainty to 0.3% in order to limit the weighting to 50%. A weighted-average emission intensity to the ground state of $I_\beta = 5.56\ (26)\%$ was determined, with the uncertainty extended on the basis of the smallest experimental uncertainty to give a evaluated value of **I_β = 5.56 (26)%**.

Table 12: References for ^{137}Cs beta decay to ^{137}Ba ground state

Reference	Emission intensity (%)	Uncertainty (%)	Comments
1957Ri41	4.76	0.27	Discarded due to an absence of detail concerning the uncertainty
1958Yo01	7.6	0.8	Discarded due to an absence of detail concerning the uncertainty
1962Da05	6.5	0.2	Discarded due to an absence of detail concerning the uncertainty
1966Hs02	6.0	0.5	
1969Ha05	5.4	0.3	
1978Ch22	6.21	0.07	Superseded by 1983Be18
1983Be18	5.57	0.07	

2.4 Gamma Transitions

A summary of the recommendations for the gamma transitions observed in the β^- decay of ^{137}Cs is given in Table 13. The energy of these gamma transitions and associated uncertainties have been calculated from the properties of the level scheme of ^{137}Ba, as described in Section 1. Various procedures adopted to derive the other recommended nuclear parameters are detailed in the subsections given below.

Table 13: Summary of recommended gamma transition properties

Initial state	Final state	Transition energy (keV)	Emission Intensity (%)	Multipolarity
$11/2^-$	$3/2^+$	661.657 (3)	85.01 (20)	M4
$11/2^-$	$1/2^+$	378.20 (7)	1.06 (9) x 10^{-5}	E5
$1/2^+$	$3/2^+$	283.46 (7)	6 (1) x 10^{-4}	M1+E2

The Half-life of the $11/2^-$ state of 137Ba is taken from the corresponding DDEP evaluation (S. Leblond 2023).

2.4.1 Intensity

As described previously, the intensity of the main gamma transition has been evaluated from the available measurements (see Subsection 4.2.1), whereas the recommended transition intensity was based on averaging independent types of measurement to provide a consistent decay scheme (see Section 2.5). On the other hand, the intensities of the two other gamma transitions can be directly deduced from analyses of absolute measurements of the gamma-ray emission intensities (see Subsections 4.2.2 and 4.2.3 for more details). Comparisons of the recommended gamma transition and emission intensities are given in Table 14.

Table 14: Comparisons between recommended gamma transition and gamma-ray emission intensities

Initial state	Final State	Transition intensity (%)	Emission intensity (%)
$11/2^-$	$3/2^+$	94.57 (26)	85.01 (20)
$11/2^-$	$1/2^+$	2.02 (17) x 10^{-5}	1.06 (9) x 10^{-5}
$1/2^+$	$3/2^+$	6.3 (11) x10^{-4}	6 (1) x 10^{-4}

2.4.2 Conversion Coefficients

Internal conversion coefficients have been calculated by means of the BrIcc version 2.2 code developed by Kibédi, *et al.* [2008Ki07]. Experimental ICC data are only available for the 661.7-keV transition, and the analysis below was undertaken to validate the relevant BrIcc calculations. Details of the assessment of the experimental data are available in the following subsections, and the summary of the comparison can be found in Table 15.

A 100% M4 transition was assumed on the basis of spin-parity considerations, and the results obtained with this multipolarity were found to be satisfactory. The ICC data calculated by BrIcc were in good agreement with the experimental recommendations for the total conversion coefficient, K-shell conversion coefficient and K/LM ratio, with relative deviations of the order or less than 1%, confirming the validity of the BrIcc calculations. **As a consequence, the BrIcc data are recommended and have been adopted in this work.**

Table 15: Comparison between BrIcc and experiments for 661.66-keV gamma ray

Conversion coefficient formulations	BrIcc v 2.2 (100% M4)	Evaluation from experimental data
total α_T	0.1124 (16)	0.1108 (3)
K-shell α_K	0.0915 (13)	0.09128 (42)
K/LM+ ratio ($\frac{\alpha_K}{\alpha_L+\alpha_M+\cdots}$)	4.38 (8)	4.41 (4)

2.4.2.1 Total conversion coefficient

Twelve independent measurements were identified for the analysis of the total conversion coefficient. These measurements were performed from 1957 to 1983, and are listed in Table 16.

