

Table of Radionuclides (Comments on evaluation)

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**TABLE DE RADIONUCLÉIDES
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COMMENTS ON EVALUATIONS

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Table of Radionuclides, Comments on evaluations - Monographie BIPM-5, volume 3

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Sommaire

Depuis quelques années, un groupe composé d'évaluateurs spécialistes des données de décroissance radioactive s'est formé, avec l'objectif de réaliser une évaluation soignée et documentée de ces données pour des radionucléides intervenant dans de nombreuses applications. Ces évaluateurs se sont mis d'accord sur une méthodologie commune. Ce rapport inclut les commentaires sur les évaluations des radionucléides figurant dans le rapport Monographie BIPM-5, volume 3 :

^3H , ^{55}Fe , ^{56}Co , ^{60}Co , ^{63}Ni , ^{65}Zn , ^{79}Se , ^{90}Sr , ^{90}Y , $^{90}\text{Y}^{\text{m}}$, ^{108}Ag , $^{108}\text{Ag}^{\text{m}}$, ^{111}In , ^{125}Sb , ^{137}Cs , ^{153}Sm , ^{159}Gd , ^{203}Pb , ^{233}Pa , ^{233}Th , ^{234}U , ^{236}Np , $^{236}\text{Np}^{\text{m}}$, ^{237}U , ^{238}U , ^{242}Cm , ^{243}Am , ^{244}Cm .

Summary

Over the past years, an informal collaboration of decay-data evaluators has been assembled with the goal of creating high-quality, well-documented evaluations of the decay data for a selected set of radionuclides that are of interest in various applications. This report includes, for each radionuclide, the evaluator's comments on how the evaluation was carried out for the radionuclides that are in the Monographie BIPM-5, volume 3 :

^3H , ^{55}Fe , ^{56}Co , ^{60}Co , ^{63}Ni , ^{65}Zn , ^{79}Se , ^{90}Sr , ^{90}Y , $^{90}\text{Y}^{\text{m}}$, ^{108}Ag , $^{108}\text{Ag}^{\text{m}}$, ^{111}In , ^{125}Sb , ^{137}Cs , ^{153}Sm , ^{159}Gd , ^{203}Pb , ^{233}Pa , ^{233}Th , ^{234}U , ^{236}Np , $^{236}\text{Np}^{\text{m}}$, ^{237}U , ^{238}U , ^{242}Cm , ^{243}Am , ^{244}Cm .

TABLE DE RADIONUCLÉIDES – COMMENTAIRES SUR LES ÉVALUATIONS

De nombreuses applications nécessitent la connaissance des données liées à la désintégration des radioéléments, telles que la période radioactive, les énergies et les intensités des divers rayonnements. Pour répondre aux demandes des utilisateurs, le Laboratoire National Henri Becquerel (BNM - LNHB, France) a, de 1982 à 1987, publié une table en quatre volumes [87Ta, 99Be]. Puis, en 1993 une coopération a été établie avec le Physikalisch-Technische Bundesanstalt (PTB, Allemagne) afin de reprendre cette étude et de la développer. En 1995, un nouveau groupe de travail international nommé Decay Data Evaluation Project (DDEP) s'est formé qui, en plus des deux laboratoires nationaux précédents, inclut : Idaho National Engineering and Environmental Laboratory (INEEL, USA), Lawrence Berkeley National Laboratory (LBNL, USA), Brookhaven National Laboratory (BNL, USA) et Khlopin Radium Institute (KRI, Russie).

Le propos de ce groupe est de fournir aux utilisateurs des données soigneusement évaluées qui puissent servir de référence. A cette fin, tous les membres du groupe suivent une méthodologie commune qui comprend :

- la lecture attentive de toutes les publications relatives à une grandeur ;
- une analyse statistique des données retenues ;
- le choix et l'utilisation des mêmes jeux de données, pour celles ayant fait l'objet d'études spécifiques par des spécialistes, tels les coefficients de conversion interne.

Tous ces points sont développés en détails dans le chapitre « Rules for evaluation and compilations ».

Par ailleurs, toutes les évaluations sont documentées et l'établissement des valeurs retenues explicité. Ce document est ensuite relu par deux membres du groupe.

Ce volume regroupe les commentaires liés à l'évaluation des radionucléides suivants :

^3H , ^{55}Fe , ^{56}Co , ^{60}Co , ^{63}Ni , ^{65}Zn , ^{79}Se , ^{90}Sr , ^{90}Y , $^{90}\text{Y}^m$, ^{108}Ag , $^{108}\text{Ag}^m$, ^{111}In , ^{125}Sb , ^{137}Cs , ^{153}Sm , ^{159}Gd , ^{203}Pb , ^{233}Pa , ^{233}Th , ^{234}U , ^{236}Np , $^{236}\text{Np}^m$, ^{237}U , ^{238}U , ^{242}Cm , ^{243}Am , ^{244}Cm .

Les données de décroissance radioactive de ces radionucléides peuvent être trouvées dans la Monographie BIPM-5 de la « Table de radionucléides », dans le CD-Rom NUCLÉIDE édité par le LNHB ou sur les pages web : <http://www.nucleide.org/NucData.htm>

TABLE OF RADIONUCLIDES – COMMENTS ON EVALUATIONS

Basic properties of radionuclides, such as half-life, decay mode and branchings, radiation energies and emission probabilities are commonly used in various research fields. To meet the demand for these data the LNHB produced a table that was published in four volumes [87Ta, 99Be] from 1982 to 1987. In 1993, a cooperative agreement was established between the Laboratoire National Henri Becquerel (BNM - LNHB, France) and the Physikalisch-Technische Bundesanstalt (PTB, Germany) to continue and expand this work. In 1995, a new international collaboration was formed, the Decay Data Evaluation Project (DDEP), which has the same objectives. Along with the evaluators from LNHB and PTB, this collaboration includes others from the Idaho National Engineering and Environmental Laboratory (INEEL, USA), the Lawrence Berkeley National Laboratory (LBNL, USA), the Brookhaven National Laboratory (BNL, USA) and the Khlopin Radium Institute (KRI, Russia). Its objective has been to provide carefully produced recommended values, which may eventually become standard data. With this goal in mind, the collaboration has adopted a uniform evaluation methodology that contains the following :

- a critical review of relevant publications;
- an accounting of all measured data;
- a uniform statistical analysis of the data;
- a presentation of values for quantities such as internal conversion coefficients, etc.
- a review of evaluation by two other members of the collaboration.

These topics are described in detail in the chapter “Rules for evaluation and compilations”.

The evaluation of each individual radionuclide has a section (presented here) that describes the procedures used for deducing the recommended values. This documentation is included in order to establish the quality and completeness of each evaluation. It can also provide the basis for any future reevaluation by the DDEP or other groups.

This volume contains the procedures and comments relevant to the evaluation for the following radionuclides :

^3H , ^{55}Fe , ^{56}Co , ^{60}Co , ^{63}Ni , ^{65}Zn , ^{79}Se , ^{90}Sr , ^{90}Y , $^{90}\text{Y}^m$, ^{108}Ag , $^{108}\text{Ag}^m$, ^{111}In , ^{125}Sb , ^{137}Cs , ^{153}Sm , ^{159}Gd , ^{203}Pb , ^{233}Pa , ^{233}Th , ^{234}U , ^{236}Np , $^{236}\text{Np}^m$, ^{237}U , ^{238}U , ^{242}Cm , ^{243}Am , ^{244}Cm .

These evaluations may be found in the BIPM-5 Monographie, on the CD-Rom NUCLÉIDE published by the LNHB or in the web pages : <http://www.nucleide.org/NucData.htm>

A goal of the DDEP is to avoid future duplication of effort by disseminating these critically evaluated data with the hope that they will be included in many other collections of decay data.

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**AUTEURS POUR CORRESPONDANCE
AUTHOR'S MAIL ADDRESSES
ADRESSEN DER AUTOREN
AUTORES PARA CORRESPONDENCIA**

Toutes demandes de renseignements concernant les données recommandées et la façon dont elles ont été établies doivent être adressées directement aux auteurs des évaluations.

Information on the data and the evaluation procedures is available from the authors listed below.

Informationen über die Daten und Evaluationsprozeduren können bei den im folgenden zusammengestellten Autoren angefordert werden.

Todos los pedidos de información sobre datos recomendados y los métodos de evaluación utilizados, deben dirigirse directamente a los autores de las evaluaciones.

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RULES FOR EVALUATION AND COMPILATIONS

1. DATA SOURCES

Two main sources of data are used to obtain the recommended values:

- specific data evaluated from all available original publications (e.g., half-life),
- data already evaluated and compiled by specialists (e.g., Q-values); if a subsequent experimental study exists, the resulting measured value may be used, and its reference be included in a list of references for such a radionuclide.

2. EVALUATION RULES

All intermediate stages in the compilation and evaluation of a decay parameter are not presented in detail in order to avoid unnecessary complexity. The main stages comprise the following:

- critical analysis of published results and, if necessary, correction of these results to account for more recent values hitherto unavailable to the original experimentalists; as a rule, results without associated uncertainties are discarded, and the rejection of values is documented;
- data obtained through private communications are used only when all of the necessary information has been provided directly by the scientist who performed the measurements;
- adjustments may be made to the reported uncertainties;
- recommended values are deduced from an analysis of all measurements (or theoretical considerations), along with their standard deviations with a 1s confidence level.

2.1. Evaluation of uncertainties

Definitions from “Guide to the expression of uncertainty in measurement” [1]:

Uncertainty (of measurement): parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

Standard uncertainty: uncertainty of the result of a measurement expressed as a standard deviation.

Type A evaluation (of uncertainty): method of evaluation of uncertainty by the statistical analysis of a series of observations.

Type B evaluation (of uncertainty): method of evaluation of uncertainty by means other than the statistical analysis of a series of observations.

The uncertainties given by authors are re-evaluated by combining the standard uncertainties σ_A and σ_B through the general law of variance propagation:

$$u_c = \sqrt{\mathbf{s}_A^2 + \mathbf{s}_B^2} \quad (1)$$

where u_c is the combined standard uncertainty,
 \mathbf{s}_A is the type A standard deviation, and
 \mathbf{s}_B is the type B standard uncertainty.

When the authors give insufficient information concerning their uncertainty calculations, the combined uncertainty u_c may be estimated by the evaluator, based on a knowledge of the measurement method(s).

2.2. Determination of the best value and associated uncertainty

(a) Results obtained by one author using one method

Sometimes only the final mean value and the combined standard uncertainty are given in the original publication. The following procedure is adopted if sufficient details are known.

For n individual values a_i ($i = 1 \dots n$), the best value is the arithmetical mean:

$$\bar{a} = \sum_{i=1}^n \frac{a_i}{n} \quad (2)$$

with type A standard deviation:

$$\mathbf{s}_A(\bar{a}) = \left[\frac{\sum_i (a_i - \bar{a})^2}{n(n-1)} \right]^{1/2} \quad (3)$$

If there are m contributions σ_{Bj} ($j = 1 \dots m$) to the type B standard uncertainty that are independent of each other:

$$\mathbf{s}_B(\bar{a}) = \left[\sum_{j=1}^m \mathbf{s}_{Bj}^2 \right]^{1/2} \quad (4)$$

Combined standard uncertainty:

$$u_c(\bar{a}) = \sqrt{\mathbf{s}_A^2(\bar{a}) + \mathbf{s}_B^2(\bar{a})} \quad (5)$$

Recommended value:

$$a = \bar{a} \pm u_c(\bar{a}) \quad (6)$$

(b) Results obtained by several authors employing the same method

For n individual values \bar{a}_i ($i = 1 \dots n$) having a standard deviation σ_{Ai} and a type B uncertainty σ_{Bi} , the best value is obtained by taking the mean weighted by the inverse of the variances.

$$\bar{a} = \frac{\sum_i (\bar{a}_i / \mathbf{s}_{Ai}^2)}{\sum_i (1 / \mathbf{s}_{Ai}^2)} \quad (7)$$

The associated values σ_A , σ_B are:

$$\mathbf{s}_A(\bar{a}) = \left[\sum_i (1 / \mathbf{s}_{Ai}^2) \right]^{-1/2} \quad (8)$$

$$\mathbf{s}_B(\bar{a}) = \sum_i (\mathbf{s}_{Bi})_{\min} \quad \text{or} \quad \mathbf{s}_B(\bar{a}) = \sqrt{\sum_i (\mathbf{s}_{Bi})_{\min}^2} \quad \text{or} \quad \mathbf{s}_B(\bar{a}) = (\mathbf{s}_B)_{\min}$$

depending on the individual case, although $\mathbf{s}_B(\bar{a})$ cannot be less than the smallest σ_{Bi} .

σ_A and σ_B are combined quadratically to determine u_c :

$$u_c(\bar{a}) = \sqrt{\mathbf{s}_A^2(\bar{a}) + \mathbf{s}_B^2(\bar{a})} \quad (9)$$

and the recommended value is given by the expression:

$$a = \bar{a} \pm u_c(\bar{a}) \quad (10)$$

(c) Results obtained by different methods

When different measurement techniques have been applied, a weighted average is calculated using the combined uncertainties of the individual values as weights.

For n independent values a_i , each with a combined standard uncertainty u_{ci} , a weight p_i proportional to the inverse of the square of the individual u_{ci} can be assigned to each value.

$$a_w = \frac{\sum_{i=1}^n p_i a_i}{\sum_{i=1}^n p_i} \quad (11)$$

where the weights are $p_i = 1 / u_{ci}^2$.

An internal and an external uncertainty can be assigned to the mean value [2, 3]:

$$\mathbf{s}_{int}(a_w) = \left[\sum_i (1 / u_{ci}^2) \right]^{-1/2} \quad (12)$$

The internal variance $\mathbf{s}_{int}^2(a_w)$ is the expected uncertainty of the mean, based on the individual *a priori* variances u_{ci}^2 (by uncertainty propagation).

The external uncertainty is given by the equation:

$$\mathbf{s}_{ext}(a_w) = \left[\frac{\sum_i (a_i - a_w)^2 / u_{c_i}^2}{(n-1) \sum 1/u_{c_i}^2} \right]^{1/2} \quad (13)$$

The external variance $\mathbf{s}_{ext}^2(a_w)$ includes the scatter of the data, and is based on the amount by which each a_i deviates from the mean when measured as a fraction of each given uncertainty u_{c_i} .

A measure of the consistency of the data is given by the ratio [2, 3]:

$$\mathbf{s}_{ext} / \mathbf{s}_{int} = \sqrt{\mathbf{c}^2 / (n-1)} \quad (14)$$

If this ratio is significantly greater than unity, at least one of the input data most probably has an underestimated u_{c_i} which should be increased.

A critical value of $\mathbf{c}^2 / (n-1)$ at 1 % confidence level is used as a practical test for discrepant data. The following table lists critical values of $\mathbf{c}^2 / (n-1)$ for an increasing degree of freedom $\mathbf{n} = n - 1$ [4].

n	critical $\mathbf{c}^2 / (n-1)$	n	critical $\mathbf{c}^2 / (n-1)$
1	6.6	12	2.2
2	4.6	13	2.1
3	3.8	14	2.1
4	3.3	15	2.0
5	3.0	16	2.0
6	2.8	17	2.0
7	2.6	18-21	1.9
8	2.5	22-26	1.8
9	2.4	27-30	1.7
10	2.3		
11	2.2	>30	$1 + 2.33 \sqrt{2/n}$

If $\mathbf{c}^2 / (n-1) \leq \text{critical } \mathbf{c}^2 / (n-1)$, the recommended value is given by:

$$a = a_w \pm \mathbf{s}_{int}(a_w) \quad (15)$$

If $\mathbf{c}^2 / (n-1) > \text{critical } \mathbf{c}^2 / (n-1)$, the method of limitation of the relative statistical weight [3, 5] is recommended when there are three or more values; uncertainty of a value contributing more than 50 % to the total weight is increased to reduce its contribution to 50 %. The weighted and unweighted average and critical $\mathbf{c}^2 / (n-1)$ are then recalculated:

if $\mathbf{c}^2 / (n-1) \leq \text{critical } \mathbf{c}^2 / (n-1)$, the recommended value is given by:

$$a = a_w \pm (\text{the larger of } \mathbf{s}_{int}(a_w) \text{ and } \mathbf{s}_{ext}(a_w)) \quad (16)$$

if $\mathbf{c}^2 / (n-1) > \text{critical } \mathbf{c}^2 / (n-1)$, the weighted or unweighted mean is chosen, depending on whether or not the uncertainties of the average values make them overlap with each other. If overlap occurs, the weighted average is recommended; otherwise the unweighted average is chosen. In either case, the uncertainty can be increased to cover the most accurate value.

Parameters evaluated according to these procedures and rules include half-lives, number of emitted particles, and some internal-conversion coefficients. All remaining data given in the tables of recommended data are generally taken from compilations.

2.3. Balanced decay schemes

All the probabilities for transitions and emitted radiations correspond to balanced decay schemes and permit the formulation of a fully consistent set of values. This balance implies the fulfillment of physical conservation principles as follows:

- The sum of the transition probabilities for all the transitions (α , β , ϵ) is equal to 1 (or 100 %); consequently, the sum of all the γ -ray transition probabilities (photons + internal conversion electrons) and all the (α , β , or ϵ) transitions feeding directly to the ground state is equal to 1 (or 100 %).
- For an excited nuclear level, the sum of the transition probabilities (α , β , γ , ϵ) feeding the level is equal to the sum of the transition probabilities depopulating this level;
- If the relative γ -ray emission probabilities $P(rel)_{g_i}$ are known, the absolute emission probability $P(abs)_{g_i}$ can be obtained from the equation:

$$P(abs)_{g_i} = P(rel)_{g_i} \times N \quad (17)$$

where N is the normalization factor, which may be determined from the equation:

$$N \sum_i P(rel)_{g_i} (1 + \alpha_i) = 1 - B, \quad (18)$$

where α_i is the total conversion coefficient, and B , the (α , β , or ϵ) absolute branching to the ground state. The sum in equation (18) includes all the γ -ray transitions feeding the ground state.

3. COMPILATIONS

3.1. β and electron capture transitions

Depending on the individual radionuclide, the β -particle transition energies are either evaluated from experimental data (maximum β energies), or deduced from the atomic mass differences obtained from the tabulations of Audi and Wapstra [6] and the γ transition energies. The average β -particle energies are generally computed [7], and their $\log ft$ values as well as their ϵ/β^+ ratios are calculated using the tables of Gove and Martin [8].

Electron-capture transition energies are deduced from atomic mass differences and γ -ray transition energies. Capture probabilities P_K , P_L ... for allowed and non-unique first forbidden transitions can be calculated from equations where the ratios of the radial wave function components of the electron [9-11] and the corrective terms for exchange $X^{L/K}$ [12-16] are evaluated from tables.

3.2. g -ray transitions

Internal conversion coefficients of pure multipolarity transitions are evaluated and compared with theoretical values that are interpolated from the tables of either Rösler *et al.* using a cubic spline method for $30 \leq Z \leq 104$ [17], or Band *et al.* [18]. The agreement of these theoretical values with experimental results is about 3 %.

Internal-conversion coefficients are calculated as described in Ref. [19] in order to include the effects of nuclear penetration in some M1 and E2 transitions.

Internal conversion coefficients for transitions with mixed multiplicities (e.g., M1 + E2) are calculated using tables of theoretical values using mixing ratios as shown below :

$$\alpha_i(\text{M1+E2}) = \alpha_i(\text{M1}) \frac{1}{1+\delta^2} + \alpha_i(\text{E2}) \frac{\delta^2}{1+\delta^2} \quad (19)$$

where $i = \text{K, L1, L2, ... T}$, refers to the individual atomic shell.

a_p coefficients for pair production are interpolated from theoretical values [20], with a precision between 5 % and 10 %.

3.3. Level spins and parities

Level spins and parities are usually from Nuclear Data Sheets [21].

3.4. Atomic shell constants

K-shell fluorescence yields w_K and their uncertainties are taken from the evaluation of Bambynek *et al.* [22-24] with uncertainties ranging from 1 % ($Z > 35$) to 10 % ($Z = 5$), and from subsequent experimental results.

Mean L-shell fluorescence yields \bar{w}_L are taken from the evaluation of Schönfeld and Janßen [25]. This evaluation includes both experimental [26-28] and theoretical values [29], and their uncertainties are equal to 4 % (for $Z > 29$).

Mean M-shell fluorescence yields \bar{w}_M are obtained from the fitting of experimental data by Hubbell [28, 30].

Relative X-ray emission rates ($K\beta/K\alpha$) are taken from Schönfeld and Janßen [25], and $K\alpha_1/K\alpha_2$ from the theoretical values of Scofield [31]; uncertainties are assumed to be of the order of 1 %.

X-ray radiation energies are taken from the tables of Bearden [32].

Relative emission probabilities of K-Auger electron groups are deduced from the X-ray ratio, with uncertainties of the order of 3 % [25].

Energies of the K and L-Auger electrons are taken from Larkins [33].

The mean number of vacancies created in the L shell (from one K hole) n_{KL} and in the M shell (from one L hole) \bar{n}_{LM} are estimated from the preceding values.

3.5. m_0c^2 energy

m_0c^2 energy is defined as 510.998902(21) keV, as given by the CODATA Group [34].

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³H – Comments on Evaluation by V.P. Chechev

The initial ³H decay data evaluation was done by Chechev in 1998 (1999Be). This current (revised) evaluation was carried out in April 2006. The literature available by April 2006 was included.

1. DECAY SCHEME

³H decays 100 % by β⁻-emission directly to the ground state of ³He.

2. NUCLEAR DATA

Q⁻ value is from 2003Au03.

The evaluated ³H half-life is based on the experimental data given in Table 1. This table has been taken from the paper of Lucas and Unterweger (2000Lu17) which contains a comprehensive review and critical evaluation of the half-life of tritium.