Table 16: Experimental measurements of ^{137}Ba total conversion coefficient for the 661.66-keV gamma ray

Reference	α_T	u(α_T)	Comments
1957Ri41	0.114	0.022	Discarded due to an absence of detail concerning the uncertainty
1962Da05	0.114	0.003	
1963Bo31	0.109	0.020	Discarded due to an absence of detail concerning the uncertainty
1965Me03	0.1100	0.0011	
1965Pa17	0.1167	0.0015	Superseded by 1973LeZJ
1965Ra12	0.112	0.005	Discarded due to an absence of detail concerning the uncertainty
1969Ha05	0.1121	0.0005	
1973LeZJ	0.1105	0.0003	
1975Go28	0.1100	0.0006	Initially superseded by 1983Be18, but re-introduced after further assessment
1978Ch22	0.1092	0.0008	Superseded by 1983Be18
1978Gr09	0.114	0.003	Discarded due to an absence of detail concerning the uncertainty
1983Be18	0.1083	0.0003	Subsequently discarded due to systematic bias

The list was refined by removing [1965Pa17], [1975Go28] and [1978Ch22], since they have been superseded by more recent articles. Furthermore, [1957Ri41], [1963Bo31, [1965Ra12] and [1978Gr09] do not contain any detail concerning data uncertainties, and have also been discarded. This reduced dataset of five measurements is highly discrepant

(χ^2 = 13.13 / χ^2_{crit} = 3.32). One of the two most precise studies ([1983Be18]) deviates significantly from the other measurements, and a similar situation can be observed in the same publication for the α_K conversion coefficient. Based on these two observations, the decision was finally taken to discard [1983Be18] from the evaluated dataset, and replace with the previously superseded data from [1975Go28].

The modified set of five references formed a consistent dataset (χ^2 = 2.79 / χ^2_{crit} = 3.32), with the Lweight algorithm recommending the weighted average. Approximately 59% of the total weighting was taken by 1973LeZJ, and a weighted average of α_T = 0.11076 (23) was derived. The evaluated total conversion coefficient of the 661.66-keV gamma ray is obtained by extending the uncertainty to the smallest experimental uncertainty to give **α_T = 0.1108 (3).**

2.4.2.2 K-shell conversion coefficient

Twenty-six measurements of K-shell conversion have been considered in this analysis that were performed from 1951 to 2018 (Table 17). A rigid selection of these measurements was implemented, as described briefly below:

- **1951Wa19, 1952He18, 1953Do31, 1954Az01, 1954Wa14, 1958Yo01**: Insufficient detail has been provided concerning the uncertainties, and the measurements depend on a sound knowledge of several properties of the decay (electron energy shape, branching ratio …) leading to overestimations of at least 5% (e.g., decay to ground state not satisfactorily taken into account).
- **1957Mc34**: Few details given of the uncertainty estimates. Measurements do not include corrections for the Auger electrons, and are based only on an approximate knowledge of the escape peaks. Fluorescent yields defined in this work need to be corrected from 0.88 to 0.93 in order to be consistent with known DDEP recommendations.
- **1961Hu12**: ^{137}Cs is not the main goal topic of this paper, and almost no detail is given concerning the measurements and uncertainty estimates.
- **1965Ra12:** No details are provided on the source activity, and little is known concerning the uncertainty budget assessment. A_T is deduced from eight inconsistent measurements, but the reported value does not match an average, and the associated uncertainty is smaller than the standard deviation of the dataset. Also α_K is deduced from the measured α_T assuming a K/LMN ratio = 4.6, and would need to be corrected.
- **1965Me03**: Not a direct measurement – α_K coefficient is deduced from the measured α_T and previously determined K/T ratio.
- **1965Pa17:** Uncertainty based on insufficient detail – superseded by 1973LeZJ.
- **1971BrYR:** Superseded by 1973LeZJ
- **1973Wi10:** Lacks any discussion of the gamma-ray detector efficiency, as well as providing inadequate information on both the experimental detail and uncertainty estimates.
- **1978Gr09:** Insufficient experimental detail, along with ill-defined uncertainty estimates.
- **2014Ha07:** Prefer 2008Ni02, which contains more detail of the experiment and uncertainty estimates.
- **2018Ha07:** Prefer 2008Ni02, which contains more detail of the experiment and uncertainty estimates.

Table 17: Experimental measurements of ^{137}Cs K-shell conversion coefficient for the 661.66-keV gamma ray

Reference	α_K	$u(\alpha_K)$	Comments
1951Wa19	0.097	0.005	Discarded[#]
1952He18	0.095	0.005	Discarded[#]
1953Do31	0.11	0.01	Discarded[#]
1954Az01	0.096	0.005	Discarded[#]
1954Wa14	0.092	0.006	Discarded[#]
1957Mc34	0.095	0.008	Discarded[#]
1958Yo01	0.0976	0.0055	Discarded[#]
1959Hu23	0.093	0.006	
1960De17	0.093	0.005	
1961Hu12	0.095	0.004	Discarded[#]
1962Da05	0.093	0.003	
1964Ch18	0.091	0.002	
1965Me03	0.0894	0.0010	Discarded[#]
1965Pa17	0.0957	0.0010	Superseded by 1973LeZJ
1965Ra12	0.093	0.009	Discarded[#]
1967Ba80	0.093		No uncertainty, discarded
1967HaZX	0.0925	0.0027	Superseded by 1969Ha05
1969Ha05	0.0916	0.0005	
1971BrYR	0.0901	0.0009	Superseded by 1973LeZJ
1973LeZJ	0.0901	0.0003	Uncertainty increased to 0.001
1973Wi10	0.0922	0.0022	Discarded[#]
1978Gr09	0.093	0.003	Discarded[#]
1983Be18	0.08807	0.00015	Subsequently discarded as outlier
2008Ni02	0.0915	0.0005	
2014Ha07	0.0915	0.0006	Prefer 2008Ni02
2018Ha07	0.0915	0.0005	Prefer 2008Ni02

[#] More details are given in the text immediately above this table.

The dataset adopted for this evaluation was initially composed of [1959Hu23], [1960De17], [1965Da05], [1964Ch18], [1969Ha05], [1973LeZJ], [1983Be18] and [2008Ni02]. However, the total conversion coefficient quantified in [1983Be18] stands out as being significantly lower than the other measurements while being the most precise. When the Chauvenet criterion was applied to the dataset, [1983Be18] was identified as an outlier and discarded. Thus, the final dataset of [1959Hu23], [1960De17], [1965Da05], [1964Ch18],

[1969Ha05], [1973LeZJ] and [2008Ni02] was found to be consistent (χ^2 = 0.98 / χ^2_{crit} = 2.80), whereby Lweight gave a weighted-average value for α_K = 0.09070 (30) with 58% weighting identified with [1973LeZJ]. However, after comparison with the respectable uncertainty budget of [2008Ni02], there was clear evidence that the uncertainty quantified by [1973LeZJ] was an underestimation. As a consequence, the latter was increased from ± 0.0003 to ± 0.001 to match the uncertainty of similar experiments performed at that time. The weighted-mean of the final modified dataset is **α_K = 0.09128 (42)** for the 661.66-keV gamma ray.

2.4.2.3 K/LM shell ratio

Many measurements have been performed to study the K/L, K/LM and K/LM+ ratios. All these measurements are listed in Table 18.

Table 18: References for the K/LM+ ratio of conversion coefficients for the 661.66-keV gamma ray

Reference	Reported ratio	Measured value	Uncertainty	Comments
1949Mi01	K/L	4.8	-	Discarded, no uncertainty
1949OsU0	K/L	5	-	Discarded, no uncertainty
1952Be33	K/LMN	4.3	-	Discarded, no uncertainty
1952Gr14	K/LM	4.64	-	Discarded, no uncertainty
1952Ke02	K/LM	4.57	0.05	Uncertainty estimate not detailed
1953Ma14	K/LM	4.52	0.07	Uncertainty estimate not detailed
1954Az01	K/L	4.62	0.18	Uncertainty estimate not detailed
1954Ve09	K/LM	4.1	0.2	Superseded by 1973LeZJ
1954Wa14	K/L	5.8	0.3	Uncertainty estimate not detailed
1956An51	K/LM	4.6	0.3	Uncertainty estimate not detailed
1958Yo01	K/LM	4.57	0.05	Uncertainty estimate not detailed
1962Da05	K/LMN	4.50	0.07	
1962Ge09	K/L	5.21	0.16	Uncertainty estimate not detailed
1963Ku09	K/LM	4.86	0.04	Uncertainty estimate not detailed
1964Ch18	K/LM	4.61	0.02	Uncertainty estimate not detailed
1964Ge05	K/LMN	4.3	0.3	Discarded[#]
1965Pa17	K/LMN	4.58	0.05	Superseded by 1973LeZJ
1966Ha41	K/LMN	4.56	0.10	Superseded by 1973LeZJ
1966Hs02	K/LM	4.55	-	Discarded, no uncertainty
1969Ha05	K/LM+	4.41	0.05	
1973LeZJ	K/LMN+	4.39	0.02	Uncertainty increased to 0.038
1978Ch22	K/LMN	4.34	0.07	
1978Gr09	K/LM+	4.3	0.1	

[#] More details are given in the text immediately below this table.