Table 1. Experimental values of the ³H half-life (in years)

Reference	Author(s)	Measurement method	Half-life (years)	Stated uncertainty (years)	Meaning of the stated uncertainty	Comments
1936 McMillan	McMillan	Ionization current	>10	None	No uncertainty	Followed decay of radiation from irradiated beryllium for 4 months. OMITTED: limit only
1939 Alvarez	Alvarez and Cornog	Beta counting	0.41	0.11	Not given	One sample followed for 80 d. Chamber had diffusion losses. OMITTED: updated in 1940Alvarez
1940 Alvarez	Alvarez and Cornog	Beta counting	>10	None	No uncertainty	One sample followed for 5 months in new chamber. OMITTED: limit only
1940On01	O'Neal and Goldhaber	Beta counting	31	8	Not given	Counted tritium from irradiated lithium metal. OMITTED: outlier
1947Go08	Goldblatt <i>et al.</i>	Ionization current	10.7	2.0	Not given	Hydrogen + tritium in ionization chamber over 18 d. OMITTED: outlier
1947No01	Novick	Helium-3 collection	12.1	0.5	Not given	Two samples; accumulation times of 51 d and 197 d
1949Jenks	Jenks <i>et al.</i>	Helium-3 collection	12.46	0.20	Not given	Repeated measurements every two weeks until stable. OMITTED: updated in 1950Je60
1950Je60	Jenks <i>et al.</i>	Helium-3 collection	12.46	0.10	Probable error ^a	Four measurements over 206 d.
1951Jo15	Jones	Beta counting	12.41	0.05	Probable error ^a	Measurement of specific activity of tritium gas
1955Jo20	Jones	Helium-3 collection	12.262	0.004	Not given	Two samples; accumulation times of 578 d and 893 d
1958Po64	Popov <i>et al.</i>	Calorimetry	12.58	0.18	Not given	One sample; 21 measurements over 13 months
1963 Eichelberger	Eichelberger <i>et al.</i>	Calorimetry	12.355	0.010	Probable error ^a	Two samples measured over four years. OMITTED: updated in 1967Jo09

1966Merritt	Merritt and Taylor	Beta counting	12.31	0.13	Not given	Five gas counting measurements over 13 years
1967Jo09	Jordan <i>et al.</i>	Calorimetry	12.346	0.002	Probable error ^a	Five samples; 266 measurements over 6 years. OMITTED: updated in 1977RuZZ
1967Jo10	Jones	Helium-3 collection	12.25 12.31	0.08 0.42	99.7 % confidence limits	Two samples; accumulation times of 450 d to 800 d. Only the first value is usually quoted
1977RuZZ	Rudy and Jordan	Calorimetry	12.3232	0.0043	95 % confidence limits	Eight samples; 1353 measurements over 16 years
1980Un01	Unterweger <i>et al.</i>	Beta counting	12.43	0.05	1 standard uncertainty	Two sets of gas counting measurements 18 years apart. OMITTED: updated in 2000Unterweger
1987Bu28	Budick <i>et al.</i>	Bremsstrahlung counting	12.29	0.10	Not given	Two samples of tritium + xenon gas measured over 320 d. OMITTED: updated in 1991Bu13
1987O104	Oliver <i>et al.</i>	Helium-3 collection	12.38	0.03	1 standard uncertainty	Fifteen samples, each with accumulation times of 1 year to 2 years
1987Si01	Simpson	Beta counting	12.32	0.03	1 standard uncertainty	Tritium implanted in Si(Li) detector measured over 5.5 years
1988 Akulov	Akulov <i>et al.</i>	Helium-3 collection	12.279	0.033	1 standard uncertainty	Five series of measurements over 846 d
1991Bu13	Budick <i>et al.</i>	Bremsstrahlung counting	12.31	0.03	1 standard uncertainty	Two samples of tritium + xenon gas measured over 5.5 years
2000 Unterweger	Unterweger and Lucas	Beta counting	12.33	0.03	1 standard uncertainty	Three sets of gas counting measurements over 38 years

^a The probable error, PE, is the deviation from the population mean, μ , such that 50 % of the observations may be expected to lie between $\mu - PE$ and $\mu + PE$. For a normal distribution, the probable error can be converted to the standard deviation by multiplying by 1.4826.

As seen from Table 1 there are a number of measurements of the tritium half-life. Three of them stand out by their high precision (1955Jo20, 1967Jo09, 1977RuZZ). However, the uncertainties stated for the half-life in these works do not include an estimation of possible systematic errors. There are available newer measurements and discussions of the tritium half-life, so it is possible to estimate an "external" minimum uncertainty due to systematic effects (σ_{\min}) that should be added to the uncertainties stated in 1955Jo20, 1967Jo09 and 1977RuZZ. At that we can take into account the following circumstances:

a) The ³He collection result of 1955Jo20 has been obtained using only two points on each decay curve (for two samples). In the later work by the same method (1967Jo09) many experimental points were obtained on the decay curves (also for two samples) and the estimated systematic uncertainty made up 0.8 % for a 99.7 % confidence level.

b) The result of 1977RuZZ is a continuation of the measurements of 1967Jo09 for two tritide solids by calorimetric method for an additional 12 years. The difference of results of 1967Jo09 and 1977RuZZ proved to be 0.2 %, more than $5\sigma_{\exp}$ from 1977RuZZ and more than $10\sigma_{\exp}$ from 1967Jo09.

c) The comparative analysis of measurements of the radioactivity concentrations in several NBS tritiated-water standards over an 18-year period 1961 - 1978 (1980Un01) showed that for agreement of measurements (at given tritium half-life) their estimated standard errors (including a calorimetric method) should not be less 0.2 %.

Thus we have sufficient grounds for adding the "external" systematic error $\sigma_{\min} = 0.002 T_{1/2} (^3\text{H})$ into the uncertainties quoted in 1955Jo20, 1967Jo09 and 1977RuZZ. Lucas and Unterweger (2000Lu17) estimated the standard uncertainty of 1955Jo20 as 0.030 yr and that of 1977RuZZ as 0.025 yr.

Table 2 shows the modified set of half-life values, which has been formed from the original set by omitting the ten measurement results (see Comments in Table 1) and adjusting the uncertainties of 1955Jo20, 1977RuZZ and 1966Merritt. Latter was re-estimated in 2000Lu17.

Table 2. Selected measurement results for tritium half-life (in years)

Reference	Half-life	Measurement method	Comments on uncertainty
1947No01	12.1(5)	³ He collection	Author's stated uncertainty (ASU)
1950Je60	12.46(15)	³ He collection	ASU multiplied by 1.4826
1951Jo15	12.41(7)	Beta counting	Author's stated uncertainty
1955Jo20	12.262(30)	³ He collection	Uncertainty re-estimated in 2000Lu17
1958Po64	12.58(18)	Calorimetry	Author's stated uncertainty
1966Merritt	12.31(4)	Beta counting	Uncertainty re-estimated in 2000Lu17
1967Jo10	12.25(3)	³ He collection	Author's stated uncertainty
1977RuZZ	12.323(25)	Calorimetry	See text
1987Ol04	12.38(3)	³ He collection	Author's stated uncertainty
1987Si01	12.32(3)	³ H implanted into Si(Li)	Author's stated uncertainty
1988Akulov	12.279(33)	³ He collection	Author's stated uncertainty
1991Bu13	12.31(3)	Bremsstrahlung	Author's stated uncertainty
2000Unterweger	12.33(3)	Three sets of gas counting measurements over 38 years	Author's stated uncertainty

A weighted average for the final data set is 12.312 with an internal uncertainty of 0.010 and an external uncertainty of 0.013 and a reduced $\chi^2/\nu = 1.6$. An unweighted average is 12.33(3). Different statistical procedures from 1994Ka08 give the similar results: UINF, LWM, NORM – 12.312(10), PINF, BAYS and MBAYS – 12.312(13), IEXW – 12.314(14), RAJ – 12.311(10), CHV – 12.317(16). Lucas and Unterweger (2000Lu17) used three other statistical procedures including the method of determining the median and the estimated standard deviation of the median and adopted the value of 12.318(25).

The LWEIGHT computer program using the LWM procedure has led to the recommended value of 12.312(10).

The EV1NEW computer program (2000Ch01) has chosen the weighted average of 12.312 and recommended the smallest experimental uncertainty of 0.025 as a final uncertainty.

The adopted value of the ³H half-life is 12.312(25) years, or 4497(9) days.

It should be noted this half-life value has been evaluated for molecular tritium. The half-life of atomic tritium is less by ~0.26% (2004Ak16). See also 2005Ak04 for a bare triton half-life.

2.1. Tritium Beta End-Point Energy (E_b^0)

The tritium beta end-point energy depends upon the chemical state of the tritium in an experiment. The expression for E_b^0 of molecular tritium differs from that of a "bare" nucleus by the "chemical shift" $\Delta E = B(\text{RHe}^+) - B(\text{RT})$ (1985Ka21, 1989Re04) which is calculated taking into account the spectrum of

final states (SFS). (Here the B values indicate electron binding energies for He⁺ ion and tritium atom, R indicates a chemical state).

For known ³He-³H atom mass difference (ΔMc^2) the tritium beta "end-point" energy measured in some experiment is :

$$E_{\beta}^0 = \Delta Mc^2 - E_{\text{rec}} - [B(\text{He}) - B(\text{T})] + [B(\text{RHe}^+) - B(\text{RT})]$$

where E_{rec} is the helium recoil energy.

For tritium atom (nuclide) $E_{\beta}^0 = \Delta Mc^2 - 3.4 \text{ eV} - 64.3 \text{ eV} + \Delta E$ where $\Delta E = 40.82 \text{ eV}$.

With the recommended value of ΔMc^2 , the beta end-point energy for tritium nuclide is obtained by this way as 18563.6 eV. It is difficult to estimate the uncertainty of the ΔE calculation in 1985Ka21. Supposing it about the evaluated uncertainty of ΔMc^2 (Q value), we have E_{β}^0 (³H nuclide) = 18.564(2) keV.

For real forms of tritium sources in beta-spectrometry experiments the ³H end-point energies differ from the atomic value. For a molecular forms HT, CH₃T, valine the calculated E_{β}^0 makes 18572(2) eV. Below the measured end-point energies in some experiments are shown.

1987Bo07	Valine	18.579.4 ± 4 eV
1993Ba08	Molecular tritium	18.574.8 ± 0.6 eV
1993Su32	C ₁₄ H ₁₅ T ₆ O ₂ N ₃	18.578.3 ± 5.1 eV
1995St26	Gaseous tritium	18.568.5 ± 2.0 eV
2003Kr17	Gaseous tritium	18.570.5 eV

It should be noted that many works devoted to study of tritium beta-spectrum as it provided the most precise data of neutrino mass upper limit (see, for example, 2005Kr03, 2003Lo10, 2002Bo31 and references therein).

2.2. Average energy of beta particles of tritium per disintegration ($\langle E_{\beta} \rangle$)

In Table 3 the available data of the $\langle E_{\beta} \rangle$ have been presented. The recommended value $\langle E_{\beta} \rangle$ has been obtained as the weighted average after corrections into the original results of the experiments and calculations. The calculation of the $\langle E_{\beta} \rangle$ with the LOGFT computer program using the adopted value $Q^- = 18.591(1) \text{ keV}$ gives 5.68 (±0.0011) keV.

Table 3. The available data of the tritium average beta energy (per disintegration, keV)

Reference	Method	Original	Re-estimated	Adopted
1950Je60	Calorimetry	5.69(4)	5.68(4) ^a	5.68(4)
1958Gr93	Calorimetry	5.57(1)	5.68(2) ^a	5.68(2)
1961Pi01	Calorimetry	5.73(3)	5.68(3) ^b	5.68(3)
1972Ma72	Calculation	5.7		5.7(1) ^d
1985Martin	Calculation	5.684(5)	5.680(5) ^c	5.68(1) ^d
1985Garcia	TDCR	5.70		5.70(2) ^d
1987Lagoutine, 1994Si21	Calculation	5.71(3)	5.70(3) ^c	5.70(3)
Recommended value 5.68(1) keV				

^a Corrected for the adopted tritium half-life of 12.312 y and heat output of 0.324(1) W/g

^b Corrected for the adopted tritium half-life of 12.312 y

^c Corrected for the adopted decay energy ($Q^- = 18.591 \text{ keV}$)

^d Uncertainty attributed by the evaluator

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⁵⁵Fe - Comments on evaluation of decay data by M. M. Bé and V. Chisté

The initial evaluation was completed in April 1998. This revised evaluation was carried out in 2005, the literature available by December 2005 was taking into account.

1. Decay scheme

An Internal Bremsstrahlung electron capture spectrum was measured by **Isaac *et al.***, the intensity was found to be $3.24 (6) \times 10^{-5}$ relatively to K capture.

The J^π value and level energy are from **NDS 64,4** (1991). From other decay modes, the excited level energy has been determined to be 125.949 (10) keV.

2. Nuclear Data

- The Q value is from **Audi and Wapstra** (2003)
- The half-life values taking into account are, in days :

(1)	977.9	2.3	Lagoutine 1982 (DSA PC) ^a
(2)	1000.4	1.3	Houtermans 1980 (PC)
(3)	1009.0	1.7	Hoppes 1982 (PC, Si(Li))
(4)	996.8	6.0	Morel 1994 (Planar Ge)
(5)	995.0	3.0	Karmalitsyn 1998 (PC)
(6)	1003.5	2.1	Schötzig 2000 (Si(Li))
(7)	1005.2	1.4	Van Ammel 2006 (DSA PC)

^a (Method of measurement, PC = Proportional counter, DSA = Defined Solid Angle)

The (1) value is rejected because it is discrepant by Chauvenet's criterion.

With this value deleted, none of the other values has a relative weight greater than 50 %.

The Lweight calculation gives, for the six remaining values, a weighted mean value of 1003.4 d, with an external uncertainty of 1.7, an internal uncertainty of 0.7 and a reduced- χ^2 of 5.4.

This set of value is inconsistent, the three values with lower uncertainties (2, 3 and 7) are not compatible within their uncertainty limits. No trend can be distinguished.

So, the external uncertainty has been expanded so range to include the most precise value of 1000.4 d.

The adopted value is *1003.4 (30) d* or *2.747 (8) a*.

Other references not used in this evaluation due to their discrepancy or their great uncertainty comparing with the set of recent values above :

- 1037 (11) G.L. Brownell, C.J. Maletskos, Phys.Rev. 80 (1950) 1102
- 950 (7) R.P. Schuman et al., I.Inorg.Nuclear Chem. 3 (1956) 160
- 880 (44) J.S. Evens, R.A. Naumann, PPAD-2137-566 (1965) 10

2.1. Electron Capture transitions

- The EC transition energies are from $Q(\text{EC}) = 231.21$ (18) and from the individual level energies.
- The transition probabilities are deduced from the total gamma-ray transition probability balances at each level.
- The electron capture coefficients, for this allowed transition, were calculated by using the EC-capture program :

$$P_K = 0.8853$$
 (16) ; $P_L = 0.0983$ (13) ; $P_M = 0.0157$ (6) ; $P_N = 0.0006$ (2)

The LOGFT program gives :

$$P_K = 0.885$$
 (9) ; $P_L = 0.0974$ (10) ; $P_M = 0.0161$ (2) ; $P_{N+} = 0.00106$ (1)

Measurements were carried out by **Pengra et al.** :

$$P_K = 0.881$$
 (4) ; $P_L = 0.103$ (4) ; $P_{M+} = 0.0161$ (8)

Results from calculations and measurements are in good agreement, nevertheless the measured values are dependent on ω_K (= 0.314) and on the intensity of the $K\alpha$ X-ray (= 0.89). So, the recommended values are those of the EC-capture program.

- Several measurements or calculations were done to study the double K-shell ionization process. One can quoted **Campbell et al.**; where the total probability for double vacancies in the K shell was found to be 1.3 (2) 10^{-4} , or **Kitahara et al.** where the probability for the ejection of another K electron during the K-capture decay was estimated to be 1.01 (27) 10^{-4} . As these phenomena have very small probabilities, these results are only quoted here as a matter of interest.

2.2. Gamma transitions

A weak gamma transition is deduced from the observation of a 126 keV gamma emission. The energy is derived from the level energy.

3. Atomic Data

Several data for ω_K are deduced from measurements :

- from **Smith**, $\omega_K = 0.320$ (3) ($P_K = 0.885$ (2))
- from **Konstantinov et al.**, $\omega_K = 0.312$ (3)
- from **Dobrilovic et al.**, $\omega_K = 0.322$ (5)
- from **Kuhn et al.**, $\omega_K = 0.310$ (23)
- from **Hubbell et al.**, $\omega_K = 0.321$ (7) (deduced from photoionization cross-section measurements)

A theoretical value was also calculated by **Chen** : $\omega_K = 0.323$.

These values are in good agreement (except **Konstantinov et al.** and **Khun et al.**) with the recommended value of $\omega_K = 0.321$ (5) from the semi-empirical fit of **Bambynek 1984**.

$\overline{\omega}_L$ and η_{KL} are from **Schönfeld et al.**

3.1.1. X Radiations

- The X-ray energies were obtained by conversion of the wavelength values from **Bearden** into energies with $1 \text{ \AA} = 1.000\ 014\ 81$ (92) 10^{-10} m.
- The emission intensities are calculated by the EMISSION program from PTB with ω_K , $\overline{\omega}_L$ and η_{KL} quoted above and, $K\beta/K\alpha = 0.1359$ (14), $K\alpha_2 / K\alpha_1 = 0.5099$ (25) (**Schönfeld et al.**).
- With $P_K = 0.8853$ (16) for this allowed transition, and $\omega_K = 0.321$ (5) the total K X-ray emission intensity is then $P_K \times \omega_K = 0.284$ (5) which can be compared with the experimental values of 0.279 (8) (**Schötzig**) and of 0.283 (2) (**Smith**).

The value given by **Smith** was obtained in an international activity measurement exercise where six laboratories reported results for $P_K \times \omega_K$. The deduced weighted mean is in good agreement with the calculated value and has a better uncertainty. However, as pointed out by **Smith**, this uncertainty is probably underestimated. So, the value of $I_K = P_K \times \omega_K \times 100 = 28.4 (5) \%$ is adopted.

3.1.2. Auger Electrons

Complete measurements of the K Auger spectrum of manganese was performed by **Kovalik et al.**, they found for the relative intensities of the K Auger groups :

$$\text{KLM/KLL} = 0.26 (2)$$

$$\text{KMM/KLL} = 0.018 (2)$$

These values are in good agreement with the recommended values calculated with the EMISSION program:

$$\text{KLM/KLL} = 0.272 (3)$$

$$\text{KMM/KLL} = 0.0185 (4)$$

The energies were taken from **Larkins** or, for the missing lines, calculated from the electron binding energies. **Kovalik et al.** also measured the energies and found a good agreement for the KLM spectrum but observed discrepancies for the KLL and KMM groups.

4.2. Gamma emissions

A weak gamma emission superimposed on the intense inner-bremsstrahlung was observed by **Zlimen et al.** and interpreted as the deexcitation of the first excited state of Mn-55. The γ -ray energy is given as 126.0 (1) keV and the γ -ray intensity as $1.3 (1) \times 10^{-7} \%$.

From the level energy 125.949 (10) keV and with a recoil energy of 0.2 eV, the retained γ -ray energy is 125.949 (10) keV.

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⁵⁶Co - Comments on evaluation of decay data by C.M. Baglin and T. D. MacMahon

This current evaluation was carried out in 2004. The literature available by September 2004 was included.

Evaluation Procedures

The *Limitation of Relative Statistical Weight* (LWM) [1985ZiZY] method, used almost exclusively for averaging numbers throughout this evaluation, provided a uniform approach for the analysis of discrepant data. In the few instances when an alternative technique was used, this fact has been noted. The uncertainty assigned in this evaluation to the recommended value is always greater than or equal to the smallest uncertainty in any of the experimental values used in the calculation.

1 Decay Scheme

⁵⁶Co decays 19.58 (11) % by positron (β^+) emission and 80.42 (11) % by electron capture (ϵ) to ⁵⁶Fe ($Q(\epsilon) = 4566.0$ (20) keV (2003Au03)). Altogether, 46 γ rays de-exciting 15 nuclear levels in ⁵⁶Fe have been reported. Except for the strong 847-keV transition, emission of conversion electrons is very low and negligible compared to that of γ rays (photons) because of the low atomic number ($Z=26$) of the daughter nucleus (⁵⁶Fe) and the high energy (> 700 keV) of the most intense γ -ray transitions. Consequently, neither conversion coefficients (most of them $< 2 \times 10^{-4}$) nor conversion electron energies and intensities have been tabulated in this evaluation. Pair production is also possible for transitions with $E_\gamma \geq 1022$ keV, but the internal-pair-formation coefficients (based on 1979Sc31) do not exceed 10^{-3} and are tabulated only for those transitions for which the coefficients exceed 4×10^{-4} or for which their omission would affect the deduced branching.

The evaluator has normalized the decay scheme assuming zero $\epsilon + \beta^+$ feeding from the 4^+ ⁵⁶Co parent to the 0^+ ⁵⁶Fe ground state. Then $\Sigma(I(\gamma + ce) \text{ to ground state}) = 100\%$. Based on the decay scheme, only the 847 γ , 2657 γ and 3370 γ feed the ground state. The 847 keV transition conversion coefficient is taken as $3.03(9) \times 10^{-4}$ (from Band *et al.*, 1976Ba63, assuming $\alpha = \alpha_K + 1.33 \alpha_L$ and a 3% uncertainty). The normalization factor N is then given by:

$$N = 100 / [I(847\gamma) (1 + \alpha(847\gamma)) + I(2657\gamma) + I(3370\gamma)]$$

Where: $I(847\gamma)$, $I(2657\gamma)$, $I(3370\gamma)$ are the relative values given in Table 2

$$= 100 / [100.0303 (9) + 0.0195 (20) + 0.0103 (8)]$$

$$= 100 / [100.0601 (23)]$$

$$= 0.999399 (23)$$

With this normalization, the probability of the 847 keV transition is : $P(847)(\gamma + ce) = 99.9702(23)\%$.

Electron-capture and β^+ transition probabilities to excited states in ⁵⁶Fe were determined from γ -ray transition intensity balance at each level and theoretical ϵ/β^+ ratios. It should be noted that the 2nd-forbidden transitions to the 2690 and 3370 levels, though weak, are probably overestimated since $\log ft$ values for these branches are significantly lower than expected from $\log ft$ systematics.

The evaluator has included level half-life data from the evaluation by Huo (1999Hu04) in the decay scheme drawing given here. The level energies shown in the drawing result from a least-squares adjustment of the γ -ray energies recommended in this evaluation.

2 Nuclear Data

The recommended value for the half-life of ⁵⁶Co is 77.236 (26) days, taken from the evaluation by Woods *et al.* (2004WoAA). This supersedes an earlier evaluation by two of these authors (2004Wo02) in which 77.20 (8) days ($\chi^2/\nu = 0.9$) was recommended. Measured values and their respective sources are:

Half-life (days)	Reference	Comments
77.2 (8)	1954Bu58	
77.3 (3)	1957Wr37	
78.76 (12)	1972Em01	statistical outlier
78.4 (5)	1974Cr05	statistical outlier
77.12 (10)	1977An13	
77.12 (7)	1978La21	
77.30 (9)	1989Al24	
77.08 (8)	1989Le17	
77.28 (4)	1989Sc17	
77.29 (3)	1990Al29	
77.210 (28)	1992Fu02	
77.29 (4)	1992Fu02	

The weighted average of all data published from 1977 onwards is 77.245 (23) days ($\chi^2/\nu = 2.2$), where the uncertainty shown is the external uncertainty (the internal uncertainty is 0.015 days).

$Q(\epsilon) = 4566.0$ (20) keV is adopted from 2003Au03.