Measurements reporting only K/L or K/LM ratios have not been analysed, but rather the focus has been preferably placed upon comparable K/LMN and K/LM+ ratios. According to BrIcc calculations, O and higher shells contribute less than 1% to the final result, which is much less than the relative uncertainty of the most precise measurement. A significant number of references can also be discarded, mainly because of the absence of any justification regarding their uncertainty estimates. As for [1964Ge05], these data were discarded because the authors mention the existence of an ill-defined experimental bias in the transmission of electrons. After applying all of these criteria, five references remain: [1962Da05], [1969Ha05], [1973LeZJ], [1978Ch22] and [1978Gr09]. As discussed previously for the α_K and α_T coefficients, inconsistencies have been observed in [1978Ch22] involving their measurements of the conversion coefficients. Therefore, 1978Ch22 has been removed from the final dataset to achieve an improved consistency ($\chi^2 = 1.1$ / $\chi^2_{crit} = 3.8$), with Lweight generating a weighted average of $\frac{\alpha_K}{\alpha_L+\alpha_M+\cdots} = 4.397\ (18)$. [1973LeZJ] possesses a significant weighting of 78% in these circumstances, so the uncertainty was increased from ±0.02 to ±0.038 to limit the weighting to 50%. The weighted average with such an adjusted uncertainty generates a value of $\frac{\alpha_K}{\alpha_L+\alpha_M+\cdots} = 4.405\ (27)$, and by increasing this uncertainty to the lowest experimental uncertainty, the weighted-average provides the evaluated ratio $\boldsymbol{\frac{\alpha_K}{\alpha_L+\alpha_M+\cdots} = 4.41\ (4)}$ for the 661.66-keV gamma ray.

2.4.3 Multipolarity

The multipolarity of each gamma transition is determined from the spin and parity assigned to the initial and final states depopulated and populated, respectively. Such a procedure can be confirmed for the 661.66-keV gamma transition from experimental data that define the conversion coefficients (see Subsection 2.4.2). As detailed above, the BrIcc calculations performed assuming a pure M4 transition type fit very well with the recommendations obtained from the experimental data.

2.5 Coherence of the overall decay scheme

As mentioned previously, the intensities of the various emissions are all correlated within this simple decay scheme. Three significant emissions exist: the two main beta-decay branches and the 661.655-keV gamma-ray emission. The beta-decay branch to the first excited state of ^{137}Ba and the other two gamma-ray emissions have minimal impact on the overall form of the decay scheme (their intensities are more than two orders of magnitude lower than the evaluated uncertainties of the other emissions). As a consequence, the emission intensities in the decay of ^{137}Cs can be reconstructed on the basis of a sound knowledge of just one of the three main emissions. Thus, the intensity of one of the two beta-decay branches can be deduced directly from the intensity of the other. Furthermore, the beta-decay intensity to the second excited $11/2^-$ state of ^{137}Ba can be deduced from the intensity of the major gamma-ray emission and total conversion coefficient.

Three different methods can be considered in the construction of a consistent and coherent decay scheme:

- via the evaluated beta-particle emission intensity directly to the ground state of ^{137}Ba – methodology presented in Subsection 2.3.2;

- via the evaluated beta-particle emission intensity to the 11/2$^-$ state of ^{137}Ba - methodology presented in Subsection 2.3.1;
- via the main ^{137}Ba gamma-ray emission intensity (evaluated in Subsection 4.2.1) and the total internal conversion coefficient from BrIcc calculations.

Both of the recommended beta-particle intensities have been used along with the BrIcc-calculated total internal-conversion coefficient to quantify the absolute emission probability of the main gamma ray. Table 19 constitutes a list of the intensities of the main emissions as determined by all three of the procedures defined above.

Table 19: Absolute beta and gamma-ray emission intensities determined by different procedures

	From beta decay to the ground state of ^{137}Ba (%)	**From beta decay to the 11/2$^-$ state of ^{137}Ba (%)**	**From γ intensity + BrIcc α_T (%)**
β transition intensity ^{137}Cs (7/2$^+$) → ^{137}Ba (11/2$^-$)	94.44 (26)	94.4 (3)	94.53 (22)
γ emission intensity ^{137}Ba (11/2$^-$) → ^{137}Ba (3/2$^+$)	84.89 (26)	84.88 (29)	84.98 (15)
β transition intensity ^{137}Cs (7/2$^+$) → ^{137}Ba (3/2$^+$)	5.56 (26)	5.6 (3)	5.471 (22)

All three methods lead to very similar results, in terms of both the evaluated intensities and their associated uncertainties. Furthermore, the procedures based on measurements of the two beta-decay branches give results that are almost identical in terms of their actual values and associated uncertainties. Small deviations occur with the calculations based on the evaluated intensity of the main gamma transition.

Given that all three methods have similar uncertainties, an average of the three methods should provide a more reliable reconstruction of the decay scheme. However, one further important point to note is the existing correlations between the intensities deduced by means of these three methods, particularly that most of the β-decay feeding measurements to the 11/2$^-$ of ^{137}Ba are based on measurements of the gamma-ray emission probability. Furthermore, the most precise intensity measurements for the gamma-ray emission and this β$^-$ transition are from references [1969Ha05, 1973LeZJ]. Hence, the evaluated intensities presented in this work are strongly correlated. The recommended intensities were thus based on an average of the most relevant measurements for each methods, converted to gamma absolute emission intensity. The recommended 662 keV BrIcc conversion coefficient was used to convert from beta emission intensity when necessary. The measurements and deduced gamma emission intensity are presented in Table 20.

Table 20: Equivalent of absolute gamma measurements for relevant measurements

Reference	Beta Emission intensity (%)	Uncertainty (%)	Gamma Emission intensity (%)	Uncertainty (%)	Comments
1965Me03	95.2	1	85.6	0.9	Superseded by 1978MeZM
1966Hs02	6.0	0.5	84.5	0.5	Discarded
1969Ha05	94.6	0.3	85.04	0.30	
1973LeZJ			85.3	0.3	
1975Go28			86	1	Superseded by 1983Be18
1978Gr09	93.6	0.5	84.1	0.5	Discarded
1978MeZM			84.7	0.7	
1983Be18	94.43	0.07	84.89	0.15	

Among these eight measurements, [1965Me03] and [1975Go28] are superseded by [1978MeZM] and [1983Be18] respectively. Both [1966Hs02] and [1978Gr09] are discarded for their relative lack of experimental details and estimation of uncertainty budget. The remaining dataset is consistent ($\chi^2 = 0.57$ / $\chi^2_{crit} = 3.78$) with a weighted average of $I_\gamma = 84.97\ (12)\%$. The uncertainty of [1983Be18] is increased to 0.20 to limit its weight to 50% to provide the recommended intensity **I_γ = 85.01 (20)%.**

The transition intensities deduced with this weighted average are presented in Table 21, and compared with the value of two previous evaluations [2006HeZT, 2007Br23]. The results are consistent with previously recommended decay data, the intensities obtained in this work falling within the equivalent quoted data limits of both of the most recent DDEP and ENSDF evaluations.

Table 21: Recommended ^{137}Cs beta decay intensities

Source	^{137}Cs (7/2$^+$) → ^{137}Ba (11/2$^-$) β intensity (%)	^{137}Ba (11/2$^-$) → ^{137}Ba (3/2$^+$) γ intensity (%)	^{137}Cs (7/2$^+$) → ^{137}Ba (3/2$^+$) β intensity (%)
Recommended weighted average	94.57 (26)	85.01 (20)	5.43 (26)
2006HeZT	94.36 (28)	84.99 (20)	5.64 (28)
2007Br23	94.7 (2)	85.1 (2)	5.3 (2)

3 Atomic Data

Fluorescence yields were calculated by means of the SAISINUC program (2008DuZX) which incorporates the data of Schönfeld ([1996Sc06]). X-ray and Auger-electron energies were also determined within the SAISINUC program, based on input data from [1999ScZX] and [1998ScZM], respectively. The 2013 version of the EMISSION code was used to calculate the X-ray emission probabilities, as described in [2000Sc47] and implemented by SAISINUC in terms of the evaluated γ-ray emission probabilities and conversion coefficients.

The evaluated X-ray ratio between the K_β and K_α emission probabilities is compared with existing measurements in Table 22.

Table 22: Comparison of K_β / K_α ratio for ^{137}Cs decay

Reference	K_β / K_α ratio
1983De11	0.241 (9)
1987Me02	0.238 (5)
1994Bu26	0.2364 (47)
2007Ya02	0.2118 (13)
Evaluated	0.239 (5)

The evaluated ratio is consistent with three of the studies [1983De11, 1987Me02, 1994Bu26], but inconsistent with respect to the most recent and precise measurement [2007Ya02]. However, the latter should be considered with some degree of caution based on a number of issues, particularly the small uncertainties assigned to the measured activities of the sources, sometimes quantified as more accurate than the equivalent uncertainties determined at National Metrology Institutes. Furthermore, the author of the paper also points out these deviations between the results and known experimental and theoretical values without furnishing a quantitatively plausible explanation [2007Ya02].

4 Emissions

4.1 Electrons

The β^- maximum energy of each of the emissions was calculated from the ^{137}Ba level energy deduced in Section 1 and the most recently evaluated Q-value (2021Wa16). Spectral shapes, mean energies and logft values were determined by means of the BetaShape code v2.2 ([2019Mo35]), and the experimental shape factor of the direct ground-state to ground-state β^- emission was taken from [1983Be18]. No experimental shape factors were available for calculations involving the β^- emissions to the excited states of ^{137}Ba. The summary of the recommended properties of the beta-decay emissions are presented in Table 23.

Table 23: Recommended beta emission properties of ^{137}Cs decay

Final state in ^{137}Ba	Nature	Probability (%)	Emission maximum energy (keV)	Emission mean energy (keV)	Logft
$11/2^-$	First forbidden unique	94.57 (26)	513.97 (17)	173.67 (6)	9.7
$1/2^+$	Second forbidden unique	6.1 (10) x 10^{-4}	892.17 (18)	332.51 (7)	16.6
$3/2^+$	First forbidden non-unique	5.43 (26)	1175.62 (17)	284.90 (5)	12.8

Auger-electron emission energies and intensities were calculated by means of the 2013 version of the EMISSION code ([2000Sc47]), and were based on the evaluated γ-ray emission probabilities and conversion coefficients.