2.1 b+ Transitions

The positron end-point energies, calculated from $E_{\beta^+} = Q(\epsilon) - E(\text{lev}) - 1022$, are the evaluator's values deduced using $Q(\epsilon) = 4566.0$ (20) keV (2003Au03) and level energies ($E(\text{lev})$) from the decay scheme. Absolute β^+ emission probabilities are from γ -ray intensity balance at each nuclear level and theoretical I_{β^+}/ϵ_i ratios. Note that the latter may not be reliable for the 2nd-forbidden branches.

2.2 Electron Capture Transitions

ϵ -transition energies, calculated from $E(\epsilon) = Q(\epsilon) - E(\text{lev})$, are evaluator's values deduced using $Q(\epsilon) = 4566.0$ (20) keV (2003Au03) and level energies ($E(\text{lev})$) from the decay scheme. Absolute ϵ transition probabilities are from γ -ray intensity balance at each nuclear level and theoretical I_{β^+}/ϵ_i ratios. These sum to 80.42(11)%, implying $I(\beta^+) = 19.58(11)\%$. Fractional atomic shell electron-capture probabilities (P_K, P_L, P_M) are evaluator's values calculated using the EC-CAPTURE computer program [2] for the relevant nuclear level energies.

3 Atomic Data

Emission probabilities are evaluator's values calculated using the EMISSION program (Version 3.04) [3], atomic data from 1996Sc06, and the γ -ray emission probabilities recommended here. The K X-ray and K-Auger electron energies are taken from Schönfeld and Rodloff [5] and [4], respectively; L X-ray and L-Auger electron energies are from Larkins [6].

4 Photon Emissions

4.1 Energies

γ -ray energies shown in boldface in Table 1 are from 2000He14. These values are based on a revised energy scale that uses the new adjusted fundamental constants and wave lengths deduced from an updated value of the lattice spacing of Si crystals [Cohen and Taylor [1]]. Helmer *et al.* (2000He14) fitted the adjusted γ -ray energy measurements for ⁵⁶Co to a level scheme, and deduced recommended γ -ray energy values from level-energy differences. Less precise energies are from 1990Me15, 1989Al25 (one transition only) and 1980St20. The latter authors adopted energies from the literature for the strongest transitions (shown in square brackets in Table 1) and made the general statement that the uncertainties in the other transition energies range from 0.05 keV to 0.8 keV; the evaluator has, therefore, assigned uncertainties of 0.8 keV to the four energies adopted from this study. The uncertainties in the γ -ray energies given in this evaluation are statistical only, as reported by authors. See Table 1.

4.2 Emission Probabilities

a. Relative intensities

Relative emission probability measurements are given in Table 2, panels a); panels b) show the results of several different analyses of those data along with the intensities recommended in the present evaluation. In cases where the authors indicated an uncertainty in the relative intensity of the 847-keV reference line, that uncertainty was combined in quadrature with the statistical uncertainty for each of the other transitions prior to all analyses of the data.

The analysis of these data is complicated on account of two factors:

- (i) Discrepant data sets. Of the approximately 770 data points, successive runs of the program LWEIGHT identify a total of 87 statistical outliers based on the Chauvenet criterion; this seems an unusually large fraction. Most outliers, though by no means all, arise from the earlier measurements.
- (ii) The use by some authors of Ge detector efficiency calibration curves which are inadequate at the highest energies. This problem was first identified by McCallum and Coote (1975Mc07) and is discussed further by Baglin *et al.* in 2002Ba38.

One prescription for dealing with discrepant data is the limitation of relative statistical weight method proposed by Zijp (1985ZiZY) and incorporated in the program LWEIGHT. The program identifies a set of data as 'discrepant' whenever its reduced chi-squared value exceeds the critical reduced chi-squared value for the relevant number of data points. For those cases, it then increases the uncertainty for any datum whose statistical weight exceeds 50% until it no longer does so, then recalculates the weighted mean. If the weighted mean overlaps the unweighted mean, the weighted mean will be adopted. The uncertainty used is usually the internal uncertainty; however, the uncertainty will be expanded to include the most precise datum, if necessary, and the external uncertainty will be used if the internal uncertainty is less than the uncertainty in the most precise datum. Otherwise, the unweighted mean will be adopted; this does not seem to be a particularly useful number since it could so easily be skewed by the least reliable data.

Two additional techniques that might reasonably be applied to the analysis of these data are the Normalised Residuals (1991JaXX) and the Rajeval (1992Ra08) techniques. Both are iterative techniques which increase the uncertainties of any deviant data, but they use different prescriptions for identifying and adjusting the deviant data. The results of these analyses are also shown in Table 2.

Another logical approach would be to use the results from LWEIGHT after all statistical outliers have been eliminated from the dataset. Table 2 also gives the results from this analysis.

The second problem could be approached by considering data from only the eight experiments (2002MoZP, 2000Ra36, 1990Me15, 1980St20, 1978Ha53, 1977Ge12, 1974BoXX and 1971Si29) in which the detector efficiency has been *measured* (not extrapolated) up to at least the highest ⁵⁶Co transition energy (3611 keV). (Details of the efficiency calibrations for many measurements are sketchy at best, and some rely partially or totally on Monte Carlo calculations.) However, this approach greatly decreases the number of data points, so one should resort to this measure only at energies where significant problems are anticipated. The high precision

data from 1971Ca14, based on a linear extrapolation to high energy of a log(efficiency) *versus* log(energy) plot, have received considerable scrutiny in the literature, and 2002Ba38 deduced a multiplicative correction factor ($F = 1.116 - 0.155 E_\gamma + 0.0397 E_\gamma^2$, where E_γ is in MeV) to correct ⁶⁶Ga intensity data in 1971Ca14; this formula implies intensity correction factors of 0.98, 1.01 and 1.06, respectively, at $E_\gamma = 2.5, 3.0$ and 3.5 MeV. These factors apply equally to the ⁵⁶Co data from 1971Ca14 and to those from 1970Ph01 and 1974Ho25, all tied to the intensity scale in 1971Ca14. This situation suggests that data from only the eight selected references should be considered for $E_\gamma > 3000$ keV. However, although used only for $E_\gamma > 3000$ keV, the analysis of data from the selected references is shown in Table 2 for transitions of all energies, for the sake of completeness.

b. Absolute Intensities

Absolute emission probabilities are based on experimental results and decay-scheme normalization arguments as follows:

- $I_{ce}(847\gamma, E2)/I_\gamma(847\gamma) = 3.03 (9) \times 10^{-4}$ (Theory (Band *et al.*, 1976Ba63), assuming $\alpha = \alpha_K + 1.33 \alpha_L$ and 3% uncertainty).
- No $\epsilon + \beta^+$ branch to ground state, so $\Sigma(I(\gamma + ce) \text{ to ground state}) = 100\%$.

The recommended absolute γ -ray emission probabilities are the relative values recommended in Table 2 multiplied by 0.999399 (23).

c. Annihilation radiation intensity

The 511-keV γ -ray intensity has not been experimentally determined but may be estimated from:

$$\begin{aligned} I(\gamma^+) &= 2 \times [100 - I(\epsilon) + I(\text{pair production})] \\ &= 2 \times [19.58 (11) + 0.024] \\ &= 39.21(22) \% \end{aligned}$$

4.3 Transition Multipolarities and Mixing Ratios

The transition multipolarities and mixing ratios have been taken directly from the evaluation by Huo (1999Hu04). Several additional transition multipolarities, deduced from the decay scheme, are shown enclosed by square brackets.

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Table 1. ⁵⁶Co Gamma-Ray Energies

2000He14	1990Me15	1989Al25	1980St20	Adopted
E _g (keV)	E _g (keV)	E _g (keV)	E _g (keV) ^a	E _g (keV)
	263.41 (10)		263.34	263.41 (10)
	411.38 (8)		410.94	411.38 (8)
	486.54 (11)		485.2	486.54 (11)
			655.0 (8) ^a	655.0 (8)
			674.7 (8) ^a	674.7 (8)
733.5085 (23)	733.72 (15)		733.6	733.5085 (23)
787.7391 (23)	787.88 (7)		787.77	787.7391 (23)
846.7638 (19)	846.772 (8)		[846.764]	846.7638 (19)
		852.78 (5)		852.78 (5)
896.503 (7)	896.56 (20)		896.55	896.503 (7)
977.363 (4)	977.485 (60)		977.39	977.363 (4)
996.939 (5)	997.33 (16)		996.48	996.939 (5)
1037.8333 (24)	1037.840 (6)		[1037.844]	1037.8333 (24)
	1089.03 (24)		1089.31	1089.03 (24)
1140.356 (7)	1140.28 (10)		1140.52	1140.356 (7)
1159.933 (8)	1160.08 (16)		1160.0	1159.933 (8)
1175.0878 (22)	1175.102 (6)		[1175.099]	1175.0878 (22)
	1198.78 (20)		1198.77	1198.78 (20)
1238.2736(22)	1238.282 (7)		[1238.287]	1238.2736(22)
	1272.2 (6)		1272.20	1272.2 (6)
1335.380 (29)	1335.56 (8)		1335.56	1335.380 (29)
1360.196 (4)	1360.215 (12)		[1360.206]	1360.196 (4)
	1442.75 (8)		1442.65	1442.75 (8)
	1462.34 (12)		1462.28	1462.34 (12)
1640.450 (5)	1640.54 (13)		1640.38	1640.450 (5)
1771.327 (3)	1771.351 (16)		[1771.350]	1771.327 (3)
1810.726 (4)	1810.714 (35)		[1810.722]	1810.726 (4)
1963.703 (11)	1963.99 (6)		[1963.714]	1963.703 (11)
2015.176 (5)	2015.181 (16)		[2015.179]	2015.176 (5)
2034.752 (5)	2034.755 (15)		[2034.159]	2034.752 (5)
2113.092 (6)	2113.185 (115)		[2113.107]	2113.092 (6)
2212.898 (3)	2212.96 (15)		[2212.921]	2212.898 (3)
	2276.36 (16)		2276.09	2276.36 (16)
	2373.7 (4)		2373.71	2373.7 (4)
	2523.86 (20)		2523.0	2523.0 (8) ^b
2598.438 (4)	2598.458 (13)		[2598.460]	2598.438 (4)
			2657.4 (8) ^a	2657.4 (8)
3009.559 (4)	3009.591 (22)		[3009.596]	3009.559 (4)
3201.930 (11)	3201.962 (16)		[3201.954]	3201.930 (11)
3253.402 (5)	3253.416 (15)		[3253.417]	3253.402 (5)
3272.978 (6)	3272.990 (15)		[3272.998]	3272.978 (6)
	3369.69 (30)		3369.97	3369.69 (30)
3451.119 (4)	3451.152 (17)		[3451.154]	3451.119 (4)
	3547.93 (6)		3548.27	3547.93 (6)
	3600.49 (40)		3600.85	3600.7 (4)
			3611.8 (8) ^a	3611.8 (8)

^a Authors took energies for the strongest lines from the literature (shown in square brackets) and stated that uncertainties varied from 0.05 to 0.8 keV for the others. The evaluator has conservatively assigned 0.8 keV to those lines whose energies are adopted in the present evaluation from this reference.

^b The datum from 1980St20 is adopted in preference to the more precise datum from 1990Me15 because the latter value fits its level-scheme placement poorly and is almost 1 keV higher than the γ -ray energy of 2522.88 (6) adopted in an evaluation (1999Hu04) which included information from sources other than ⁵⁶Co ϵ decay.

Table 2: ^{56}Co Relative Gamma-Ray Emission Probabilities[@], a) Experimental Data

Ref./Eg	263.4g	411.4g	486.5g	655.0g	674.7g	733.5g	787.7g	846.8g	852.8g	896.5g
65Pe18							1.04* (21)	100		
66Do07								100		
66Hu17								100		
66Sc01								100		
67Au01						0.10* (5)	0.4 (2)	100		
67Ba75								100		
68Sh07						0.13 (6)	0.2 (1)	100		
67Ch20							0.36 (5) (8)	100 (15) (0)		
69Ar04								100		
69Au09								100		
69Sc09							0.37 (4)	100		0.14* (4)
70Ph01	0.03 (1)		0.066 (6)			0.21 (4)	0.31 (6)	100		0.06 (1)
71Ca14	0.021 (4)	0.025 (5)	0.041 (7)			0.193 (3)	0.308 (8)	100		0.071 (4)
71Ge07								100		
71Ge08	0.05* (1)	0.024 (7)	0.050 (12)		0.03 (1)	0.18 (3)	0.28 (4)	100	0.04 (1)	0.08 (2)
71Si29 ^S							0.21 (6)	100		
72Pe20 ^d								100.0 (60) (0) 100.0 (56) (0) 100.0 (57) (0)		
74BoXX ^S								100		
74Ho25	0.020 (6)	0.025 (9)	0.07 (2)		0.03 (1)	0.165 (8)	0.29 (3)	100		0.062 (6)
75Ka06						0.219 (7)	0.311 (12)	100		0.089 (11)
77Ge12 ^S								100 (1) (0)		
78Ha53 ^S						0.143 (13)	0.34 (3)	100		0.077 (10)
80St20 ^S	0.022 (4)	0.031* (4)	0.069 (7)	0.038 (8)	0.038 (7)	0.195 (14)	0.320 (7)	100		0.063 (6)
80Sh28	0.031 ^c (9)	0.026 (8)	0.065 (11)		0.045 (20)	0.166 (12)	0.28 (1)	100		0.089 (13)
80Yo05			0.061 (10) (10)			0.193 (12) (12)	0.305 (13) (13)	100.0 (3) (0)		0.095 (18) (18)
82Gr10								100		
89Al25								100	0.050 (3)	
90Me15 ^S	0.022 (4)	0.025 (5)	0.055 (5)			0.20 (1)	0.31 (1)	100		0.070 (5)
92ScZZ						0.190 (7) (7)	0.315 (10) (10)	100.00 (26) (0)		0.086 (20) (20)
00Ra36 ^S								100		
02MoZP ^S								100.0 (2) (0)		

Table 2: ⁵⁶Co Relative Gamma-Ray Emission Probabilities[@]
b) Analysis

Eg	263.4g	411.4g	486.5g	655.0g	674.7g	733.5g	787.7g	846.8g	852.8g	896.5g
All Data										
# data points, N	7	6	8	1	4	13	17	33	2	12
$\chi^2/(N-1)$	1.5	0.31	1.7	N/A	0.31	4.2 ^b	2.0 ^b	N/A	0.92	1.4
I _γ : UWM	0.028 (4)	0.0260 (10)	0.060 (4)	-	0.036 (4)	0.176 (9)	0.350 (45)	100	0.045 (5)	0.082 (6)
I _γ : WM	0.0234 (20)	0.0269 (23)	0.0583 (27)	-	0.035 (5)	0.1909 (22)	0.309 (3)	100	0.049 (3)	0.0704 (22)
I _γ : LWM	= WM	= WM	= WM	-	= WM	0.176 (17) ^x	0.309 (11) ^x	100	= WM	= WM
I _γ : Norm Res	0.0234 (20)	0.0269 (23)	0.0583 (27)	-	0.035 (5)	0.1905 (37)	0.310 (4)	100	0.049 (3)	0.0704 (22)
I _γ : Rajeval	0.0227 (20)	0.0269 (23)	0.0602 (29)	-	0.035 (5)	0.1914 (24)	0.311 (4)	100		0.0704 (22)
Statistical Outliers Excluded			N/A	N/A	N/A				N/A	
# data points, N	6	5	-	-	-	12	16	33	-	11
$\chi^2/(N-1)$	0.36	0.01	-	-	-	4.3 ^b	1.4	N/A	-	1.3
UWM	0.0243 (20)	0.0250 (3)	-	-	-	0.182 (8)	0.307 (13)	100	-	0.077 (4)
WM	0.0223 (21)	0.0250 (28)	-	-	-	0.1911 (22)	0.309 (3)	100	-	0.0701 (22)
LWM	= WM	= WM	-	-	-	0.1909 (48) ^e	= WM	100	-	= WM
Selected Data										
# data points, N	2	2	2	1	2	3	4		0	3
$\chi^2/(N-1)$	0	0.88	2.7	N/A	0.43	6.6 ^b	1.5	N/A	N/A	0.83
I _γ : UWM	0.022 (0)	0.028 (3)	0.062 (7)	-	0.034 (4)	0.179 (18)	0.295 (29)	100	-	0.070 (4)
I _γ : WM	0.022 (3)	0.029 (3)	0.060 (4)	-	0.035 (6)	0.183 (7)	0.317 (6)	100	-	0.068 (4)
I _γ : LWM	= WM	= WM	= WM	-	= WM	0.183 (18) ^e	= WM	100	-	= WM
I _γ : Norm Res										
I _γ : Rajeval										
Adopted I_g	0.0234 (20)	0.0269 (23)	0.058 (3)	0.038 ^a (8)	0.035 (5)	0.191 (4)	0.310 (4)	100	0.049 (3)	0.0704 (22)
Source	All; WM	All; WM	All; WM	1980St220	All; WM	All; NR	All; NR	N/A	All; WM	All; WM

Table 2: ^{56}Co Relative Gamma-Ray Emission Probabilities (continued)[®], a) Experimental Data

Ref./Eg	977.4g	996.9g	1037.8g	1089.0g	1140.4g	1159.9g	1175.1g	1198.8g	1238.3g	1272.2g
65Pe18	1.73* (35)		14.1 (15)				2.1 (6)		66.8 (40)	
66Do07			12.4 (5)						71.2 (26)	
66Hu17			14.5 (15)				2.8* (5)		70.5 (70)	
66Sc01			14.0 (20)				1.4* (2)		66.3 (60)	
67Au01	1.36 (36)		12.8 (9)				2.4 (2)		69.5 (35)	
67Ba75	1.62* (10)		13.7 (8)				2.03* (14)		72.1 (50)	
68Sh07	1.01* (30)		12.1* (8)				2.2 (1)		70.2 (25)	
67Ch20	1.50* (23) (32)		14.0 (21) (30)		0.170 (26) (36)		1.60* (24) (34)		64 (10) (14)	
69Ar04	1.1 (1)		9.6* [†] (6)				1.9* (2)		69.6 (35)	
69Au09			13.08 (35)				1.73* (13)		68.3 (14)	
69Sc09					0.17 (3)					
70Ph01	1.35 (5)		14.0 (7)		0.24* (4)	0.11 (2)	2.25 (5)		68.5 (12)	
71Ca14	1.448 (14)	0.112 (6)	14.24 (14)	0.048 (9)	0.142 (9)	0.100 (9)	2.300 (25)	0.050 (7)	67.64 (68)	0.019 (1)
71Ge07			12.9 (5)				2.26 (23)		67.8 (15)	
71Ge08	1.42 (14)	0.13 (3)	14.4 (9)	0.04 (1)	0.16 (3)	0.11 (2)	2.29 (22)	0.06 (2)	69.6 (35)	0.024 (7)
71Si29 ^S	1.21* (6)		12.44 (31)				2.11 (5)			
72Pe20 ^d			13.45 (190) (206) 13.03 (172) (187) 12.72 (153) (169)				1.99* (27) (30) 2.18 (34) (36) 1.93* (25) (27)		70.9 (77) (88) 68.2 (72) (81) 66.9 (75) (84)	
74BoXX ^S			13.7 (6)				2.3 (1)		66.2 (10)	
74Ho25	1.37 (4)	0.17 (5)		0.07 (2)	0.13 (2)	0.078 (7)	2.25 (11)	0.028 (9)		0.022 (3)
75Ka06	1.386 (15)		13.922 (116)		0.107 (3)	0.095 (6)	2.180 (24)		66.37 (74)	
77Ge12 ^S	1.426 (15) (21)		14.04 (14) (20)				2.28 (2) (3)		66.4 (7) (10)	
78Ha53 ^S	1.38 (4)	0.170 (14)	13.5 (2)	0.06 (2)	0.117 (13)	0.08 (1)	2.11 (10)	0.044 (8)	65.1 (4)	0.035* (4)
80St20 ^S	1.41 (2)	0.092 (14)	14.11 (19)	0.050 (7)	0.125 (6)	0.074 (8)	2.30 (32)	0.04 (1)	68.47 (87)	0.038* (6)
80Sh28	1.38 (3)	0.11 (1)	14.06 (28)	0.075 (9)	0.11 (1)	0.079 (9)	2.22 (5)	0.035 (10)	67.59 (131)	0.022 (8)
80Yo05	1.435 (16) (16)	0.129 (14) (14)	14.16 (5) (7)	0.05 (3) (3)	0.131 (21) (21)	0.095 (14) (14)	2.241 (12) (14)	0.051 (9) (9)	66.06 (21) (29)	0.025 (8) (8)
82Gr10			13.85 (35)						65.8 (16)	
89Al25										
90Me15 ^S	1.440 (15)	0.112 (6)	14.0 (1)	0.05 (1)	0.15 (1)	0.10 (1)	2.28 (2)	0.05 (1)	67.6 (4)	0.020 (2)
92ScZZ	1.450 (15) (15)		14.18 (13) (13)		0.137 (5) (5)		2.289 (21) (21)		66.96 (60) (60)	0.024 (10) (10)
00Ra36 ^S			14.11 (22)				2.25 (4)		66.6 (10)	
02MoZP ^S	1.424 (6) (7)		14.07 (4) (5)				2.252 (9) (10)		66.20 (11) (17)	

Table 2: ⁵⁶Co Relative Gamma-Ray Emission Probabilities (continued)[@]
b) Analysis

Eg	977.4g	996.9g	1037.8g	1089.0g	1140.4g	1159.9g	1175.1g	1198.8g	1238.3g	1272.2g
All Data:										
# data points, N	20	8	30	8	13	10	29	8	29	9
$\chi^2/(N-1)$	2.7 ^b	3.0 ^b	4.5 ^b	1.3	5.3 ^b	1.6	2.8 ^b	0.92	1.8 ^b	3.1 ^b
I _γ ; UWM	1.39 (3)	0.128 (10)	13.51 (18)	0.055 (4)	0.145 (10)	0.092 (4)	2.15 (5)	0.045 (4)	67.84 (36)	0.0254 (22)
I _γ ; WM	1.423 (4)	0.116 (3)	14.018 (31)	0.054 (4)	0.1204 (21)	0.088 (3)	2.249 (6)	0.044 (3)	66.42 (12)	0.0206 (8)
I _γ ; LWM	1.423 (7) ^e	0.116 (6) ^e	13.51 (56) ^x	= WM	0.145 (38) ^x	= WM	2.15 (10) ^x	= WM	67.8 (16) ^x	0.025 (6) ^x
I _γ ; Norm Res	1.423 (7)	0.114 (4)	14.04 (5)	0.054 (4)	0.131 (4)	0.088 (3)	2.250 (9)	0.044 (3)	66.45 (16)	0.0205 (9)
I _γ ; Rajeval	1.425 (5)	0.113 (4)	14.055 (31)	0.051 (4)	0.133 (3)	0.088 (3)	2.254 (6)	0.044 (3)	66.44 (12)	0.0199 (8)
Statistical Outliers Excluded:		N/A		N/A		N/A		N/A	N/A	
# data points, N	14	-	28	-	11	-	21	-	-	7
$\chi^2/(N-1)$	1.7	-	2.6 ^b	-	4.0 ^b	-	1.6	-	-	0.36
UWM	1.406 (9)	-	13.70 (11)	-	0.137 (7)	-	2.240 (16)	-	-	0.0223 (8)
WM	1.424 (4)	-	14.03 (3)	-	0.1164 (23)	-	2.252 (6)	-	-	0.0196 (8)
LWM	= WM	-	13.70 (37) ^x	-	0.137 (30) ^x	-	= WM	-	-	= WM
Selected Data:										
# data points, N	6	3	8	3	3	3	8	3	7	3
$\chi^2/(N-1)$	3.1 ^b	9.1 ^b	4.9 ^b	0.12	2.8	2.1	1.9	0.25	4.4 ^b	8.5 ^b
I _γ ; UWM	1.382 (35)	0.125 (23)	13.75 (20)	0.053 (3)	0.131 (10)	0.085 (8)	2.24 (3)	0.045 (3)	66.65 (41)	0.031 (6)
I _γ ; WM	1.422 (6)	0.117 (5)	14.01 ((4)	0.0508 (55)	0.130 (5)	0.083 (5)	2.254 (8)	0.045 (5)	66.31 (14)	0.0242 (17)
I _γ ; LWM	1.422 (12) ^e	0.122 (21) ^e	13.98 (11) ^e	= WM	= WM	= WM	= WM	= WM	66.36 (36) ^e	0.028 (8) ^x
I _γ ; Norm Res										
I _γ ; Rajeval										
Adopted I_g	1.423 (7)	0.116 (6)	14.04 (5)	0.054 (4)	0.132 (4)	0.088 (3)	2.250 (9)	0.044 (3)	66.45 (16)	0.0202 (8)
Source	All; LWM	All; LWM	All; NR	All; WM	All; NR-Raj	All; WM	All; NR	All; WM	All; NR	All; NR-Raj

Table 2: ^{56}Co Relative Gamma-Ray Emission Probabilities (continued)[@], Experimental Data

Ref./Eg	1335.4g	1360.2g	1442.8g	1462.3g	1640.5g	1771.3g	1810.7g	1963.7g	2015.2g	2034.8g
65Pe18		4.0 (8)				16.2 (14)		0.75 (27)	4.1* (12)	9.2* (17)
66Do07		3.8 (3)				15.6 (13)			3.8* (7)	7.8 (10)
66Hu17		4.5 (7)				12.5* (13)	0.70* (14)	0.80 (15)	3.7* (6)	8.3 (15)
66Sc01		3.8 (4)				13.5* (14)		1.10* (15)	3.5* (4)	6.5* (8)
67Au01		4.5 (3)				16.1 (8)	0.4* (2)	0.59 (9)	2.7 (2)	7.4 (6)
67Ba75		4.8* (3)				16.9 (10)	1.3* (6)	1.1* (2)	2.93 (30)	7.37 (50)
68Sh07		4.2 (4)				16.7 (10)	0.5* (3)	0.63 (20)	2.9 (4)	7.7 (5)
67Ch20		4.0 (6) (8)				14.0* (21) (30)		0.68 (10) (14)	2.6 (4) (6)	6.6* (10) (14)
69Ar04		4.6 (3)				16.2 (10)		0.9* (2)	3.9* (3)	8.2 (5)
69Au09		4.15 (12)				14.95 (40)			2.78 (14)	7.56 (21)
69Sc09	0.12 (2)		0.23* (3)	0.12* (3)			0.65 (6)	0.63 (5)		
70Ph01	0.15* (2)	4.37 (13)	0.20 (2)	0.08 (2)	0.05 (2)	16.0 (5)	0.62 (6)	0.74 (3)	3.13 (10)	8.1 (2)
71Ca14	0.123 (3)	4.340 (45)	0.200 (8)	0.077 (1)	0.065 (9)	15.78 (16)	0.641 (8)	0.721 (15)	3.095 (31)	7.95 (8)
71Ge07		4.16 (21)				16.5 (8)			2.99 (20)	8.2 (6)
71Ge08	0.11* (2)	3.96 (40)	0.14* (2)	<0.02	0.07 (1)	14.9 (9)	0.55* (6)	0.67 (7)	2.83 (30)	7.7 (6)
71Si29 ^S		4.42 (8)					0.47* (6)	0.58 (5)	2.60 (12)	7.0* (3)
72Pe20 ^d		4.08 (51) (57) 4.4 (6) (6) 5.30* (78) (84)				15.36 (174) (197) 15.98 (180) (201) 14.55 (166) (186)			2.88 (42) (45) 2.28* (27) (30) 2.59 (45) (47)	6.25* (88) (96) 6.8* (8) (9) 6.85* (80) (89)
74BoXX ^S		4.4 (1)				15.9 (3)			3.1 (1)	7.8 (1)
74Ho25	0.120 (12)	4.35 (12)	0.177 (9)	0.065 (12)	0.063 (6)		0.63 (3)	0.71 (3)		
75Ka06	0.120 (3)	4.189 (52)	0.172 (4)	0.078 (3)	0.062 (3)	15.369 (241)	0.665 (23)	0.667 (21)	3.025 (72)	7.694 (146)
77Ge12 ^S		4.24 (4) (6)				15.65 (16) (22)	0.650 (7) (10)	0.724 (8) (11)	3.09 (5) (6)	7.95 (12) (14)
78Ha53 ^S	0.12 (2)	4.24 (15)	0.195 (10)		0.05 (1)	15.26 (15)	0.59* (3)	0.70 (2)	2.97 (3)	7.64 (6)
80St20 ^S	0.128 (6)	4.32 (6)	0.173 (7)	0.091 (13)	0.062 (7)	15.5 (4)	0.629 (13)	0.719 (15)	3.182 (66)	8.14 (17)
80Sh28	0.124 (10)	4.29 (8)	0.182 (11)	0.086 (3)	0.055 (9)	15.61 (30)	0.62 (2)	0.71 (2)	2.95 (6)	7.74 (2)
80Yo05	0.130 (6) (6)	4.265 (17) (21)	0.172 (7) (7)	0.084 (6) (6)	0.070 (11) (11)	15.49 (5) (7)	0.657 (23) (23)	0.707 (11) (11)	3.026 (14) (17)	7.766 (28) (36)
82Gr10		4.27 (15)				15.11 (38)			2.97 (11)	7.60 (19)
89Al25										
90Me15 ^S	0.125 (5)	4.33 (4)	0.20 (1)	0.077 (5)	0.06 (1)	15.70 (15)	0.64 (1)	0.720 (15)	3.08 (3)	7.89 (7)
92ScZZ	0.118 (6) (6)	4.29 (4) (4)	0.185 (7) (7)	0.065 (8) (8)	0.072 (12) (12)	15.48 (14) (15)	0.638 (8) (8)	0.724 (10) (10)	3.04 (5)(5)	7.90 (13) (13)
00Ra36 ^S		4.23 (7)				15.42 (25)			3.03 (5)	7.835 (120)
02MoZP ^S		4.22 (15) (15)				15.24 (8) (9)	0.641 (5) (5)	0.698 (3) (3)	2.976 (14) (15)	7.69 (3) (3)

Table 2: ⁵⁶Co Relative Gamma-Ray Emission Probabilities (continued)[®]
a) Analysis

E _g	1335.4g	1360.2g	1442.8g	1462.3g	1640.5g	1771.3g	1810.7g	1963.7g	2015.2g	2034.8g
All Data										
# data points, N	12	31	12	10	11	29	19	23	30	30
$\chi^2/(N-1)$	0.57	0.90	2.5 ^b	1.8	0.44	1.3	1.2	1.9 ^b	2.5 ^b	1.7
I _γ ; UWM	0.124 (3)	4.29 (5)	0.186 (6)	0.082 (5)	0.0617 (23)	15.43 (17)	0.64 (4)	0.738 (27)	3.06 (7)	7.64 (11)
I _γ ; WM	0.1229 (16)	4.283 (13)	0.1797 (23)	0.0779 (9)	0.0621 (21)	15.46 (4)	0.639 (3)	0.7030 (25)	3.015 (9)	7.746 (13)
I _γ ; LWM	= WM	= WM	0.180 (8) ^x	= WM	= WM	= WM	= WM	0.7060 (42) ^e	3.015 (39) ^x	=WM
I _γ ; Norm Res	0.1229 (16)	4.283 (13)	0.1797 (36)	0.0779 (9)	0.0621 (21)	15.46 (4)	0.639 (3)	0.7038 (37)	3.019 (14)	7.746 (18)
I _γ ; Rajeval	0.1229 (16)	4.283 (13)	0.1792 (25)	0.0774 (9)	0.0621 (21)	15.49 (4)	0.640 (3)	0.7094 (37)	3.025 (10)	7.744 (14)
Statistical Outliers Excluded					N/A					
# data points, N	10	29	10	9	-	26	12	20	24	23
$\chi^2/(N-1)$	0.45	0.80	2.3	1.7	-	1.2	0.43	1.6	2.3 ^b	1.6
UWM	0.1228 (12)	4.24 (4)	0.186 (4)	0.078 (3)	-	15.67 (11)	0.640 (4)	0.694 (12)	2.94 (4)	7.82 (5)
WM	0.1228 (16)	4.282 (13)	0.1799 (23)	0.0779 (9)	-	15.47 (4)	0.641 (3)	0.7028 (25)	3.014 (9)	7.748 (14)
LWM	= WM	= WM	= WM	= WM	-	= WM	= WM	= WM	2.94 (4) ^x	= WM
Selected Data										
# data points, N	3	8	3	2	3	7	6	6	8	8
$\chi^2/(N-1)$	0.12	0.89	3.1	1.0	0.50	2.0	115 ^b	2.9	4.7 ^b	3.5 ^b
I _γ ; UWM	0.1243 (23)	4.300 (28)	0.189 (8)	0.084 (7)	0.057 (4)	15.52 (9)	0.60 (3)	0.690 (22)	3.00 (6)	7.74 (12)
I _γ ; WM	0.126 (4)	4.309 (24)	0.185 (5)	0.079 (5)	0.059 (5)	15.40 (6)	0.590 (3)	0.7008 (28)	3.001 (11)	7.727 (23)
I _γ ; LWM	= WM	= WM	= WM	= WM	= WM	= WM	0.59 (5) ^x	= WM	3.006 (30) ^x	7.736 (48) ^e
I _γ ; Norm Res								0.701 (5)	2.999 (22)	7.727 (44)
I _γ ; Rajeval								0.713 (6)	2.997 (14)	7.713 (24)
Adopted I_g	0.1229 (16)	4.283 (13)	0.180 (4)	0.0779 (9)	0.0621 (21)	15.46 (4)	0.639 (3)	0.706 (4)	3.019 (14)	7.746 (13)
Source	All; WM	All; WM	All; NR	All; WM	All; WM	All; WM	All; WM	All; LWM	All; NR	All; WM

Table 2: ⁵⁶Co Relative Gamma-Ray Emission Probabilities (continued)[@] Experimental Data

Ref./E _g	2113.1g	2212.9g	2276.4g	2373.7g	2523.0g	2598.4g	2657.4g	3009.6g
65Pe18						17.4 (15)		1.3* (4)
66Do07						16.0* (27)		1.9* (8)
66Hu17	0.40 (9)	0.43 (9)	0.12 (3)	0.15* (3)	<0.03	20.0* (20)		1.25* (25)
66Sc01						17.4 (17)		1.5* (2)
67Au01	0.29 (5)					17.3 (9)		0.9 (2)
67Ba75	0.4 (1)	0.4 (1)				15.0* (13)		0.8 (3)
68Sh07	0.32 (15)	0.20* [†] (2)				17.0 (6)		1.0 (1)
67Ch20	0.56* (8) (12)	0.60* (9) (13)				14.0* (21) (30)		0.60* (9) (13)
69Ar04	0.3 (1)					18.7* (11)		0.9 (5)
69Au09						16.55 (44)		
69Sc09	0.32 (4)	0.46* (5)	0.14 (2)	0.11 (2)	0.09 (3)			
70Ph01	0.39 (3)	0.40 (3)	0.15 (2)	0.12 (2)	0.054 (15)	17.2 (4)		0.93 (6)
71Ca14	0.387 (4)	0.377 (10)	0.106 (5)	0.055 (12)	0.060 (5)	16.85 (17)		1.010 (11)
71Ge07						18.0* (9)		
71Ge08	0.26* (3)	0.28* (3)	0.10 (2)	0.08 (2)	0.07 (2)	16.5 (10)	~0.02	0.92 (10)
71Si29 ^S	0.34 (4)	0.30* (6)						1.55* (12)
72Pe20 ^d						15.65* (204) (224) 17.3 (22) (24) 14.44* (175) (193)		
74BoXX ^S						17.3 (4)		1.0 (2)
74Ho25	0.37 (2)	0.36 (2)	0.128 (8)	0.059 (12)	0.044 (10)		0.016 (5)	0.98 (9)
75Ka06	0.0.375 (17)	0.387 (18)	0.146 (7)			16.64 (22)		0.922 (29)
77Ge12 ^S	0.387 (8) (9)	0.406 (9) (10)				17.34 (26) (31)		1.06 (3) (3)
78Ha53 ^S	0.34 (2)	0.39 (2)	0.15 (2)	0.050 (6)	0.084 (9)	17.19 (15)	0.029 (4)	1.05 (3)
80St20 ^S	0.375 (14)	0.42 (2)	0.117 (9)	0.097 (12)	0.079 (11)	17.40 (38)	<0.05	0.84 (4)
80Sh28	0.35 (1)	0.35 (1)	0.115 (10)	0.079 (10)	0.14* [†] (1)	16.41 (33)	0.015 (3)	1.02 (2)
80Yo05	0.363 (7) (7)	0.389 (8) (8)	0.124 (7) (7)	0.083 (11) (11)	0.068 (11) (11)	16.96 (6) (8)	0.021 (6) (6)	
82Gr10								
89Al25								
90Me15 ^S	0.385 (5)	0.35 (1)	0.110 (5)	0.08 (1)	0.060 (5)	17.29 (15)		1.05 (1)
92ScZZ	0.376 (10) (10)	0.395 (14) (14)	0.128 (19) (19)	0.082 (22) (22)		17.26 (28) (28)		1.16 (3) (3)
00Ra36 ^S						17.1 (3)		
02MoZP ^S	0.372 (4) (4)	0.388 (4) (4)				16.82 (7) (8)		1.033 (11) (11)

Table 2: ^{56}Co Relative Gamma-Ray Emission Probabilities (continued)[®]

a) Analysis

Eg	2113.1g	2212.9g	2276.4g	2373.7g	2523.0g	2598.4g	2657.4g	3009.6g
All Data								
# data points, N	21	19	13	12	10	28	4	23
$\chi^2/(N-1)$	2.5 ^b	7.6 ^b	2.8 ^b	3.6 ^b	7.6 ^b	1.3	2.8	4.9 ^b
I_{γ} , UWM	0.365 (13)	0.383 (18)	0.126 (5)	0.087 (8)	0.075 (8)	16.89 (22)	0.020 (3)	1.07 (6)
I_{γ} , WM	0.3764 (21)	0.3795 (27)	0.1192 (24)	0.071 (3)	0.0687 (27)	16.97 (4)	0.0195 (20)	1.029 (5)
I_{γ} , LWM	0.376 (11) ^x	0.380 (8) ^x	0.119 (13) ^x	0.087 (37) ^x	0.069 (9) ^x	= WM	= WM	1.029 (21) ^x
I_{γ} , Norm Res	0.3761 (31)	0.385 (5)	0.1179 (36)	0.077 (6)	0.064 (4)	16.97 (4)	0.0184 (22)	1.030 (9)
I_{γ} , Rajeval	0.3756 (22)	0.387 (3)	0.1187 (28)	0.079 (4)	0.062 (3)	16.96 (4)	0.0168 (23)	1.029 (6)
Statistical Outliers Excluded			N/A				N/A	
# data points, N	19	14	-	11	9	20	-	17
$\chi^2/(N-1)$	1.9	2.8 ^b	-	3.3 ^b	1.7	1.2	-	4.4 ^b
UWM	0.360 (8)	0.389 (6)	-	0.081 (7)	0.068 (5)	17.06 (7)	-	0.975 (22)
WM	0.3769 (21)	0.3835 (27)	-	0.070 (3)	0.0631 (28)	16.96 (4)	-	1.028 (5)
LWM	= WM	0.384 (5) ^e	-	0.070 (20) ^x	= WM	= WM	-	0.975 (75) ^x
Selected Data								
# data points, N	6	6	3	3	3	7	1	7
$\chi^2/(N-1)$	1.9	4.4 ^b	2.0	7.8 ^b	3.4	2.2	N/A	7.5 ^b
I_{γ} , UWM	0.367 (9)	0.376 (18)	0.126 (12)	0.076 (14)	0.074 (7)	17.21 (7)	0.029 (4)	1.08 (8)
I_{γ} , WM	0.3770 (29)	0.386 (3)	0.113 (4)	0.064 (5)	0.067 (4)	17.01 (6)	-	1.039 (7)
I_{γ} , LWM	= WM	0.385 (9) ^e	= WM	0.068 (18) ^x	= WM	= WM	-	1.039 (19) ^e
I_{γ} , Norm Res	0.3770 (29)	0.389 (6)	0.113 (4)	0.080 (7)	0.072 (5)	17.13 (8)	-	1.043 (11)
I_{γ} , Rajeval	0.3773 (35)	0.390 (4)	0.112 (4)	0.082 (8)	0.080 (7)	17.20 (8)	-	1.043 (7)
Adopted I_{γ}	0.376 (3)	0.385 (5)	0.118 (4)	0.078 (6)	0.063 (4)	16.97 (4)	0.0195 (20)	1.039(19)
Source	All; NR	All; NR	All; NR	All; NR-Raj	All; NR-Raj	All; WM	All; WM	Sel; LWM

Table 2: ⁵⁶Co Relative Gamma-Ray Emission Probabilities (continued)[®], Experimental Data

Ref./E _g	3201.9g	3253.4g	3273.0g	3369.7g	3451.1g	3547.9g	3600.7g	3611.8g
65Pe18	3.2 (5)	8.5 (6)	1.5 (4)		0.95 (15)			
66Do07	2.9 (11)	5.8* (22)	1.2 (5)		0.7 (3)	0.2 (1)		
66Hu17	3.80* (45)	9.2* (9)	2.1 (4)		1.1 (2)	0.16 (3)	0.010 (5)	<0.005
66Sc01	3.4 (4)	8.3 (8)	1.9 (3)		0.7 (1)	0.21 (3)		
67Au01	3.4 (2)	7.8 (4)	1.5 (3)		0.87 (9)	0.15 (3)		
67Ba75	2.9 (3)	6.6 (6)	1.35 (20)		0.63* (15)	0.11* (5)		
68Sh07	2.8 (4)	7.3 (5)	1.5 (4)		0.83 (10)	0.15 (5)	0.02 (1)	
67Ch20	2.9 (4) (6)	7.2 (11) (15)	1.60 (24) (34)		0.72 (11) (15)	0.20 (3) (4)		
69Ar04	3.0 (2)	7.1 (4)	1.3 (1)		0.8 (1)	0.1* (1)		
69Au09	3.03 (14)	7.35 (21)	1.72 (13)		0.85 (7)			
69Sc09							0.024* (4)	0.007 (3)
70Ph01	3.10 (11)	7.5 (2)	1.72 (5)		0.89 (3)	0.18 (1)	0.014 (4)	0.011 (3)
71Ca14	3.03 (3)	7.390 (75)	1.755 (18)	0.011 (2)	0.875 (9)	0.178 (3)	0.015 (1)	0.0065 (10)
71Ge07	3.20 (35)	7.7 (9)	1.71 (25)		0.93 (20)	0.2 (1)		
71Ge08	2.81 (28)	7.0 (6)	1.69 (17)	0.015 (3)	0.82 (1)	0.15 (2)	0.014 (3)	0.007 (2)
71Si29 ^S			1.71 (9)		0.94 (2)	0.20 (3)		
72Pe20 ^d	2.86 (34) (38) 3.03 (36) (40) 2.55* (33) (36)	6.98 (86) (96) 7.4 (8) (9) 6.52 (78) (86)	- 1.57 (21) (23) 1.25 (20) (21)		0.98 (24) (25) 1.03 (14) (15) 0.84 (13) (14)			
74BoXX ^S	3.2 (1)	8.2 (4)	1.9 (1)		1.00 (4)	0.20 (2)		
74Ho25				0.008 (2)	0.89 (4)	0.178 (9)	0.016 (2)	0.008 (2)
75Ka06	3.067 (157)	7.45 (43)	1.697 (103)		0.936 (84)	0.164 (18)		
77Ge12 ^S	3.18 (10) (10)	7.79 (24) (25)	1.85 (6) (6)		0.93 (3) (3)	0.190 (6) (6)	0.0165 (7) (7)	0.0085 (4) (4)
78Ha53 ^S	3.24 (3)	7.97 (11)	1.84 (3)	0.010 (1)	0.95 (2)	0.196 (5)	0.012 (3)	0.005 (2)
80St20 ^S	3.03 (7)	7.60 (15)	1.815 (36)	0.011 (2)	0.90 (2)	0.196 (6)	0.015 (2)	0.010 (2)
80Sh28	3.04 (6)	7.52 (15)	1.77 (4)	0.007 (2)	0.90 (2)	0.19 (5)	0.015 (3)	0.007 (2)
80Yo05								
82Gr10								
89Al25								
90Me15 ^S	3.24 (3)	7.937 (65)	1.89 (2)	0.011 (2)	0.954 (10)	0.198 (5)	0.018 (1)	
92ScZZ	3.32 (7) (7)	8.13 (17) (17)	1.93 (4) (4)		0.973 (20) (20)	0.200 (5) (5)		
00Ra36 ^S	3.16 (6)	7.815 (160)	1.84 (4)		0.93 (3)	0.19 (1)		
02MoZP ^S	3.196 (17) (18)	7.85 (4) (4)	1.854 (12) (13)		0.94 (1) (1)	0.196 (2) (2)		