4.2 Photons

The energies of the gamma-ray emissions were calculated from the energies of the gamma transitions, taking into account the gamma recoil energy of ^{137}Ba (see Section 1). These conversions from the gamma transition energy to the gamma-ray emission energy are given in Table 24.

Table 24: Energy comparison between gamma transitions and gamma-ray emissions

Initial state	Final state	Transition energy (keV)	Emission energy (keV)
$11/2^-$	$3/2^+$	661.657 (3)	661.655 (3)
$11/2^-$	$1/2^+$	378.2 (7)	378.2 (7)
$1/2^+$	$3/2^+$	283.46 (7)	283.46 (7)

Gamma-ray emission intensities have been determined from analyses of the measurements for each transition, and are detailed in the following subsections.

4.2.1 Gamma-ray emission at 661.66 keV: $11/2^- \rightarrow 3/2^+$

Although the gamma-ray emission from the 2nd excited state to the ground state of ^{137}Ba is frequently used in the determination of detector efficiency, only a handful of measurements of the absolute emission probability can be found, as listed in Table 25.

Three of the seven references have been superseded by more recent measurements in the same laboratory ([1965Me03] by [1978MeZM]; [1975Go28] by [1978Ch22], and effectively both [1975Go28] and [1978Ch22] by [1983Be18]). The resulting dataset of four remaining measurements is consistent ($\chi^2 = 0.23$ / $\chi^2_{crit} = 3.78$), and generates a weighted-average of

I_γ = 85.21 (7)% which is dominated by [1983Be18] with a relative weighting of approximately 91% (uncertainty nearly an order of magnitude less than other measurements). As detailed in Subsection 2.4.2, there may be a systematic bias in the experimental studies of [1983Be18] because deduced α_T and α_K are discrepant with respect to the other experimental data.

Table 25: Intensity measurements of the 661.66-keV gamma-ray emission in ^{137}Ba

Reference	Emission intensity (%)	Uncertainty (%)	Comments
1965Me03	85.7	0.9	Superseded by 1978MeZM
1969Ha05	85.1	0.4	
1973LeZJ	85.3	0.3	
1975Go28	86	1	Superseded by 1978Ch22
1978Ch22	86.56	0.08	Superseded by 1983Be18
1978MeZM	84.7	0.7	
1983Be18	85.21	0.07	

Given the doubts concerning [1983Be18], care is required as how best to include this result in the gamma-ray emission intensity dataset. Three different methods have been considered:

- Limit the weight of [1983Be18] to 50% by increasing the uncertainty to 0.23% - dataset is consistent (χ^2 = 0.23 / χ^2_{crit} = 3.79), and the Lweight algorithm generates a weighted-mean I_γ = 85.19 (16)%.
- Replace [1983Be18] by [1975Go28] which had been initially superseded - dataset is consistent (χ^2 = 0.44 / χ^2_{crit} = 3.79), and the Lweight algorithm generates a weighted-mean I_γ = 85.21 (22)%.
- Correct the gamma-ray emission probability of [1983Be18] by adopting the total internal-conversion coefficient determined by means of BrIcc (see Subsection 2.4.2). A new emission probability and associated uncertainty can be calculated: $I_{corrected} = \frac{I(\beta)_{1983Be18}}{(1+\alpha_{BrICC})} = 84.89\ (15)\%$.
  The modified dataset is consistent (χ^2 = 0.13 / χ^2_{crit} = 3.79), with the Lweight algorithm generating a weighted-mean I_γ = 84.98 (13)%.

The results obtained via these three independent procedures are consistent, with the third method judged to be the most reasonable when taking into account the quality of the work described in [1983Be18] compared with [1975Go28]. Thus, **I_γ = 84.98 (15)%** is evaluated, after extending the uncertainty to cover the most precise measurement ([1973LeZJ]).

4.2.2 Gamma-ray emission at 378.2 keV: 11/2$^-$ → 1/2$^+$

The emission probability of the E5 gamma transition from the 11/2$^-$ state to the 1/2$^+$ state of ^{137}Ba was assumed to be very low. Nevertheless, experimental studies by Moran, *et al*. have succeeded in determining this gamma transition to be near-pure E5 with intensity **I_γ = 1.06 (9) x 10^{-5}%** [2014Mo32]. Although the uncertainty budget lacks detail and is judged

to be underestimated, this low-intensity gamma transition has been recommended in the proposed decay scheme of ^{137}Cs.