Table 2: ⁵⁶Co Relative Gamma-Ray Emission Probabilities (continued)[@], Analysis

Eg	3201.9g	3253.4g	3273.0g	3369.7g	3451.1g	3547.9g	3600.7g	3611.8g
All Data								
# data points, N	27	27	27	7	29	24	12	9
$\chi^2/(N-1)$	2.4 ^b	2.8 ^b	3.7 ^b	1.1	5.8 ^b	2.2 ^b	1.2	1.1
I _y ; UWM	3.10 (5)	7.55 (13)	1.68 (4)	0.0104 (10)	0.888 (19)	0.179 (6)	0.0158 (11)	0.0078 (6)
I _y ; WM	3.172 (11)	7.776 (27)	1.826 (8)	0.0100 (7)	0.905 (4)	0.1914 (13)	0.0162 (4)	0.0081 (3)
I _y ; LWM	3.10 (10) ^x	7.55 (30) ^x	1.68 (17) ^x	= WM	0.905 (30) ^x	0.179 (17) ^x	= WM	= WM
I _y ; Norm Res	3.188 (16)	7.82 (4)	1.838 (13)	0.0100 (7)	0.931 (7)	0.1934 (14)	0.0162 (4)	0.0081 (3)
I _y ; Rajeval	3.194 (12)	7.825 (28)	1.837 (9)	0.0100 (7)	0.932 (5)	0.1939 (14)	0.0162 (5)	0.0080 (4)
Statistical Outliers Excluded			N/A	N/A				N/A
# data points, N	25	25	-	-	28	22	11	-
$\chi^2/(N-1)$	2.4 ^b	2.9 ^b	-	-	5.8 ^b	2.2 ^b	0.99	-
UWM	3.089 (34)	7.56 (10)	-	-	0.897 (18)	0.185 (4)	0.0150 (8)	-
WM	3.173 (11)	7.775 (27)	-	-	0.905 (4)	0.1914 (13)	0.0161 (4)	-
LWM	3.09 (11) ^x	7.56 (29) ^x	-	-	0.905 (30) ^x	0.185 (11) ^x	= WM	-
Selected Data								
# data points, N	7	7	8	3	8	8	4	3
$\chi^2/(N-1)$	1.6	1.1	1.1	0.17	1.2	0.22	1.7	1.8
I _y ; UWM	3.178 (27)	7.88 (7)	1.837 (21)	0.0107 (3)	0.943 (10)	0.1958 (14)	0.0154 (13)	0.0078 (15)
I _y ; WM	3.205 (13)	7.868 (31)	1.856 (9)	0.0103 (8)	0.943 (6)	0.1957 (16)	0.0167 (5)	0.0084 (4)
I _y ; LWM	= WM	=WM	=WM	=WM	= WM	=WM	= WM	= WM
I _y ; Norm Res	3.205 (13)	7.868 (31)	1.856 (9)	0.0103 (8)	0.943 (6)	0.1957 (16)	0.0167 (5)	0.0084 (4)
I _y ; Rajeval	3.209 (13)	7.871 (31)	1.853 (10)		0.944 (6)	0.1957 (16)	0.0166 (6)	0.0085 (4)
Adopted I_g	3.205 (13)	7.87 (3)	1.856 (9)	0.0103 (8)	0.943 (6)	0.1957 (16)	0.0167 (5)	0.0084 (4)
Source	Sel; WM	Sel; WM	Sel; WM	Sel; WM	Sel; WM	Sel; WM	Sel; WM	Sel; WM

[@] Experimental data are listed along with the authors' statistical uncertainty in the least significant digits (given in parentheses). If two numbers are shown in parentheses, the second is the uncertainty after any uncertainty in the reference line (847 γ) has been combined in quadrature with the former uncertainty. Note that reference codes are given with the leading two digits of the code omitted. In the 'Analysis' section, the following abbreviations have been used: UWM= unweighted mean; WM= weighted mean; LWM= values recommended by the program LWEIGHT; Norm Res = result from Normalised residuals analysis; Rajeval = result from Rajeval technique analysis; NR-Raj = mean of values from Normalised Residuals and Rajeval technique analyses, using the larger of the two uncertainties 'Sel' refers to data from eight selected references in

which the detector efficiency curves were well-characterised to at least 3600 keV (2002MoZP, 2000Ra36, 1990Me15, 1980St20, 1978Ha53, 1977Ge12, 1974BoXX and 1971Si29).

* This γ -ray intensity datum is identified by LWEIGHT as a statistical outlier based on the Chauvenet criterion.

^a Transition reported in one study only.

^b Exceeds critical value for $\chi^2/(N-1)$ so LWEIGHT considers the data in this dataset to be discrepant.

^c Reported as 0.310 in 1980Sh28, but this is clearly a typographical error; the value from the literature with which it is compared is also an order of magnitude too large.

^d 1972Pe20 took data using three different detectors (cylindrical, rectangular and trapezoidal), each calibrated using Monte Carlo calculations; data from these detectors are shown separately.

^e Weighted mean, external uncertainty recommended by LWEIGHT.

^f Datum rejected by Rajeval analysis.

^s Data from this reference included in 'selected data' analysis.

^x LWEIGHT has expanded the uncertainty to encompass the most precise datum.

⁶⁰Co - Comments on evaluation of decay data by R. G. Helmer

This evaluation was originally completed in September 1996 with minor editing in February 1997 and post-review editing in January 2006 ; the literature available by January 2006 was included by M.-M.Bé (LNE-CEA/LNHB).

1 Decay scheme

In addition to the levels reported in this decay, there are levels in ⁶⁰Ni below the decay energy at 2284 keV (0+) and 2626 (3+). However, based on the limits on the β- branches to these levels (see sect. 2.1), this scheme is considered complete. The scheme is internally consistent since the total decay energy computed from the decay scheme is 2823.0 (5) keV compared to the Q value of 2823.07 (21) keV.

2 Nuclear Data

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

The half-life values available, in days, are listed. If the value was published in years, it is shown here in years and also converted to days (365.242 days/year).

	Years	Days	Uc	Remarks
1940Li01	5,3 ± 0,7	1936	256	As quoted in 1963Go03 - Outlier (CHV)
1949Se20	5,08 ± 0,08	1855	29	As quoted in 1963Go03 - Outlier (3*S)
1950Br76	5,26 ± 0,17	1921	62	
1951Si25	5,25 ± 0,02	1917,5	7,3	As quoted in 1963Go03
1951To25	5,27 ± 0,07	1925	26	As quoted in 1963Go03
1953Ka21	5,21 ± 0,04	1903	15	Outlier (CHV)
1953Lo09	4,95 ± 0,04	1808	15	Omitted from analysis
1957Ge07	5,24 ± 0,03	1914	11	
1958Ke26	5,33 ± 0,04	1947	15	As quoted in 1965An07 - Outlier (CHV)
1963Go03	5,263 ± 0,003	1922,3	1,1	
1965An07	5,242 ± 0,008	1914,6	2,9	
1968La10	5,270 ± 0,007	1924,8	2,6	
1970Wa19	5,2719 ± 0,0011	1925,5	0,4	Replaced by 1983Wa26
1973Ha60	5,24 ± 0,21	1914	77	
1977Va30	5,283 ± 0,003	1929,6	1,1	
1980Ho17		1925,2	0,4	
1982HoZJ	5,282 ± 0,007	1929,2	2,6	Replaced by 1992Un01
1982RyZX		1924,8	1,0	
1982RyZX		1925,5	0,3	Omitted - unpublished result
1983Ru04		1925,02	0,47	
1983Wa26		1925,5	0,4	
1992Un01		1925,12	0,46	Replaced by 2002Un02
2002Un02		1925,20	0,25	
Adopted	5,2710 ± 0,0008	1925,21	0,29	

One input value (1949Se20) is outlier by 3 sigma, three others are outlier due to Chauvenet criterion (1940Li01, 1953Ka21, 1958Ke26).

For the remaining 14 values, the critical χ^2 is 2.1 ; the reduced χ^2 is 3 ; no value contributes over 50 % of the relative weight. The weighted average is 1925.21 with an internal uncertainty of 0.17 and an external uncertainty of 0.29.

2.1 β^- Transitions

In addition to the main decay to the $J^\pi = 4^+$ level at 2505 keV, there is the possibility of β^- decay from the 5^+ parent to the 0^+ levels at 0 and 2284 keV, the 2^+ levels at 1332 and 2158 keV, and the 3^+ level at 2626 keV.

The β^- decay to the 0^+ levels at 0 and 2284 keV are unique 4^{th} forbidden with expected $\log ft$ values (1973Ra10) > 23 and corresponding $P_{\beta^-} < 1 \times 10^{-10}\%$ and $< 1 \times 10^{-13}\%$, respectively. The decay to the 3^+ level at 2626 is 2^{nd} forbidden with an expected $\log ft > 11$ and a corresponding $P_{\beta^-} < 0.01\%$. This level decays mainly by γ 's of 467 and 1293 keV; the $P_{\gamma}(467)$ has been reported as $< 0.00023\%$ (1976Ca18) and $< 0.0004\%$ (1969Va20), which indicates $P_{\beta^-}(2626) < 0.001\%$.

The β^- decay to the 1332 level is unique 2^{nd} forbidden with an expected $\log ft \geq 12.8$ and a corresponding $P_{\beta^-} \leq 12\%$. The measured values are (in %): 0.15 (1) (1954Ke04), 0.010 (2) (56Wo09), 0.12 (61Ca05), and 0.08 (2) (1968Ha03). The average of 0.12% (3) is adopted.

The decay to the 2158-keV level is unique 2^{nd} forbidden with an expected $\log ft \geq 12.8$ and a corresponding $P_{\beta^-} \leq 0.02\%$. This branch is given as 0.000% (2) from 1969Ra23. (Value is given as 0.18% (3) in 1968Ha03, but this is apparently from a misinterpretation of the γ -ray spectrum.)

The decay to the 2505-keV level is then $100.0 - P_{\beta^-}(1332) - P_{\beta^-}(2158) = 0.12(3) - 0.000(2) = 99.88(3)\%$.

The β^- energies and $\log ft$ values are from the program LOGFT.

2.2 Gamma Transitions

The multiplicities are from the adopted γ data in the Nuclear Data Sheets (1993Ki10).

The total and K-shell internal-conversion coefficients, α and α_K , for the 1173- and 1332-keV γ rays are from the evaluation of the experimental measurements (1985HaZA) and the remaining values were interpolated from the Band tables (2002Ba85).

The internal-pair-formation coefficients were interpolated from the theoretical values of 1979Sc31 and are $\alpha_{\pi}(1173) = 0.000\ 006\ 2$ (7) and $\alpha_{\pi}(1332) = 0.000\ 034$ (4). The former is negligible since it is only about 5% of the corresponding α , but the latter is about 25% of the α , so it needs to be taken into account.

3 Atomic Data (Ni, Z=28)

The data are from Schönfeld and Janßen (1996Sc06).

3.1 and 3.2 X Radiation and Auger Electrons

The data were computed by RADLIST with the Schönfeld atomic data.

4 Radiation Emission

4.1 Electron Emission

Data were computed by the program RADLIST.

4.2 Photon Emissions

The γ -ray energies are from 2000He14 for the 1173-keV and 1332-keV lines and the others are deduced from the level energies resulting from a fit to the γ -ray energies. Besides the 1173 and 1332 values, the input to this fit included:

346.93 (7) from 1976Ca18 where the authors average their result and that of 1969Va20;
other: 346.95 (10) (1969Va20);

826.06 (3) from ⁵⁹Co(p, γ)⁶⁰Ni (1975Er05); others: 826.18 (20) (1969Va20) and 826.28 (9) (1976Ca18, but includes value of 1969Va20);

2158.57 (10) from ⁵⁹Co(p, γ) (1975Er05); others: 2158.8 (4) (1970Di01) from ⁶⁰Co decay and 2158.9 (2) (1969Ra07) and 2159.6 (8) (1969Ho22) from ⁶⁰Cu decay.

For the relative γ -ray emission probabilities, the following data were used.

Relative γ -ray emission probability

γ energy (keV) =	347	467	826	1173/1332	2158	2505
Reference						
1949Fl				100		<2. 5x10 ⁻⁵
1955Wb44	<0. 005			100	0. 0012 (2)	
1959Mb				100		- 4x10 ⁻⁵
1968Ha03			0. 19 (2)	100		
1969Ra23			<0. 02	100	<0. 002	
1969Va20	0. 0078 (12)	<0. 0004	0. 0055(47)	100		
1970Di 01	<0. 006		<0. 04	100	0. 0092 (16)	<4x10 ⁻⁵
1972Le14			0. 003 (2)	100	0. 0005 (2)	
1973Fu15				100	0. 0020 (13)	9(7) 10 ⁻⁶
1976Ca18	0. 00758 (50)	<0. 00023	0. 00762(80)	100. 0	0. 00111 (18)	
1977HaXC				100		<0. 001
1977Lo01	0. 0069 (10)	<0. 0012		100		
1978Fa03				100		<1. 0x10 ⁻⁵
1978Fu05				100		2. 0(4) x10 ⁻⁶
1988Se09				100		5. 2(20) 10 ⁻⁶
Adopted	0. 0075 (4)		0. 0076 (8)	100	0. 0012 (2)	2. 0(4) 10 ⁻⁶

These relative emission probabilities were normalized by requiring that the total β^- emission probability is 100%. For the 1332-keV γ ray, this means :

$$\begin{aligned} P_{\gamma}(1332) &= \{100.00 - P_{\gamma}(2158) \times [1+\alpha(2158)] - P_{\gamma}(2505) \times [1+\alpha(2505)]\} / [1.00+\alpha(1332)+\alpha_{\pi}(1332)] \\ &= [100.00 - 0.0012(2) - 0.0000020(4)] / [1.000 + 0.000128(5) + 0.000034(4)] \\ &= 99.9988(2) / 1.000162(6) = 99.9826(6)\%. \end{aligned}$$

In the evaluation 1991BaZS, this value is computed in the same fashion, but is given as 99.983 (6)% ; the origin of the larger uncertainty is not clear. Similarly, for the 1173-keV γ ray, this means :

$$\begin{aligned} P_{\gamma}(1173) &= \{P_{\beta^-}(2505) - P_{\gamma}(347) \times [1+\alpha(347)] - P_{\gamma}(2505) \times [1+\alpha(2505)]\} / [1.00+\alpha(1173)+\alpha_{\pi}(1173)] \\ &= [99.88(3) - 0.0075(4) - 0.0000020(4)] / [1.000 + 0.000168(4) + 0.0000062(7)] \\ &= 99.87(3) / 1.000174(4) = 99.85(3) \%. \end{aligned}$$

6 References

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⁶³Ni - Comments on the Evaluation of Decay Data by K. B. Lee

This evaluation was completed in August 2005.

1. Decay Scheme

⁶³Ni disintegrates by β^- emission (100%) to the ground state of the stable nuclide ⁶³Cu.

2. Nuclear Data

The Q value (66.980 (15) keV) is from the measured value of Holzschuh (1999Ho09). This value is in agreement with 66.975 (15) keV from the atomic mass table of Audi et al. (2003Au03).

The measured ⁶³Ni half-life values are given below.

Reference	Values (years)	Comments
Brosi (1951Br)	85 (20)	Omitted from analysis
Wilson (1950Wi)	61	Omitted from analysis
McMullen (1956Mc)	125 (6)	Omitted from analysis
Horrocks (1962Ho)	93.9 (20)	Revised by Collé (1996Co25)
Barnes (1971Ba89)	101.21 (20)	Revised by Collé (1996Co25)
Collé (1996Co25)	101.06 (197)	

The first three older and less precise historical values were omitted from the analysis. The Horrocks (1962Ho) and Barnes (1971Ba89) values were revised by Collé (1996Co25) using more accurate nuclear data and thereby more rigorously calculated liquid scintillator detection efficiencies. The weighted average for the last three values is 98.7 years; with an internal uncertainty of 1.1 years; an external uncertainty of 2.4 years and a reduced- χ^2 of 4.38.

The evaluator's recommended value is the weighted average : 98.7 (24) years.

2.1 β^- Transitions

The evaluator has calculated (using the LOGFT program) a *log ft* of 6.7 for this allowed transition.

The various measured β^- end-point energy values (or Q-values) are summarized below.

Reference	Values (keV)	Comments
Preiss (1957Pr)	67.0 (5)	Omitted
Hsue (1966Hs01)	65.87 (15)	Omitted
Hetherington (1987He14)	66.946 (20)	Omitted
Kawakami (1992Ka29)	66.9451 (39)	Omitted
Ohshima (1993Oh2)	66.9459 (54)	Omitted
Ohshima (1993Oh2)	66.9433 (126)	Omitted
Holzschuh (1999Ho09)	66.980 (15)	Adopted value

Uncertainties given in 1993Oh2 include systematic values combined in quadrature with statistical uncertainties.

Holzschuh et al. (1990Ho09) pointed out that in the previous measurements of end-point energies the excitation of atomic electrons was not taken into account. That means that all the other values are biased by an amount of the order of the mean electron excitation energy (85 eV). Therefore the evaluator has recommended the value given in 1990Ho09. Besides, a second end-point energy given in 1993Oh2 was obtained under the assumption of the existence of a 17 keV neutrino.

3. Atomic Data

The fluorescence yield is from the compilation of 1996Sc33.

4. Radiations

The mean energy of beta particles has been computed as 17.434 (4) keV using the LOGFT program.

4. Main Production Modes



6. References

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⁶⁵Zn - Comments on evaluation of decay data by M.M. Bé, V. Chisté and R. G. Helmer

1 Decay scheme

This evaluation was originally completed in September 1996. New evaluation was completed in January 2005 taking into account results obtained as a part of a specific exercise dedicated to the ⁶⁵Zn activity and emission intensity measurements managed by the Euromet organization.

The decay scheme is complete since only two excited levels in ⁶⁵Cu below the decay energy are populated. Also, there is excellent agreement between the total decay energy of 1352.1 (19) keV computed from the evaluated decay scheme and the Q value of 1352.1 (3) keV.

2 Nuclear Data

Q = 1352.1 (3) value is from Audi *et al.* (2003Au03).

The measured ⁶⁵Zn half-life values, in days, are as follow:

245.0 (8)	1953To17	
243.5 (8)	1957Ge07	
246.4 (22)	1957Wr37	outlier
243.1 (7)	1965An07	replaced by 1982HoZJ
244.12 (12)	"	replaced by 1982HoZJ
242.78 (19)	"	omitted from analysis
243 (4)	1968Ha47	
258 (4)	1972Cr02	omitted from analysis
246 (5)	"	"
251 (6)	"	"
252 (6)	"	"
244.0 (2)	1972De24	replaced by 2004Va02
244.52 (7)	1973Vi13	Uncertainty given per 3 σ
244.3 (4)	1974Cr05	
243.75 (12)	1975La16	replaced by 2003Lu06
244.2 (1)	1982HoZJ	replaced by 1992Un01
243.97 (8)	1982DeYX	replaced by 1983Wa26
243.9 (3)	1983Wa26	replaced by 2004Sc04
244.16 (10)	1992Un01	(or 2002Un02)
244.15 (10)	2003Lu06	
243.66 (9)	2004Sc04	
243.8 (3)	2004Va02	

244.01 (9) Adopted

The four values of 1972Cr02 were omitted because they were not intended as $T_{1/2}$ measurements, but rather to determine the origin of certain γ -rays.

The very small uncertainty, 0.07 (3.3 σ), given by 1973Vi13 appears unrealistic when compared to the other quoted uncertainties at the same period of time, at least this uncertainty value should be increased. Moreover, this result is far from the mean and the published paper not detailed enough, so this result is omitted from analysis.

The value of 1957Wr37 was found outlier according to the Chauvenet's criterion.

As a rule, only one result per laboratory is retained in order to avoid possible correlation.

Then, the weighted average of the remaining eight values is 244.01 with an internal uncertainty of 0.05, an external uncertainty of 0.09 and, a reduced- χ^2 of 3.11 (the critical reduced- χ^2 is 2.60), no input value has more than 50% of the weight. The Lweight program suggested to expand the uncertainty to 0.31 in order to include the most precise value of 243.66 within its range.

But a small increased of the uncertainty given by 2004Sc04 from 0.09 to 0.11 leads to a reduced- χ^2 of 2.48 less than the critical one, then the Lweight program recommended the internal uncertainty as final uncertainty.

With these results in mind, the evaluator has chosen the weighted average and the external uncertainty.

2.1 Electron Capture Transitions

The ϵ branch to the 770-keV level is 2nd forbidden. From the log ft systematics (1973Ra10), the expected log ft value is > 11.0 and the corresponding $I_\epsilon(0)$ is $< 0.003\%$.

The P_K etc. values are computed from the Schönfeld tables (1995ScZY) for allowed transitions.

Level energy (keV) =	0	1115
P_K (S)	0.8853 (16)	0.8794 (17)
P_L (S)	0.0977 (15)	0.1027 (16)

The total branching ratios to each level were computed from the measured I_γ and adopted theoretical conversion coefficients.

The total branching ($\epsilon + \beta^+$) to the ground state is 49.77 (11) %. From the 511-keV gamma emission intensity measurements, the β^+ transition probability is deduced as 1.421 (7) % (see § Photon emissions).

The LOGFT program gives the theoretical ϵ/β^+ ratio as 34.03 (18). Using the ($\epsilon + \beta^+$) branching to the ground state as 49.77 (11) % ; the β^+ transition probability is then 1.42 (1)%. This value is in good agreement with the experimental observations.

From the LOGFT program, the theoretical ϵ_K/β^+ ratio is calculated as 29.86. This value can be compared with the corresponding experimental values of:

28.0 (32)	1953Pe14
30.3 (12)	1963Ta04
27.7 (15)	1968Ha47
31.3 (20)	1977Bo10
30.7 (11)	1984ScZP
30.3 (10)	1990Ku11

The measured 1115 γ/β^+ ratio is 35.1 (17) (1968Ha47).

For comparison with the adopted value for the β^+ transition probability of 1.421 (7)%, the measured values are :

	I_{β^+} (%)
1959Gl55	1.70 (10)
1962Be28	1.2 (3)
1963Ta04	1.40 (4)
1972De24	1.46 (2)

2.2 Gamma Transitions

The multiplicities are from the adopted γ -ray data (deduced from Coulomb excitation study and angular correlation data) in the journal Nuclear Data Sheets (1993Bh04).

The internal-conversion coefficients are interpolated from the tables of Band (2002Ba85). Mixing ratio of the 1115-keV transition is from Krane (1976Kr09). The ICC values for this high energy transition is very low so the influence of the uncertainty for the mixing ratio is negligible.

For the 1115-keV transition, the total and K-shell values of $1.85 (7) \times 10^{-4}$ and $1.66 (6) \times 10^{-4}$ respectively, evaluated by Hansen (1985HaZA) from measured values are in excellent agreement with the theoretical ones.

From the theoretical tables of 1979Sc31, the internal-pair-formation coefficients are $\alpha_{\pi}(1115, M1) = 1.2 \times 10^{-6}$ and $\alpha_{\pi}(1115, E2) = 1.6 \times 10^{-6}$, so $\alpha_{\pi}(1115) = 1.3 \times 10^{-6}$. This value is about 1% of the internal-conversion coefficient and therefore is negligible.