4.2.3 Gamma-ray emission at 283.5 keV: $1/2^+ \rightarrow 3/2^+$

As with the gamma ray described above, the low emission probability of the 285-keV gamma transition has been sparsely studied. Along with a low beta-decay branch, there is also very little gamma feeding of the $1/2^+$ state from the $11/2^-$ state. Only four references have been found that quantify the emission intensity, and they are listed in Table 26.

Table 26: Intensity measurements of the 283.5-keV gamma-ray emission in ^{137}Ba

Reference	Emission intensity (%)	Uncertainty (%)	Comments
1996Bi23	5.3×10^{-4}	1×10^{-4}	
1997Wa37	6.1×10^{-4}	1×10^{-4}	
2006SeZY	9.0×10^{-4}	2×10^{-4}	Superseded by 2007Se05
2007Se05	9.0×10^{-4}	2×10^{-4}	

One of these references has been superseded by a more recent analysis of the same measurement by the same authors. All of these studies were performed by means of HPGe detectors, and contain assessments of their uncertainty budgets. The dataset is consistent ($\chi^2 = 1.186$ / $\chi^2_{crit} = 4.60$), and Lweight generates a weighted average of $I_\gamma = 6.3\ (8) \times 10^{-4}$% associated with the external uncertainty. Extending the uncertainty to the most precise measurements leads to a recommendation of **$I_\gamma = 6\ (1) \times 10^{-4}$%**.

4.2.4 Double-gamma emission from $11/2^-$ state of ^{137}Ba

^{137}Ba is one of a few nuclides for which double-gamma emission is competitive enough to be measured. Effectively, the 661.66-keV $11/2^-$ state of ^{137}Ba can decay to the ground state via the simultaneous emission of two photon emissions, as well by the much more common single 661.66-keV gamma ray. Two gamma rays can be emitted simultaneously, sharing the energy corresponding to the transition between the two states. Hence, these forms of emission do not exhibit a discrete energy spectrum, but rather a continuous spectrum with a shape that depends on the phase space of the decay.

The first investigations of possible ^{137}Cs double-decay were performed in the 1960s and 1970s with the detection of two K-electrons [1960Be20, 1969Lj01, 1971Lj02]. While the first and only gamma-electron detection was performed at approximately the same time [1971Lj01], the first tentative detection of the two-gamma emission did not occur until the 1990s [1992Ba45]. Quite recently, the topic has drawn more interest and a series of measurements has been performed to detect the double-gamma emission [2015MeZZ, 2015Wa29, 2016PiZW]. The probability of such an event is extremely small at more than six orders of magnitude less probable than the direct single-photon emission [2015Wa29, 2016PiZW]:

$$I_{\gamma\gamma}(661.66\ \text{keV}) = 2.05\ (37) \times 10^{-6}\ I_\gamma(661.66\ \text{keV}).$$

Given the nature of the double-gamma emission and the extremely low probability, this particular decay mode has not been included in the tabulated recommendations.

5 Prospects for improvements

5.1 Half-life

Doubts remain regarding the low uncertainty given by Martin and Taylor [1990Ma15] to their measurements of the half-life of ^{137}Cs, which represents a large weighting and therefore dominates the averaging procedure. A number of additional precise measurements are required that would hopefully lower the dependency of the evaluation on the experimental studies of 1990Ma15. The analysis of existing known measurements by PTB and NRC would be warmly welcome as the beginnings of a proposed international initiative.

5.2 Beta emissions

The intensities of the beta emissions have not been evaluated with any great confidence: one of these emissions possesses an extremely low probability, and only a few references are known to be available to assist in determining this and the direct ground-state to ground-state β^- emission probabilities.

I would also like to highlight the important role of the evaluator concerning the treatment of [1973LeZJ], [1978Ch22] and [1983Be18] in the datasets considered. These references are among the most precise data of the datasets, but doubts remain as to the validity of their accuracy (see Foreword). Their (1) inclusion, (2) rejection, or (3) modification and inclusion of the associated uncertainty would have a significant impact on the decay-data recommendations. As a consequence, I am strongly advocating new high-precision measurements of the intensities of the two main β^- branches of ^{137}Cs.

The β^--decay branch directly to the ground state of ^{137}Ba is a 2nd non-unique forbidden transition, which plays an important role in determining the shape of the beta spectrum. BetaShape calculations are based on the measurements of [1978Ch22] and [1983Be18], which have been discussed previously. A new measurement of the beta shape would therefore be of interest and value for the β^- transition directly to the ground state of ^{137}Ba.

5.3 Gamma transitions

The situation for the γ transitions is similar to that of the β^- emissions: emission probabilities of two of the three γ rays are extremely small, and only a limited number of references are relevant to the evaluation of the decay characteristics of the third γ ray. Once more, the acceptance of the relevant data in [1973LeZJ] and [1983Be18] has a significant impact on the recommendations. Therefore, I strongly propose new high-precision measurements of the intensity of the main gamma-ray emission of ^{137}Cs with an energy of 661.55 keV.

6 References

All the publications used in this work are sorted below in terms of their associated NSR keynumbers [2011Pr03]. If no keynumber has been assigned to a paper, a NSR-type substitute has been attributed to the reference with U0 as the terminator. A full reference is given for each publication, and the type of information extracted is specified within square brackets.

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[^{137}Cs half-life]

1948To02 J. Townsend, *et al.*, Physical Review 74 (1948) 99-100
[^{137}Cs half-life]

1949Mi01 A.C.G. Mitchell, C.L. Peacock, Physical Review 75 (1949) 197
[K/LM coefficient ratio]

1949OsU0 J.S. Osoba, Physical Review 76 (1949) 345-349
[K/LM coefficient ratio]

1950Ag01 H.M. Agnew, Physical Review 77 (1950) 655-660
[^{137}Cs half-life]

1951GlZY L.E. Glendenin, R.P. Metcalf, Radiochemical Studies: The Fission Products – Book 2, National Nuclear Energy Series IV-9 (1951) 1067-1069
[^{137}Cs half-life]

1951Wa19 M.A. Waggoner, Physical Review 82 (1951) 906-909
[α_K coefficient]

1952Be33 W.L. Bendel, *et al.*, Physical Review 87 (1952) 195A
[K/LM coefficient ratio]

1952Gr14 G.A. Graves, *et al.*, Physical Review 88 (1952) 344-348
[K/LM coefficient ratio]

1952He18 R.L. Heath, P.R. Bell, Physical Review 87 (1952) 176
[α_K coefficient]

1952Ke02 W.C. Kelly, Physical Review 85 (1952) 101-103
[K/LM coefficient ratio]

1952Mu45 D.E. Muller, *et al.*, Physical Review 88 (1952) 775-793
[^{137}Ba level energy]

1953Do31 V.M. Dolishnyuk, *et al*., Doklady Akademii nauk SSSR 92 (1953) 1141
[α_K coefficient]

1953Ma14 R.E. Maerker, R.D. Birkhoff, Physical Review 89 (1953) 1159
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1953Wi09 D.R. Wiles, *et al.*, Canadian Journal of Physics 31 (1953) 419-431
[^{137}Cs half-life]

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1954Ve09	J. Verhaeghe, J. Demuynck, Comptes rendus de l'Académie des Sciences 239 (1954) 1374-1375 [K/LM coefficient ratio]
1954Wa14	A.H. Wapstra, Arkiv för Fysik 7 (1954) 275-277 [α_K coefficient, K/LM coefficient ratio]
1955Br06	F. Brown, *et al.*, Journal of Inorganic Chemistry 1 (1955) 241-247 [^{137}Cs half-life]
1955Wi21	D.M. Wiles, R.H. Tomlinson, Physical Review 99 (1955) 188 [^{137}Cs half-life]
1956An51	I.A. Antonova, Izvestia Akademii nauk SSSR, Seriya Fizicheskaya. 20 (1956) 896 [K/LM coefficient ratio]
1957Mc34	F.K. McGowan, P.H. Stelson, Physical Review 107 (1957) 1674-1680 [α_K coefficient]
1957Ri41	R.A. Ricci, Physica 23 (1957) 693-703 [α_T coefficient, Beta-decay intensity]
1958MoZY	A.J. Moses, H.D. Cook, USAEC Report TID-7568 (1958) 192-197 [^{137}Cs half-life]
1958Yo01	Y. Yoshizawa, Nuclear Physics 5 (1958) 122-140 [Beta-decay intensity, α_K coefficient, K/LM coefficient ratio]
1959Hu23	S. Hultberg, R. Stockendal, Arkiv Fysik 14 (1959) 565 [α_K coefficient]
1960Be20	W. Beusch, Helvetica Physica Acta 33 (1960) 363-392 [Double gamma decay]
1960BuU0	T.A. Butler, Isotopes Catalog (Oak Ridge National Laboratory) Footnote 2, 3rd Revision (1960) 87 [^{137}Cs half-life]
1960De17	C. de Vries, *et al.*, Nuclear Physics 18 (1960) 454-472 [α_K coefficient]
1960GlU0	L.E. Glendenin, *et al*., private communication (1960). Reported by [1961Fa03] [^{137}Cs half-life]
1960Gr38	R.L. Graham, *et al.*, Nuclear Instruments and Methods 9 (1960) 245-286 [^{137}Ba level energy]
1960RiU0	B.F. Rider, *et al*., AEC-documentation GEAP-3373 (1960) 20 [^{137}Cs half-life]
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1965Me03	J.S. Merritt, J.G.V. Taylor, Analytical Chemistry 37 (1965) 351-354 [Beta-decay intensity, α_T coefficient, α_K coefficient, Gamma-ray intensity]
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