3 Atomic Data (Cu, Z=29)

Data are from 1996Sc06.

4.1 Electron Emission

The β^+ intensity to the ground state was deduced from the measured intensity of the 511-keV gamma ray.

4.2 Photon Emissions

The γ -ray energies are from the evaluation of Helmer *et al.* (2000He14) for the 1115-keV line where the values are on a scale on which the strong line from the decay of ¹⁹⁸Au is 411.80205 (17); from level energy differences for the 344-keV line; and from ⁶⁵Cu Adopted γ data in Nuclear Data Sheets (1993Bh04) and based on data from ⁶⁵Ni β^- decay for 770-keV line.

Photon emission intensities are deduced from the Euromet exercise results (2005Be**) and from other published values.

Absolute measured intensities of the 1115-keV line

	I (1115) (%)	Uc	
1959Gl55	51.3	3.0	
1960Go	46		
1963Ta04	50.7	0.5	
1966Ra21	51.3	1.5	
1968Ha47	52.4	1.0	Outlier
1972De24	50.75	0.10	Replaced by Euromet participant
1973Po10	49.3	0.8	
1982DeYX	50.39	0.26	replaced by 1990Sc08
1990Sc08	50.2	0.4	Replaced by Euromet participant
2003Lu06	49.76	0.21	Replaced by Euromet participant
Euromet-01	50.15	0.28	
Euromet-02	50.10	0.33	
Euromet-03	50.60	0.29	
Euromet-04	50.34	0.25	
Euromet-05	49.84	0.25	
Euromet-06	50.05	0.57	
Euromet-07	49.62	0.65	
Euromet-08	50.7	0.5	
Euromet-09	50.3	0.5	
Adopted	50.22	0.11	

The first part of the above Table lists the results published in various journals and the second part lists the values obtained as a part of the Euromet exercise (2005Be*).

The value from 1968Ha47 is omitted as outlier due to application of the Chauvenet's criterion. The results from 1972De24, 1990Sc08 and 2003Lu06 have been superseded by the results obtained by laboratories which have participated in the present Euromet exercise.

The LRSW analysis of the remaining 13 values gives a reduced χ^2 of 0.77 so the weighted mean of 50.22 and the internal uncertainty of 0.11, are adopted as final result.

344- and 770-keV Relative γ -ray emission intensities :

γ -ray energy (keV)	I(344)	I(770)	I(1115)
1960Ri06	≤ 0.5	≤ 1	100
1968St05	0.0060 (6)		100
Euromet-02	0.005067 (365)	0.005358 (439)	100
Euromet-09	0.00220 (86)	0.003 (17)	100
Adopted relative	0.005067 (365)	0.005358 (439)	100
Adopted absolute	0.00254 (18)	0.00269 (22)	50.22 (11)

The adopted relative values are those given by the participant 2 in the Euromet exercise. This participant activated Zinc (99.99 %) foil by thermal neutrons and obtained a Zn-65 activity of the order of 10 MBq, so he had a better counting statistic and then a better uncertainty.

511-keV photon emission

This particular emission is due to the annihilation of the β^+ positrons in the source and in the surrounding material (annihilation-in-flight). In γ -ray spectrometry, this phenomenon has the effect of removing, from the 511-keV peak, a fraction of the annihilation photons, the magnitude of this effect depends on the material in which the β^+ are stopped and then must be calculated by each experimentalist.

reference	Intensity (%)	Uc	Correction for annihilation, in %
1990Sc08	2.84*	0.04	0.5
Euromet-01	2.81 *	0.03	0.2
Euromet-02	2.841 *	0.027	Wider peak region
Euromet-03	2.75	0.017	
Euromet-04	3.00	0.018	
Euromet-05	2.848 *	0.020	0.34
Euromet-07	2.86	0.04	
Euromet-09	2.88 *	0.04	0.5

(*) taking annihilation-in-flight into account, magnitude given in the last column.

Reference 1990Sc08 is superseded by one of the Euromet participant. The weighted mean and standard uncertainty of the four values taking annihilation-in-flight into account, are : 2.842 ± 0.013 %.

The emission of additional 511-keV photons created by electron-positron pair creation is negligible (see § Gamma transitions).

X-ray emissions and Auger electron emissions

From the gamma-ray emission intensities, the internal conversion coefficients, the electron capture probabilities and electron capture sub shell probabilities, the X-ray and Auger electron emission intensities have been deduced.

Calculated K X-ray are compared with the measured values in the following table.

Reference	K α		K β		KX	
	Intensity	Uc	Intensity	Uc	Total	Uc
1963Ta19					40.0	0.6
1968Ha47					39.27	0.26
1968Ba**					38.66	0.17
1973Mu**					38.0	1.0
Euromet-05	32.1	1.6	4.50	0.023	36.6	1.6
Euromet-09	39	3.5	5.2	0.47	44.2	3.5
Weighted mean					38.87	0.22
Calculated	34.7	0.4	4.82	0.07	39.5	0.4

The weighted mean of the KX measured values (except Euromet-09 which is outlier) is lower than the calculated value deduced from the decay scheme. They barely agree within their uncertainty limits.

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**⁷⁹Se - Comments on evaluation of decay data
by M. M. Bé and V. Chisté**

This evaluation was completed in January 2006.

1. Decay scheme

The J^π value and level energy are from **NDS 70,3** (1993).

2. Nuclear Data

- The Q value is from **Audi *et al.*** (2003)
- Published values of the half life are, in years :

Historical values		<i>a</i>	
1949	Parker <i>et al.</i>	$\leq 6.5 \times 10^4$	Report ORNL- 499, p.45
1951	Glendenin	$\geq 7 \times 10^6$	Radiochemical studies : The fission products, C.D. Coryell, N. Sugarman, New-York, McGraw Hill (1951) 596
Revised value			
1993	B. Singh	$\leq 6.5 \times 10^5$	NDS 70,3 p. 452
Measured Values			
1995	Yu Runlan, Guo Jingru <i>et al.</i>	$4.8 (4) \times 10^5$	J. Radioanalytical and Nuclear Chemistry, Articles, 196,1 p. 165
1997	Jiang Songsheng, Guo Jingru <i>et al.</i>	$1.1 (2) \times 10^6$	Nucl. Instr. Methods B123, p 405
2000	Ming He, Shan Jiang <i>et al.</i>	$1.24 (19) \times 10^5$	Nucl. Instr. Methods B172, p 177
2002	Songsheng Jiang, Ming He <i>et al.</i>	$2.95 (38) \times 10^5$	Nucl. Instr. Methods A489, p 195 or Chin. Phys. Lett. 18 (2001) 746
2002	Ming He, Songshen Jiang <i>et al.</i>	$2.80 (36) \times 10^5$	Nucl. Instr. Methods B194, p 393
2006	Bienvenu, <i>et al.</i>	$3.77 (19) \times 10^5$	To be published
Adopted		$3.56 (40) \times 10^5$	

Assessments of the Se-79 half-life were done in the years 49-50 (Parker, Glendenin) and a value of $6.5 \times 10^4 a$ was accepted by the various tables and chart of isotopes.

In 1993, due to inconsistencies in the measured and calculated fission yields of ⁷⁹Se for an irradiated fuel from a reactor, the calculations of Parker were reviewed (Singh) and a new value of $6.5 \times 10^5 a$ (i.e. one order of magnitude more) was deduced. Hence, in 1995 a Chinese team carried out the first measurement of this half-life by the means of a radiochemical method, they obtained $4.8 (4) \times 10^5 a$. However, and since this date, the same team, using the same ⁷⁹Se source published various results (see table above), the highest being $1.1 (2) \times 10^6 a$ (1997), and the last $2.80 (36) \times 10^5 a$ (2002).

Only one value (the last) will be used in this evaluation.

In NDS 96,1 (2002) B. Singh adopts the result of 2.96 (38) from the Chinese team.

In 2006, an independent result was published by P. Bienvenu *et al.* confirming the range 10^5 a for this half-life. In this study, the concentration of ⁷⁹Se was measured using ICP-MS coupled with Electro-Thermal Vaporisation to eliminate potential isobaric interferences and, the activity was measured using LSC after gamma ray spectrometry to check the contribution of residual radioactive contaminants.

In this evaluation, the adopted value is the weighted mean of the last Chinese value (NIM B194) and of the Bienvenu *et al.* value. They are in the same range but not consistent so, the adopted uncertainty is the external uncertainty.

2.1 b emission

⁷⁹Se is a pure beta minus emitter which disintegrates directly to the ground state level of ⁷⁹Br, no gamma rays are emitted.

The end-point energy is deduced from the Q value. The mean beta energy was calculated for a 1st forbidden unique transition.

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⁹⁰Sr - Comments on evaluation of decay data by V. Chisté

This evaluation was completed in 2005. The literature available by August 2005 was included.

1 Decay Scheme

⁹⁰Sr disintegrates by β^- emission to the fundamental level of ⁹⁰Y ($T_{1/2} = 2.6684 (13) \text{ d}$). The decay scheme and level spins and parities are from the evaluation of E. Browne (1997Br34).

2 Nuclear Data

The Q value is from the atomic mass evaluation of Audi *et al.* (2003Au03).

The ⁹⁰Sr half-life has been evaluated from the following data (in days):

1950Po67	7270 (110)
1955Wi15	10117 (146)
1958An40	10702 (584)
1965FI01	10227 (146)
1965FI01	10410 (329)
1965An07	10527 (51)
1978La21	10282 (13)
1983Ra09	10589 (92)
1989Ko57	10665 (37)
1992ScZZ	10513 (14)
1994Ma50	10561 (14)
1996Wo06	10495 (4)
2004Sc49	10557 (11)
Adopted	10522 (27) d or 28.80 (7) y

The half-life experimental values of 1950Po67 (7270 (110) d), 1955Wi15 (10117 (146) d), 1978La21 (10282 (13) d), 1983Ra09 (10589 (92) d) are rejected by the evaluator following the recommendation given by 1996Wo06.

The half-life weighted average has been calculated by LWEIGHT computer program (version 3).

The evaluator has chosen to take into account the nine values with associated uncertainty for the calculation. One of them (10227 (146) d) from Flynn (1965FI01) is rejected by the LWEIGHT computer program, based on the Chauvenet's criterion. The largest contribution to the weighted average comes from the value of Woods (1996Wo06) amounting to 76 %. The LWEIGHT program has increased the uncertainty of the 1996Wo06 value from 4.0 to 7.1 in order to reduce its relative weight from 76 % to 50 %.

The recommended value is the weighted average of 10522 d (28.80 (7) y), with an uncertainty of 27 d (expanded so range includes the most precise value of Woods (1996Wo06)). The reduced χ^2 value is 8.

2.1 b- Transitions

The maximum energy of the β^- transition in the decay of ⁹⁰Sr to ground state in ⁹⁰Y has been adopted from the Q value of 2003Au03 ($E_{\beta^-} = Q = 545.9$ (14) keV), and is in agreement with the experimental value of 546.0 (16) keV, measured with a magnetic β -ray spectrometer (1983Ha15).

The lg ft value (9.3) for the 546-keV unique first forbidden transition and mean energy value (196 (1) keV) have been calculated with the Logft computer program (version 7.2a).

For measured first forbidden shape factors, see 1964Da16 and 1983Ha35.

3 Atomic Data

Atomic values, ω_K , ω_L and n_{KL} , are from Schönfeld and Janßen (1996Sc33).

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⁹⁰Y - Comments on evaluation of decay data by V. Chisté

This evaluation was completed in 2005. Updated version in November 2006 and the literature available by this date included.

1 Decay Scheme

⁹⁰Y disintegrates by β^- emission mainly (99.983 %) to the stable ⁹⁰Zr ground state level. The decay scheme and level energies, spins and parities are based on the evaluation of E. Browne (1997Br34).

A weak beta branch occurs to the 1760 keV excited level which decays by a E0 gamma transition. This 0+ - 0+ transition undergoes with the emission of two particles materialized by the emission of two gamma, or an electron-positron pair, or internal conversion.

2 Nuclear Data

The Q value is from the atomic mass evaluation of Audi *et al.* (2003Au03).

The half-life of the ⁹⁰Y ground state has been evaluated from the following data (in hours) :

1937Po07	57.6 (24)
1937St08	60.5 (20)
1938Sa01	66 (3)
1940Sa02	66 (2)
1946Bo01	61 (1)
1954Ch29	64.60 (43)
1955Sa27	64.029 (24)
1955Vo03	64.24 (30)
1956He77	64.8 (2)
1957Pe05	63.97 (10)
1961He09	64.10 (8)
1963Vo02	63.74 (10)
1966Ri01	64.06 (11)
1967Bi02	64.6 (8)
1968La10	64.21 (8)
1969Gr38	63.46 (13)
2004Ko18	64.053 (20)

Adopted **64.041 (31) h** or **2.6684 (13) d**

The weighted average has been calculated with LWEIGHT computer program (version 3).

The evaluator has chosen to take into account the twelve most precise values for the calculation, since the 50's: 1954Ch29, 1955Sa27, 1955Vo03, 1956He77, 1957Pe05, 1961He09, 1963Vo02, 1966Ri01, 1967Bi02, 1968La10, 1969Gr38 and 2004Ko18. The evaluator's choice is supported by the fact that in preliminary calculation with LWEIGHT program, the 1937P07, 1937St08 and 1946Bo01 values have been rejected based on the Chauvenet's criterion.

With the data set of twelve values, the largest contribution to the weighted average comes from the value of Kossert amounting to 51%. The LWEIGHT program has increased the uncertainty of the 2004Ko18 value

from 0.020 to 0.0202 in order to reduce its relative weight from 51 % to 50 % .

The weighted average of 64.041 h and the external uncertainty of 0.031 is the half-life adopted value. The reduced- χ^2 value is 4.7.

2.1 b⁻ Transitions

The maximum energy of the β^- transitions in the decay of ⁹⁰Y to excited states in ⁹⁰Zr has been calculated from the relation of

$$E_{\beta^-} = Q_{\beta^-}(\text{from 2003Au03}) - E_{\text{level in Zr-90}}(\text{from 1997Br34})$$

In the case of the transition $\beta_{0,0}^-$ (to the ground state), many experimental values of E_{β^-} have been found in literature (measured with β -ray spectrometer), as shown in the following table (Table 1). It can be noted that the evaluated value, 2279.8 (17) keV, is in agreement with all experimental values.

Table 1: Experimental and adopted energy of the $\beta_{0,0}^-$ transition

Reference	E_{β^-} (keV)
T. Yuasa and J. Laberrigue-Frolov (1957Yu06)	2265 (5)
O.E. Johnson et al. (1958Jo33)	2261 (3)
R.T. Nichols et al. (1961Ni02)	2271 (2)
S. André and P. Depommier (1964An12)	2268 (2)
L.M. Langer et al. (1964La13)	2273 (5)
H. Daniel et al. (1964Da16)	2284 (5)
P.G. Hansen et al. (1966Ha15)	2275 (5)
P. Riehs (1966Ri01)	2280 (5)
T. Nagarajan et al. (1971Na09)	2288 (3)
H. Hansen (1983Ha35)	2279.5 (29)
C. Greenwood and M.H. Putnam (1993Gr17)	2274.8 (30)
Adopted value	2279.8 (17)

For the probabilities of the β^- transitions, the available published data are given in Table 2:

Table 2: Measured and adopted probabilities of β^- transitions in %.

Populated level (keV)	1961La07	1970Va09	1976Gr16	Adopted values
ground state	99.9885 (15)	99.977 (9)		99.983 (6)
1760.72	0.0115(15)	0.023(9)		0.017 (6)
2186.282			0.0000014 (3)	0.0000014 (3)

For the ground state and 1760.72-keV β transitions, the adopted values are the weighted averages of the two values given with uncertainties.

The lg ft values have been calculated with the LOGFT program (version 7.2a).

2.2 g Transitions

The 1760- and 2186-keV γ -ray transition probabilities are 0.017 (6) % and 0.0000014 (3) %, respectively. These values come directly from the evaluated β^- transition probabilities and adopted decay scheme.

Multipolarities of these γ -ray transitions are from 1997Br34.

The internal conversion coefficients (α_T , α_K and α_L) for 2186-keV γ -ray transition has been calculated using the ICC Computer Code (program Icc99v3a – GETICC dialog). The adopted values have been interpolated from the new tables of Band et al.(2002Ba85). The uncertainties in α_T , α_K and α_L have been estimated as 3 %.

The intensity of the conversion electrons was measured by Legrand (1972) being $1,3 (7) \times 10^{-2} \%$.

3 Atomic Data

Atomic values, ω_K , ω_L and n_K , are from Schönfeld and Janßen (1996Sc33).

5 Photon emissions

5.1 g-ray Emissions

The 2186-keV γ -ray absolute emission probability has been deduced from the total ($\gamma+ce$) transition probability of 0.0000014 (3) % (§ 2.2) and the theoretical α_T (2002Ba85) for a E2 transition.

The ratio of two photon decay $P_{\gamma\gamma}$, occurring during the $0+ - 0+$ gamma transition, to the sum of internal-pair decay P_{e+e-} and internal-conversion decay P_{ic} : $P_{\gamma\gamma} / (P_{e+e-} + P_{ic})$ is 0,040 (5) (1997Br34).

The number of positrons (leading to the emission of the 511 keV annihilation peak) is : $31,9 (5) \times 10^{-4}$ per 100 beta decays (R.G.Selwyn). Other values : $36 (5) \times 10^{-4}$ (1956Gr21) and $34 (4)$ (1961La07).

X-ray emissions aren't given in the table file. $IK\alpha$ was measured by Legrand (1972) being $3,7 (5) \times 10^{-4} \%$.

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⁹⁰Y^m - Comments on evaluation of decay data by V. Chisté

This evaluation was completed in 2005. The literature available by August 2005 was included.

1 Decay Scheme

⁹⁰Y^m disintegrates 99.9981 (2) % through isomeric transition to the ⁹⁰Y ground state and 0.0019 (2) % by β⁻ emission to the 2318 keV excited state in ⁹⁰Zr. The decay scheme, level energies, spins and parities and half-lives of excited states are based on the evaluation of E. Browne (1997Br34).

2 Nuclear Data

The Q value in the decay of ⁹⁰Y^m → ⁹⁰Zr (2961.8 (17) keV) has been calculated from the following relation:

$$Q(^{90}\text{Y}^{\text{m}} \rightarrow ^{90}\text{Zr}) = Q(^{90}\text{Y} \rightarrow ^{90}\text{Zr}) + Q(^{90}\text{Y}^{\text{m}} \rightarrow ^{90}\text{Y})$$

Both latter values are from the atomic mass evaluation of Audi *et al.* (2003Au03).

The experimental ⁹⁰Y^m half-life values (in hours) are given in Table 1:

Table 1: Experimental values of ⁹⁰Y^m half-life

Reference	Value (h)
Carter-Waschek and Linder (1961Ca12)	3.2 (1)
Heath et al.(1961He09)	3.14 (10)
Haskin and Vandenbosch (1961Ha17)	3.19 (6)
Abecasis et al.(1962Ab03)	3.15 (5)
Grench et al.(1967Gr02)	3.19 (1)
Anthony et al.(1992An19)	3.244 (5)
Adopted	3.19 (6)

The weighted average has been calculated with the LWEIGHT computer program (version 3).

The evaluator has chosen to take into account the seven values with associated uncertainties for the statistical processing. The largest contribution to the weighted average comes from the value of Anthony (1992An19) amounting to 79 %. The LWEIGHT program has increased the uncertainty for the 1992An19 value from 0.005 to 0.010 in order to reduce its relative weight from 79 % to 50 %.

The recommended value is the weighted average of 3.19 h with a final uncertainty of 0.06, expanded to include the most precise value of Anthony (1992An19, 3.244 (5) h). The reduced-χ² value is 3.5.

2.1 b- Transitions

The maximum energy of the β⁻ transition in the decay of ⁹⁰Y^m → ⁹⁰Zr has been calculated from the relation:

$$E_{\beta^-} = Q(^{90}\text{Y}^{\text{m}} \rightarrow ^{90}\text{Zr}, \text{ from } 2003\text{Au03}) - E_{\text{level in Zr-90}}(\text{from } 1997\text{Br34}) = 642.9 (17) \text{ keV.}$$

The *lg ft* of 9.6 and mean energy of 231.7 (7) keV have been calculated with the LOGFT computer program for the 642-keV unique first forbidden transition.

The 642-keV β^- transition probability is deduced from the ratio $I_\gamma(2319 \text{ keV})/I_\gamma(479 \text{ keV})$ given by H. C. Griffin (1976Fr16). The value of this ratio has been recalculated by the evaluator with the adopted photon branching ratio (see **5.2 g-ray Emission**).

2.2 g Transitions

For the $^{90}\text{Y}^m \rightarrow ^{90}\text{Y}$ and $^{90}\text{Y}^m \rightarrow ^{90}\text{Zr}$ branching, the transition probabilities have been calculated using gamma-ray intensities and the internal conversion coefficients (see **5.2 g-ray emissions**).

Multipolarities of γ -ray transitions in both decays of $^{90}\text{Y}^m$ are from 1997Br34:

202-keV γ -ray : M1 + E2, $\delta = -0.04$ (4)

479-keV γ -ray : M4 (+ E5)

682-keV γ -ray : E5

2319-keV γ -ray (from $^{90}\text{Y}^m \rightarrow ^{90}\text{Zr}$): E5

The internal conversion coefficients (ICC's) have been calculated using the Icc99v3a computer program (GETICC dialog). The adopted values have been interpolated from new tables of Band et al.(2002Ba85). The uncertainties of internal conversion coefficients have been estimated as 3 %.

3 Atomic Data

Atomic values are from 1996Sc33.

4 Electron Emissions

The Auger electrons emission probabilities have been calculated from γ -ray and conversion electron data by using the EMISSION computer program. The Auger electrons emission probabilities of ^{90}Zr aren't given in the table file, because they are negligible (of the order of 10^{-7}).

5 Photon Emissions

5.1 X-ray Emissions

The X-ray emission probabilities have been calculated from γ -ray and conversion electron data by using the EMISSION computer program. The X-ray emission probabilities of ^{90}Zr aren't given in the table file, because they are negligible (of the order of 10^{-7}).

5.2 g-ray Emissions

The relative emission probabilities measured in the isomeric decay of $^{90}\text{Y}^m$ are given in Table 2. The 479-keV line as been taken as 100 %.

Table 2: Relative γ -ray emission probabilities measured in the isomeric decay of $^{90}\text{Y}^m$, in %.

Energy (keV)	Heath (1961He09)	Hanser (1973Ha18)	Raman (1973Ra10)	Kluge (1974K106)	Griffin (1976Gr17)	Rao (1978Ra05)	Evaluated Values
202.53	104.99 (44)	107.2 (4)	103.7 (33)	none	none	none	106.1 (11)
682.04	< 0.01	none	none	0.40 (8)	0.34 (5)	0.35 (3)	0.352 (24)

For each γ -ray, the evaluated relative γ -ray emission probabilities are weighted averages (calculated with the LWEIGHT computer program, version 3) of the three values measured with uncertainties.

The normalization factor to convert the relative emission probabilities to the absolute emission probabilities has been calculated from the intensity balance at the ⁹⁰Y ground state. As β⁻ branching in the ⁹⁰Y^m is negligible (1976Gr16), the normalization factor is:

$$\text{Normalization factor} = \frac{100\%}{[(1 + a_T(202))P_{rel}(202)] + [(1 + a_T(682))P_{rel}(682)]}$$

From the theoretical α_T and the evaluated relative emission probabilities of the 202- and 682-keV γ-rays (Table 2), the normalization factor becomes **0.915 (9) %**. The uncertainty was calculated through the propagation on the formula given above.

The 479-keV transition probability is given by:

$$P_{(\gamma+ce)}(682 \text{ keV}) + P_{(\gamma+ce)}(479 \text{ keV}) = 100 \%$$

Taking into account the evaluated normalization factor, the theoretical α_T and the evaluated relative emission probability of the 682-keV γ-rays (Table 2), then P_(γ+ce)(682 keV) = 0.329 (23) % and, therefore, P_(γ+ce)(479 keV) = 99.671 (23) %.

The evaluated relative and absolute emission intensities for the 202-, 479- and 682-keV γ-rays are given in Table 3:

Table 3: Evaluated relative and absolute γ-ray emission intensities.

Energy (keV)	Relative emission intensity (%)	Absolute emission intensity (%)
202.53	106.1 (11)	97.1 (14)
479.53	99.4 (10)	90.97 (24)
682.04	0.352 (24)	0.322 (22)

From the 479-keV γ-ray absolute emission intensity value (Table 3) and the value of I_γ(2319 keV)/I_γ(479 keV) = 2.1 (2) 10⁻⁵, as given by Griffin (1976Gr16), then I_γ(2319 keV) = 0.0019 (2) %.

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¹⁰⁸Ag – Comments on evaluation of decay data by V. Chisté and M. M. Bé

The full decay data evaluation was completed in 2005. The literature available by January 2005 was included.

1. Decay Scheme

¹⁰⁸Ag disintegrates by electron capture (2,19 (14) %) and β^+ emission (0,283 (20) %) to excited states of ¹⁰⁸Pd and by β^- emission (97,53 (14) %) to excited states of ¹⁰⁸Cd .

2. Nuclear Data

The Q values are from the 2003Au03 evaluation.

Level energies, spin, parities and half-life of excited states are from J. Blachot (2000B104, see also 1982Ha37).

The half-life of the ¹⁰⁸Ag ground state has been determined from the following data (in minutes):

1958Gu31	2,43 (5)
1960Wa10	2,42 (2)
1965Eb38	2,41 (2)
1971Jo07	2,38 (3)
1974HeYW	2,41 (1)
1974Ry01	2,37 (1)
1991Yamamoto	2,353 (9)
Adopted	2,382 (11)

The half-life weighted average has been calculated by Lweight program (version 3).

The evaluator has chosen to take into account the seven values with associated uncertainty for the calculation. The largest contributions to the weighted average come from values of Head (1974HeYW), Ryves (1974Ry01) and Yamamoto (1991Yamamoto) (25 %, 25 % and 31 %, respectively).

The weighted average value is 2,382 *min* with a reduced- χ^2 value of 4,35. The external uncertainty is 0,011 min. Then, the adopted value is 2,382 (11) min.

2.1 β^- transition

The maximum energy of the β^- transitions in the decay of ¹⁰⁸Ag to excited states in ¹⁰⁸Cd is calculated from:

$$E_{\beta^-} = Q(\text{from 2003Au03}) - E_{\text{level in Cd-108}}(\text{from 2000B104})$$

For the probabilities of the β^- transitions, the published data are (table 1):

Table 1: β^- transition measured intensity values in %.

Populated Level	1953Pe16	1960Wa10	1962Fr02	1965Fr01
β^- ¹⁰⁸ Cd ground state	97,3	93,8	95,0 (3)	95,9 (3)
β^- ¹⁰⁸ Cd 632 keV	0,8	1,9	1,73 (10)	1,75 (10)

Comments on evaluation

For the β^- ¹⁰⁸Cd ground state transition, the values given by 1953Pe16 and 1960Wa10 have no uncertainties and the other two values are from the same author; the evaluators have chosen the most recent value published by L. Frevert (1965Fr01). This value, 95,9 (3) %, is important to determine the decay-scheme normalization factor (see **Gamma Ray Transition and Emission**).

For the β^- transition to the ¹⁰⁸Cd 632 keV level, the adopted value (1,63 (26) %), consistent with the Frevert value (1,75 (10) %) (table 1) has been deduced from the decay scheme balance.

The total β^- branching ratio was deduced taking into account that gamma-ray adopted relative emission intensities (see **4.1 Gamma Emissions**), the normalization factor (see **4.1 Gamma Emissions**) and the $I_{\beta^+, \epsilon}$ (g.s.) = 2,01 (12) % (see **2.3 Electron capture transition**):

$$I_{\beta^+, \epsilon} = I_{\beta^+, \epsilon}(\text{g.s.}) + N * [I_{\gamma}(433 \text{ keV}) + I_{\gamma}(931 \text{ keV}) + I_{\gamma}(1441 \text{ keV}) + I_{\gamma}(1539 \text{ keV})]$$

$$I_{\beta^+, \epsilon} = 2,01(12) \% + 0,0046(7) * [100 + 0,105(8) + 0,585(28) + 0,205(14)] = 2,47 (14)\%$$

And $I_{\beta^-} = 100 - 2.47(14) \% = 97,53 (14) \%$

The lg ft values have been calculated by Logft program (version 7.2a).

2.2 β^+ transition

The maximum energy of the β^+ transitions in the decay of ¹⁰⁸Ag is calculated by the same way as for the β^- transition.

For the probability of β^+ transition to the ground state, the published data are (table 2):

Table 2: β^+ transition probability measured values in %.

Level Populated	1953Pe16	1960Wa10	1962Fr02	1965Fr01
β^+ ¹⁰⁸ Pd ground state	0,14	0,36	0,28 (2)	0,28 (2)

From the total of 0,283 (20) % (2 transitions: to the 433-keV level and to the ground state) β^+ transition decaying by this mode, 0,28 (2)%, measured by Frevert (1965Fr01) go directly to the ground state. Most of the remaining 0,0026 (3) % (2000Bl04 and 1982Ha37) populate the 433-keV level (from theoretical ratio ϵ/β^+) (this electron-capture transition to the 433-keV level hasn't been measured by Frevert (1965Fr01)).

2.3 Electron capture transition

Some values for the electron capture branching ratio (in %) have been found in the literature, as shown in the following table:

Populated Level	1953Pe16	1960Wa10	1962Fr02	1965Fr01
EC ¹⁰⁸ Pd ground state	1,5	3,35	2,49 (25)	1,73 (12)
EC ¹⁰⁸ Pd 433 keV level	0,06	0,18	0,19 (3)	0,19 (3)
EC ¹⁰⁸ Pd 1052 keV level	0,22	0,42	0,26 (3)	0,27 (3)

For the ground state, the adopted value is the most recent measurement of Frevert (1965Fr01). For the other levels, the electron-capture probabilities have been deduced from the imbalance at each level of the decay scheme. It can be noted that for the levels at 433 keV and 1052 keV the adopted electron capture branchings of 0,19 (8) % and 0,243 (39) %, respectively, are consistent with the Frevert measured values.

P_K, P_L, P_M values have been calculated for allowed electron-capture transitions in the decay of ¹⁰⁸Ag to the excited states in Pd-108 using the EC-Capture computer program.

2.4 Gamma transitions

Probabilities

The transitions probabilities have been calculated from the gamma-ray emission intensities and the internal conversion coefficients (see **Gamma ray emission**).

Multipolarity and internal conversion coefficients

For the 433- ([E2]), 633-(E2) and 1441-keV ([E2]) gamma-ray transitions, multipolarities are from J. Blachot (2000Bl04, see also 1982Ha37)

The internal conversion coefficients (α_T , α_K and α_L) for these transitions have been calculated using the ICC Computer Code (program Icc99v3a – GETICC dialog). The adopted values have been interpolated from the new tables of Band (2002Ba85).

Their uncertainties are taken as 3% of the calculated values with the ICC computer code.

3. Atomic data

Atomic values, ω_K , ω_L and η_{KL} , are from Schönfeld (1996Sc33).

The X-ray and Auger electrons emission probabilities are calculated from the data set values by using the program EMISSION.

4. Photon Emissions

4.1 Gamma Emissions

The measured relative emission intensities are given in table 3, they are relative to the 433-keV gamma ray taken as 100. Energy values are in keV.

Table 3: Measured relative gamma emission intensities in %.

Energy (keV)	Okano et al. (1971Ok01)	Singhal (1973Si02)	Adopted values
383,13 (16)	none	0,18 (6)	0,18 (6)
388,36 (7)	none	0,37 (12)	0,37 (12)
433,938 (5)	100	100	100
497,13 (12)	0,25 (9)	0,45 (11)	0,33 (7)
618,86 (5)	54,1 (24)	52,4 (26)	53,3 (18)
632,98 (5)	355,1 (14,9)	349,6 (175)	353 (11)
880,26 (10)	0,65 (3)	0,64 (5)	0,647 (26)
931,07 (12)	0,091(16)	0,11 (1)	0,105 (8)
1007,22 (5)	2,71 (11)	2,79 (14)	2,74 (9)
1106,01 (7)	0,26 (2)	0,33 (3)	0,282 (17)
1441,15 (5)	0,56 (4)	0,61 (4)	0,585 (28)
1539,94 (7)	0,20 (2)	0,21 (2)	0,205 (14)

The adopted values are the weighted averages of the two values given with uncertainties. One set of values, N. D. Johnson (1971Jo07), was not taken into account by the evaluator because the measured relative emission probabilities were relative to that of the 633 keV gamma ray and not to that of the 433 keV gamma ray as done by the other authors (normalization could introduce an overestimation of uncertainties).

The normalization factor to convert the relative emission intensities to absolute emission intensities is calculated with the formula:

$$\text{Normalization} = \frac{100 - I_{\beta^-}(g.s.) - I_{\beta^+,e}(g.s.)}{(\sum(1 + a_T)P_{rel})}$$

where the sum is to be done over all the gamma transitions to the ground state, and:
 $I_{\beta^-}(g.s.) = 95,9$ (3) % and $I_{\beta^+,e}(g.s.) = 2,01$ (12) %. (see explanations above)

From the theoretical α_T and the evaluated relative emission intensities (table 3), the calculated normalization factor is 0,0046 (7). The uncertainties were propagated on the above formula. Absolute emission intensities are given in table 4.

Table 4: Absolute emission intensities for the γ -rays in the decay of the ¹⁰⁸Ag (in %).

Energy (keV)	Relative Emission intensity	Absolute emission intensity
383,13 (16)	0,18 (6)	0,00083 (30)
388,36 (7)	0,37 (12)	0,0017 (6)
433,938 (5)	100	0,46 (7)
497,13 (12)	0,33 (7)	0,00152 (40)
618,86 (5)	53,3 (18)	0,245 (39)
632,98 (5)	353 (11)	1,62 (26)
880,26 (10)	0,647 (26)	0,00298 (48)
931,07 (12)	0,105 (8)	0,00048 (8)
1007,22 (5)	2,74 (9)	0,0126 (20)
1106,01 (7)	0,282 (17)	0,00130 (22)
1441,15 (5)	0,585 (28)	0,00269 (44)
1539,94 (7)	0,205 (14)	0,00094 (16)

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¹⁰⁸Ag^m – Comments on evaluation of decay data by V. Chisté and M. M. Bé

The full decay data evaluation was completed in 2005. The literature available by January 2005 was included.

1. Decay Scheme

¹⁰⁸Ag^m disintegrates 90.9 (6) % by electron capture to the 1771 keV excited state in Pd-108, and by 9.1(6)% through isomeric transitions (two gamma-rays in cascade) in ¹⁰⁸Ag.

2. Nuclear Data

The Q value (= 2031 (6) keV) is from the 2003Au03.

Level energies, spin and parities are from J. Blachot (2000Bl04).

The measured ¹⁰⁸Ag^m half-life values are, in years :

1969Ha07	127 ± 7
1969Vo06	310 ± 132
1992Sc25	418 ± 15
2004Sc49	438 ± 9

The evaluators have chosen as their recommended value the most recent result from Schrader (2004Sc49) who followed the decay by using a ionisation chamber for about 20 years.

2.1 Electron capture transition

For the 260 keV electron capture transition, the adopted value has been deduced from the decay-scheme balance at the 1771-keV level.

P_K, P_L, P_M have been calculated for allowed electron capture transition in the decay of ¹⁰⁸Ag^m to the 1771-keV excited state in Pd-108 using the EC Capture computer program.

2.4 Gamma transitions

Probabilities

The transition probabilities have been calculated using the gamma-ray emission intensities and the relevant internal conversion coefficients (see **Gamma ray Emission**)

Multipolarity and internal conversion coefficients

The multipolarities for the 30- (M4) and 79-keV gamma-ray transitions (E1) in ¹⁰⁸Ag, and the 433-([E2]), 614- (E2) and 722-keV (E2) gamma-ray transitions in ¹⁰⁸Pd have been taken from J. Blachot (2000Ba04, see also 1982Ha37).

The internal conversion coefficients (α_T , α_K and α_L) for these gamma-ray transitions have been interpolated from the tables of Band (2002Ba85) using the ICC Computer Code (program Icc99v3a – GETICC dialog). Their uncertainties are taken to be 3%.

3. Atomic data

Atomic values for ω_K , ω_L and η_{KL} , are from Schönfeld (1996Sc33).

The X-ray and Auger electron emission probabilities have been calculated from the data set values by using the program EMISSION.

4. Photon Emissions**4.1 Gamma-ray Emissions**

The energy of the 433-, 614- and 722-keV gamma-ray lines are from Helmer et al. (2000He14).

The measured relative emission intensities are given in table 1, they are relative to the 433-keV gamma ray taken as 100. Energy values are in keV.

Table 1: Measured relative emission intensities, in %.

Energy (keV)	Kistner (1966Ki03)	Kracíková (1968Kr23)	Hamilton (1971Ha31)	Heath (1974HeYW)	Weighted Average values
γ in ¹⁰⁸ Ag					
30.309 (8)	none	none	none	none	none
79.131 (3)	7.3 (8)	8.3 (9)	none	none	7.7 (6)
γ in ¹⁰⁸ Pd					
433.938 (4)	100	100	100	100 (5)	100
614.276 (4)	103 (3)	105 (10)	99.3 (20)	100 (5)	100.5 (16)
722.907 (10)	102 (2)	102 (10)	100.4 (20)	100 (5)	100.8 (16)

Adopted values are weighted averages (calculated by the Lweight program, version 3) of the four values measured with uncertainties. The normalization factor to convert the relative emission intensities to absolute emission intensities is calculated with the formula:

$$\text{Normalization} = \frac{100}{[(1 + a_T(433))P_{rel}(433)] + [(1 + a_T(79))P_{rel}(79)]}$$

where the 79- and 433-keV gamma-ray transitions populate the ground state level of ¹⁰⁸Ag and ¹⁰⁸Pd, respectively.

From the theoretical α_T and the relative evaluated emission intensities of the 79- and 433-keV gamma-rays (table 1), the normalization factor becomes 0.901 (6). The uncertainty was calculated through the propagation on the formula given above. Absolute emission intensities are given in table 2.

Table 2: Absolute emission intensities for the γ -rays, in %.

Energy (keV)	Relative Emission intensity	Absolute emission intensity
79.131 (3)	7.7 (6)	6.9 (5)
433.938 (4)	100	90.1 (6)
614.276 (4)	100.5 (16)	90.5 (16)
722.907 (10)	100.8 (16)	90.8 (16)

The 30-keV transition probability in the decay of $^{108}\text{Ag}^m \rightarrow ^{108}\text{Ag}$ is equal to 9.1 (6) % (from decay scheme transition probability balance).

Energy (keV)	Transition probability (%)	Absolute emission intensity (%)
30.309 (8)	9.1 (6)	0.0000215 (18)

The 30-keV absolute emission intensity has been deduced from the total transition probability and the theoretical α_T (Band *et al.*, 2002) for a M4 transition.

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¹¹¹In - Comments on evaluation of decay data by V.P. Chechev.

The initial ¹¹¹In decay data evaluation was done by V.P. Chechev in 1998 (1999Be). This current (revised) evaluation has been carried out in March 2006. The literature available by March 2006 has been included.

1 Decay Scheme

Transitions to the ground state and the excited level of 245 keV of ¹¹¹Cd have not been observed. Limits on the electron capture branches to these levels can be deduced from the log ft systematics of 1998Si17. The transitions to the levels at 0 and 245 keV are 4th and 2nd forbidden with expected log ft's of > 22 and > 10.6, respectively. The corresponding electron capture branch limits are < 1.0×10⁻¹⁴ % and < 5×10⁻⁴ %, respectively (2003B110).

The upper limit of 0.01 % has been found for the electron capture branch to the excited level of 396 keV by Meyer and Landrum (1972MeZD).

2 Nuclear Data

Q_{EC} value is from 2003Au03.

The evaluated ¹¹¹In half-life is based on the experimental data given in Table 1.

Table 1. Experimental values of the ¹¹¹In half-life (in days)

<u>Reference</u>	<u>Author(s)</u>	<u>Value</u>	<u>Comments</u>
1949He06	Helmholz <i>et al.</i>	2.84 (3)	
1957Ma26	Maier	2.81 (1)	
1968Li08	Liskien	2.84 (11)	
1968Sm08	Smend <i>et al.</i>	2.96 (8)	
1972Em01	Emery <i>et al.</i>	2.83 (1)	
1972Gu19	Gureev <i>et al.</i>	2.84	Uncertainty is not quoted
1978La21	Lagoutine <i>et al.</i>	2.802 (1)	Quoted uncertainty, corresponding to 99.7 % confidence level, has been reduced by a factor 3
1980Ho17	Houtermans <i>et al.</i>	2.8071 (15)	
1982HoZY	Hoppes <i>et al.</i>	2.8048 (5)	Replaced by 1992Un01
1983Wa26	Walz <i>et al.</i>	2.8049 (5)	
1986Ru09	Rutledge <i>et al.</i>	2.8048 (1)	
1992Un01	Unterweger <i>et al.</i>	2.80477 (53)	Cited also in 2002Un02
2004Sc04	Schrader	2.8063 (7)	

The value of 1972Gu19 has been omitted because of the absence of an estimated uncertainty. The value of 1982HoZY has been omitted as it is replaced in 1992Un01. The value of 1968Sm08 has been omitted as outlier using the Chauvenet's criterion. Hence the eleven values have been used for the statistical data processing.

The uncertainty of 1986Ru09 was increased to 0.00030 to adjust weights according to the LRSW method. A weighted average for the final data set is 2.8049 with an internal uncertainty of 0.00021 and an external uncertainty of 0.00034 and a reduced $\chi^2/\nu = 2.5$. An unweighted average is 2.815 (5).

Different statistical procedures (1994Ka08) give the following results: UINF, PINF and NORM – 2.8049 (3), LWM – 2.815 (10), IEXW – 2.805 (13), RAJ – 2.8049 (2), BAYS and MBAYS – 2.8049 (4).

The adopted value of the ¹¹¹In half-life is 2.8049 (4) days.

The evaluated half-life of the metastable level of 396 keV (^{111m}Cd) is based on the experimental results given in Table 2.

Table 2. Experimental values of the ^{111m}Cd half-life (in minutes)

Reference	Author(s)	Value
1945Wi11	Wiedenbeck	48.7 (3)
1948Ho37	Hole	50 (2)
1949He06	Helmholz et al.	48.6 (3)
1968Bo28	Bornemisza-Pauspertl et al.	49.4 (7)
1987Ne01	Nemeth et al.	48.54 (5)
1997We13	Wen et al.	48.30 (15)

The uncertainty of 1987Neo1 was increased to 0.12 to adjust weights according to the Limitation of Relative Statistical Weight (LRSW) method. A weighted average for the final data set is 48.50 with an internal uncertainty of 0.085 and an external uncertainty of 0.082 and a reduced $\chi^2/\nu = 0.93$. An unweighted average is 48.9 (3).

Different statistical procedures (1994Ka08) give the following results: IEXW, LWM, MBAYS, NORM and UINF – 48.50 (9), PINF – 48.50 (8), RAJ – 48.51(9), BAYS – 48.50 (11).

The adopted value of the ¹¹¹In half-life is 48.50 (9) minutes.

2.1 Electron Capture Transitions

The electron capture transition energies have been calculated from Q_{EC} value and the ¹¹¹Cd level energies given in Table 3 from 2003B110. The electron capture transition probability $P_{\epsilon_{0,2}} = 5 (5) 10^{-3}$ has been evaluated taking into account the observed upper limit of 1×10^{-2} (1972MeZD). The fractional electron capture probabilities P_K, P_L, P_M have been calculated using the LOGFT computer program.

Table 3. ¹¹¹Cd levels populated in the ¹¹¹In ϵ -decay

Level number	Energy, keV	Spin and parity	Half-life	Probability of EC-transition (x100)
0	0.0	1/2 ⁺	Stable	$< 1.0 \times 10^{-14}$
1	245.35 (4)	5/2 ⁺	84.5 ns	$< 5 \times 10^{-4}$
2	396.16 (5)	11/2 ⁻	48.50 min	0.005 (5)
3	416.63 (5)	7/2 ⁺	0.12 ns	99.995 (5)

2.2 g Transitions

The energies of γ -ray transitions are virtually the same as the γ -ray energies because nuclear recoil is negligible. The γ -ray transition probabilities have been calculated from the γ -ray emission probabilities and the evaluated total internal conversion coefficients (α_T).

The evaluated α_T values for $\gamma_{1,0}$ (245 keV) and $\gamma_{3,1}$ (171 keV) gamma-ray transitions have been obtained from the sets of 5 data including theoretical values (Table 4). The values of $\alpha_K, \alpha_L, \alpha_M$ have been calculated from the evaluated α_T using the theoretical ratios $\alpha_K/\alpha_L/\alpha_M/\alpha_{NO}$. The relative uncertainties of $\alpha_K, \alpha_L, \alpha_M$ have been taken as 2 %.

The theoretical α_T has been used for the E3 $\gamma_{2,1}$ (151 keV) gamma-ray transition (see also 1973Pathak).

Table 4. Experimental, theoretical and evaluated values of the total internal conversion coefficients (α_T)

	1956St64	1966Sp04	1975Sh29	1985Ka29	Theory (2006Ra03)	Evaluated
$\gamma_{1,0}$ (245 keV)	0.0621 (15)	0.0618 (15)	0.0634 (30)	0.0620 (7)	0.0637 (9)	0.0625 (7)
$\gamma_{3,1}$ (171 keV)	0.099 (3)	0.100 (3)	0.124 (6)	0.1018 (13)	0.1068 (15)	0.1036 (24)

The theoretical α_T values have been calculated using the BRICC computer program (2006Ra03).

The gamma-ray transition multipolarities have been adopted from measurements of 1956St54 and 1974Kr03. The gamma-ray multipolarity mixing ratio $\delta(E2/M1)$ of the $\gamma_{3,1}$ (171 keV)-transition has been evaluated using the following data:

0.146(3)	Steffen (1956St64)
0.141(3)	Budz-Jorgensen (1973)
0.145	Kreische and Lampert (1974Kr03)
0.144(3)	Weighted average of 1956St04 and 1973Budz-Jorgensen

The adopted value of 0.144 (3) corresponds to an E2 admixture of 2.07 (9) %.

3 Atomic Data

3.1. Fluorescence yields

The fluorescence yield data ω_K , ω_L , n_{KL} are from 1996Sc06 (Schönfeld and Janßen).

3.2. X Radiations

The energy values for X-rays have been calculated from the wavelengths given by Bearden (1967Be65). The relative emission probabilities of KX ray components have been taken from 1996Sc06.

3.3. Auger Electrons

The energies of Auger electrons are from 1977La19 (Larkins) and Table of Isotopes. The ratios $P(KLX)/P(KLL)$, $P(KXY)/P(KLL)$ are taken from 1996Sc06.

4 Electron Emissions

The energies of the conversion electrons have been calculated from the gamma transition energies and the electron binding energies. The emission probabilities of conversion electrons have been deduced from the evaluated $P(\gamma)$ and ICC values.

The total absolute emission probability of K Auger electrons has been calculated with the EMISSION computer program using the adopted $\omega_K = 0.842$ (4).

The absolute total emission probability of L Auger electrons has been calculated with the EMISSION computer program using the adopted $\omega_L = 0.0632$ (16).

Experimental data on conversion electrons (1951Mc61, 1966Sp04, 1975Sh29) and Auger electrons (2005Ya03) are concordant with the adopted values

5 Photon Emissions

5.1 X-ray Emissions

The absolute emission probabilities of Cd KX-rays have been calculated with the EMISSION computer program using the adopted values of P_K and ω_K (Cd).

The absolute emission probabilities of Cd LX-rays have been calculated with the EMISSION computer program using the adopted values of P_L , ω_L (Cd), P_K , ω_K (Cd), n_{KL} (Cd).

5.2 g-ray Emissions

The energy of $\gamma_{2,1}$ -ray (151 keV) has been taken from 1975Sh29.

The energy of the $\gamma_{3,1}$ -ray (171 keV) has been evaluated using the experimental results given below:

172.1 (5)	McGinnis (1951Mc11) - Omitted from data processing
171.29 (3)	Sparrman et al. (1966Sp04)
171.20 (10)	Heath (1974HeYW)
171.28 (3)	Shevelev et al. (1975Sh29)
171.28 (3)	Weighted average (adopted value)

The energy of the $\gamma_{1,0}$ -ray (245 keV) has been evaluated using the experimental results given below:

246.6 (7)	McGinnis (1951Mc11) - Omitted from data processing
245.35 (4)	Sparrman et al.(1966Sp04)
245.27 (10)	Heath(1974HeYW)
245.35 (4)	Shevelev et al. (1975Sh29)
245.35 (4)	Weighted average (adopted value)

The absolute emission probabilities of $\gamma_{2,1}$ (151 keV), $\gamma_{3,1}$ (171 keV) and $\gamma_{1,0}$ (245 keV) gamma rays have been calculated using the below relations:

$$P\gamma_{2,1} (\times 100) = 99.995 (5) / (1 + \alpha_T (\gamma_{2,1}))$$

$$P\gamma_{3,1} (\times 100) = 0.005 (5) / (1 + \alpha_T (\gamma_{3,1}))$$

$$P\gamma_{1,0} (\times 100) = 100 / (1 + \alpha_T (\gamma_{1,0})).$$

In 1975Sh29 the latter value has been estimated as ~ 0.003 .

The relative intensity of $\gamma_{1,0} / \gamma_{3,1}$ from 0.90 to 0.97 has been measured with an accuracy not better than 3 % in the above works. This accuracy is considerably worse in comparison with the calculation from the decay scheme using α_T values.

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¹²⁵Sb - Comments on evaluation
by R. G. Helmer and E. Browne

The initial ¹²⁵Sb decay data evaluation was done by R.G.Helmer in May 2004 . This current (revised) evaluation was carried out in November 2004. The literature available by November 2004 was included.

1. Decay Scheme

¹²⁵Sb decays by β^- emission to levels in ¹²⁵Te.

The γ ray at 109 keV depopulates the isomeric level at 144 keV (half-life of 57.4 days), so its intensity depends on any chemical separation and its grow-in time. It takes about 1 year for it to be in equilibrium with the other γ rays to within 1%. The level at 35 keV is primarily fed from higher-lying levels, but 27% of the 35-keV γ -ray intensity comes via the isomeric level when it is at equilibrium. So, for a chemically separated source, it needs about 8 months grow-in to be at equilibrium at the 1% level.

The (direct β^- , and indirect, through γ rays) population of the isomer is 22.9 (9) % calculated from this adopted decay scheme.

2. Nuclear Data

The decay energy of 766.7 (21) keV is from the 2003 mass evaluation (2003Au03).

For the adopted decay scheme, the total radiation energy per decay is calculated to be 767 (8) keV, which agrees well with the decay energy of 766.7 (21) keV and confirms the internal consistency of this decay scheme.

The population of several additional levels has been reported, especially by 1998Sa55, but these levels are uncertain; they are : 402-, 538-, 652- and 728- keV. Verification of the associated γ rays is needed. Thus, β and γ transitions to and from these levels have not been included here.

The adopted parent half-life is 1007.54 (9) days, or 2.75855 (25) years, from the following data:

2.7 y	1950Le09
2.6 (1) y	1960Kl04
2.78 (4) y	1961Wy01
2.71 (2) y	1965F102
2.81 (5) y	1966La13
1007.3 (3) d	1980Ho17
1008.1 (8) d	1983Wa26
1007.3 (3) d	1992Un01, superseded by 2002Un02
1007.56 (10) d	2002Un02
1007.54 (9) d	Weighted average

Adopted value is the weighted average of the three precise values (which are from after 1970) which are not superseded. The reduced- χ^2 value for this average is 0.58 and the value from 2002Un02 has 89% of the relative weight.

The values from other evaluations are 2.75856 (25) years from 1999Ka26, which did not have available the value from 2002Un02, and 1007.48 (21) days from 2004Wo02 where the relative weight of the value from 2002Un02 was presumably reduced to 50%.

The level half-lives are also taken from the evaluation 1999Ka26 and are as follows:

Energy (keV)	Half-life
0	Stable
35	1.48 (1) ns
144	57.40 (15) d
321	0.673 (13) ns
443	19.1 (6) ps
463	13.2 (5) ps
525	<160 ns
636	40 (20) ps
642	≤ 70 ps
671	1.26 (6) ps

The references that provide measured values of the level half-lives are: 1965An05, 1966In02, 1967Vo21, 1968Ho05, 1968Ko08, 1969Ho42, 1970Ba69, 1970Be47, 1970Be51, 1970Ma20, 1972Be21, 1972La21, 1972Sa08, 1972Sa33, 1988GeZS, and 1992De26. Half-lives for the levels at 443, 463, and 671 keV were calculated from B(E2) values from Coulomb excitation studies (1999Ka26).

2.1 β^- Transitions

The probabilities for the β^- transitions branches are computed from the intensity balances from the γ -ray transitions for the excited states above 150 keV. Upper limits for the β^- probabilities to the 0- and 35-keV levels can be computed from the $\log ft$ systematics (1998Si17); these values are 0.002% and 1.9%, respectively. In the adopted level scheme it is assumed that both of these values are 0. The resulting values are :

Level (keV)	P_{β^-} (%)	Character	$\log ft$
0	<0.002	unique 2 nd forb.	>13.9
35	≡0	2 nd forb.	>10.6
144	13.4(9)	unique 1 st forb.	9.77
321	7.54 (9)	1 st forb.	9.32
443	0.089 (10)	2 nd forb.	10.79
463	40.3 (4)	allowed	8.04
525	1.251 (12)	1 st forb.	9.23
636	18.07 (19)	allowed	7.23
642	5.82 (5)	allowed	7.66
671	13.58 (12)	allowed	6.93

For comparison, the measured values to the 144-keV level are 13.6 (9)% by 1998Gr13, 13.4% by 1959Na06, and 13.7% by 1964Ma30.

2.2 γ Transitions

The γ -ray multiplicities and mixing ratios have been taken from 1999Ka26 and the internal-conversion coefficients are interpolated from the tables of 1978Ro22, except the E5, which is from 1976Ba63. These values are as given in the following table. The uncertainties in the internal-conversion coefficients are taken to be 3% of the value, unless otherwise given. The total theoretical conversion coefficient of the M4 109-keV γ ray, calculated from 1978Ro22, has been reduced by 2.5% as suggested by 1990Ne01.

Energy (keV)	Multi-polarity.	Δ	%E2 or M2	α	α_K
19	[M1]			11.3	0.0
35	M1+E2	0.029 (+3-2)	0.084 (18)	14.3	12.1
109	M4			354.6	182
117	E1			0.127	0.109
(144)	[E5]			265	39.8
172	M1(+E2)	-0.004 (8)	<0.014	0.151	0.129
176	M1+E2	-0.60 (2)	26.5 (18)	0.167	0.139
178	M1+E2			0.18 (4)	0.147 (26)
198	[E2]			0.154	0.123
204	M1+E2	+1.60 (3)	72 (3)	0.128	0.104
208	M1+E2	+0.105 (14)	1.1 (3)	0.092	0.0791
227	(M1+E2)			0.084 (13)	0.070 (11)
315	(E1)			0.00839	0.00726
321	E1			0.00798	0.0691
380	E2			0.0183	0.0154
408	M1+E2	+1.50 (7)	69 (6)	0.0152	0.0129
427	M1+E2	-0.538 (11)	22.4 (9)	0.0138	0.0119
443	M1+E2	-2.3 (1)	84 (7)	0.0118	0.0100
463	E2			0.0102	0.0086
497	[M2]			0.0318	0.0271
600	E2			0.00498	0.00421
606	E2			0.00485	0.00415
635	M1+E2	+0.332 (3)	9.9 (2)	0.00526	0.00455
672	E2			0.00373	0.00319

The references that provide data on the multiplicities and mixing ratios are: 1968An15 [from α_K], 1970Na12 [α_K , K/L], 1970Wy01 [$\gamma\gamma(\theta)$], 1971Kr11 [$\gamma(\theta)$ oriented nuclei], 1971Ro17 [$\gamma\gamma(\theta)$], 1971Sa24 [$\gamma\gamma(\theta)$], 1972Ba12 [$\gamma\gamma(\theta)$], 1972Br02 [L_i/L_j], 1975Ma32 [M_i/M_j], 1982Mu02 [α_K], 1982Si18 [$\gamma\gamma(\theta)$], 1983Si14 [$\gamma\gamma(\theta)$], 1997De38

$[\gamma\gamma(\theta)]$, 1998Ro20 $[\gamma\gamma(\theta)]$, 1998Sa36 $[\alpha_K, K/L]$, 1998Sa55 $[\alpha_K]$, and 1999Sa73 $[\alpha_K]$.

The γ -ray energies have been reported by 1969Ch09, 1970Na12, 1973Gu10, 1976Wa13, 1990He05, 1998Sa55, and 2000He14, with the last three references giving the more precise values. The calibration details are not given in 1998Sa55, so it is not possible to compare these values with the others. The values of 2000He14 are on the most recent energy scale on which the energy of the strong γ ray from the decay of ^{198}Au is 411.80205 (17) keV, while those from 1990He05 are on a scale for which this energy is 411.8044 (11) keV. No correction is made here for this difference. The energies are taken from 2000He14 if they are available there, from 1990He05 as a second choice, and as indicated otherwise. (Often these values are from use of energy combinations so they can not be averaged with direct measurements). These values are: from 2000He14: 176.314 (2), 204.138 (10), 208.077 (5), 427.874 (4), 443.555 (9), 463.365 (4), 600.597 (2), 606.713 (3), 635.950 (3), and 671.441 (6); from 1990He05: 35.489 (5), 172.719 (8), 178.842 (5), 198.654 (11), 227.891 (10), 380.452 (8), and 408.065 (10); 1976Wa13 and 1998Sa55: 19.981 (6), 110.86 (7), 314.96 (8), and 497.38 (9); 1973Gu10, 1976Wa13, and 1998Sa55: 109.27 (11), and 116.95 (7).

The recommended relative and absolute γ -ray emission probabilities are discussed in section 4.2.

3. Atomic Data

3.1 X rays and Auger electrons

The fluorescence yield data are from Schönfeld and Janßen (1996Sc06) and the EMISSION code; these values are ω_K , 0.875(4); mean ω_L , 0.086 (4); and η_{KL} , 0.917 (4).

The EMISSION code also supplies the Auger electron emission probabilities; these values are: KLL, 7.0 (4); KLX, 3.17 (17); and KXY, 0.359 (20).

4 Emissions

4.1 K x-rays

The relative K x-ray emission probabilities are from 1996Sc06 and the absolute probabilities have been computed from these relative probabilities, the above γ -ray emission probabilities, and internal-conversion coefficients by using the EMISSION code.

4.2 g rays

The measured relative γ -ray emission probabilities (or intensities) are given in the following table. The values for the 109-keV γ ray are for a source in equilibrium.

Part 1

Energy	68An15 ^a	68Se11 ^b	69Ch09	70Na12	73Gu10	74II02 ^c	76Wa13	77Ar10	77Ge12
19.9							0.068 (33)		
35.5				19.6 (20)		1.42 (9)			
58.3									
109.3		0.3	0.3 (1)	0.39 (4) ^f	0.18 (2)	0.36 (4)			
110.8		~ 0.05				0.170 (23)	0.0031 (3)		
117.0		0.75		1.13 (1) ^f	0.75 (4) ^f	0.96 (7)	0.866 (14)	0.89 (4)	0.910 (29)
172.6		0.8	0.9 (1)	0.90 (10)	0.65 (4)	0.47 (3)	0.618 (10)	0.65 (5)	
176.3		20.5	21.2 (11)	24.9 (20)	23.9 (8)	23.2 (13)	23.06 (7) ^g	22.9 (7)	23.9 (7)
178.7		~0.1			0.08 (1)	0.05 (1)	0.092 (14)	0.10 (2)	
198.6		~0.04			0.04 (1)		0.044 (10)	0.055 (10)	
204.1		0.9	1.0 (1)	1.15 (10)	1.21 (5)	1.10 (8)	1.097 (14)	0.99 (5)	1.15 (4)
208.1		0.7	0.8 (1)	0.85 (8)	0.90 (4)	0.83 (5)	0.802 (14)	0.79 (4)	0.829 (25)
227.9	0.4 (1)	0.4		0.44 (4)	0.47 (2)	0.64 (4)	0.448 (14)	0.45 (2)	
315.0							0.0143 (14)	0.020 (4)	
321.0	1.4 (2)	1.25	1.4 (1)	1.41 (10)	1.42 (5)	1.6 (1)	1.393 (14)	1.41 (7)	1.422 (16)
380.4	5 (1)	5	5.0 (4)	5.27 (40)	5.22 (17)	5.43 (32)	5.16 (3)	5.15 (20)	5.10 (5)
408.1	0.9 (4)	0.6		0.62 (6)	0.59 (3)	0.50 (3)	0.62 (2)	0.59 (3)	

Energy	68An15 ^a	68Se11 ^b	69Ch09	70Na12	73Gu10	74II02 ^c	76Wa13	77Ar10	77Ge12
427.9	100.	100.	100.	100.	100.	100.	100.0 (3)	100.	100.0 (10)
443.4	0.5 (3)	1		1.03 (10)	1.07 (4)	1.10 (7)	1.03 (2)	1.05 (5)	
463.4	33 (4)	35.5	35.3 (20)	35.4 (28)	35.3 (13)	35.2 (23)	35.50 (7)	35.2 (10)	35.26 (37)
497.0							0.0122(14)	0.011 (2)	
600.6		61	61.2 (34)	61.5 (49)	59.6 (18)	53.6 (32)	60.39 (10)	60.1 (18)	60.6 (6)
606.6		17	17.1 (12)	16.4 (12)	16.9 (6)	19.0 (11)	17.052 (34)	16.8 (5)	17.12 (17)
635.9	42 (2)	37	37.0 (22)	37.31 (30)	38.2 (12)	35.6 (23)	38.45 (7)	38.4 (11)	38.6 (4)
671.4	6.5 (5)	6	5.6 (5)	6.0 (5)	6.09 (20)	6.24 (38)	6.11 (14)	6.02 (24)	6.18 (6)

Part 2

Energy	79Pr08	80Ro22	83Si14	84Iw03	86Wa35	93Fa02	98Sa55	90He05
19.9			0.068 (2)			0.072 (6)	0.068 (3)	
35.5			14.53 (35)			14.79 (8) ^d	17.7 (2)	
58.3			0.091 (4)			0.093 (2)	0.0042 (20)	
109.3	0.26 (4)		0.232 (5)	0.241 (24)		0.235 (16)	0.232 (6)	
110.8	0.02 (1) ^h		0.0042 (3)				0.0039 (3)	
117.0	0.91 (5)	1.01 (12)	1.060(10) ^f	0.867 (25)		0.885 (5) ^j	0.945 (15)	0.867 (24)
172.6	0.74 (6)	0.89 (6)	0.86 (2) ^f	0.69 (4)		0.72 (4)	0.67 (4)	0.659 (11)
176.3	22.9 (6)	25.45 (60)	24.5 (8)	22.62 (21)	22.91 (41)	23.65 (34)	23.09 (20)	22.96 (24)

Energy	79Pr08	80Ro22	83Si14	84Iw03	86Wa35	93Fa02	98Sa55	90He05
178.7	0.11 (1)		0.130 (5)	0.11 (4)		0.099 (6)	0.121 (2) ^j	
198.6	0.06 (1)		0.081 (4) ^f	0.030 (11)		0.046 (9)	0.044 (3)	
204.1	1.12 (4)	1.19 (22)	1.14 (4)	1.08 (3)		1.19 (5)	1.014 (10)	1.080 (23)
208.1	0.80 (4)	0.96 (10)	0.82 (2)	0.788 (21)		0.89 (3)	0.860 (10)	0.825 (16)
227.9	0.42 (2)	0.42 (7)	0.44 (2)	0.433 (12)		0.465 (25)	0.442 (9)	0.443 (23)
315.0			0.013 (2)				0.0144 (15)	
321.0	1.48 (6)	1.46 (8)	1.30 (5)	1.391 (24)		1.45 (5)	1.43 (2)	1.41 (3)
380.4	5.18 (20)	5.26 (10)	6.02 (25) ^f	5.06 (4)	5.12 (15)	5.09 (3)	5.17 (4)	5.14 (5)
408.1	0.57 (4)	0.66 (8)	0.61 (3)	0.608 (21)		0.59 (2)	0.624 (7)	0.630 (19)
427.9	100.	100.	100.	100.0 (7)	100.	100.	100.	100.0 (8)
443.5	1.06 (2)	1.03 (8)	1.12 (5)	0.989 (23)		1.03 (1)	1.05 (11)	1.019 (29)
463.4	35.1 (8)	35.45 (84)	35.50 (7)	35.23 (14)	35.4 (9)	35.64 (10)	35.12 (18)	35.07 (28)
497.0			0.015 (3)	0.009 (8)		0.018 (3)	0.009 (1)	
600.6	60.4 (11)	59.3 (12)	60.50 (10)	59.54 (22)	60.95 (67)	59.70 (10)	59.22 (18)	59.09 (45)
606.6	16.6 (5)	16.25 (62)	17.2 (3)	16.94 (7)	16.97 (26)	16.98 (21)	16.92 (6)	16.70 (14)
635.9	38.7 (8)	37.7 (10)	39.1 (2)	37.87 (14)	37.47 (27)	38.78 (32)	38.32 (12)	37.52 (30) ^h
671.4	6.04 (16)	6.92 (14) ^f	5.9 (3)	6.039 (24)	5.65 (12)	5.97 (11)	6.03 (2)	6.05 (6)

Part 3 – Adopted relative and absolute values

Energy	Adopted	wtd. avg.	S _{int}	reduced- χ^2	σ_{ext}	σ_{LWM}	P _{γ} (%) × 0.2955 (24)	90Lo03 eval.	1999Ka26 eval.
19.9	0.0683 (16)	0.0683	0.0016	0.14			0.0202 (5)	0.068 (2)	0.069 (3)
35.5	19.6 (6) ⁱ	16.0	0.13	43	0.9	1.7	5.79 (18)	14.53 (35)	15.2 (10)
58.3		^e						0.091 (4)	0.05 (4)
109.3	0.231 (4)	0.2310	0.0036	1.3	0.0041		0.0683 (12)	0.233 (5)	
110.8	0.0037 (3)	0.00373	0.00017	3.6	0.00033		0.00109 (9)	0.0036 (6)	0.0035 (4)
117	0.890 (9)	0.890	0.006	2.5	0.009		0.263 (4)	1.03 (4)	0.887 (9)
172.6	0.65 (3)	0.649	0.007	4.6	0.014	0.031	0.192 (9)	0.75 (5)	0.646 (24)
176.3	23.09 (15)	23.09	0.09	2.6	0.15		6.82 (7)	23.06 (14)	23.11 (5)
178.7	0.116 (5)	0.116	0.002	5.0	0.005		0.0343 (15)	0.110 (9)	0.114 (8)
198.6	0.0448 (24)	0.0448	0.0024	0.9			0.0132 (7)	0.054 (11)	0.0432 (20)
204.1	1.06 (5)	1.061	0.007	4.6	0.015	0.047	0.313 (15)	1.105 (11)	1.070 (21)
208.1	0.833 (27)	0.833	0.006	2.3	0.009	0.027	0.246 (8)	0.808 (9)	0.837 (14)
227.9	0.443 (9)	0.443	0.005	0.5			0.131 (3)	0.437 (12)	0.443 (6)
315	0.0144 (9)	0.0144	0.0009	0.8			0.0043 (3)	0.0138 (9)	0.0136 (16)
321	1.409 (8)	1.409	0.008	0.9			0.416 (4)	1.40 (2)	1.404 (9)
380.4	5.145 (13)	5.145	0.012	1.2	0.013		1.520 (15)	5.13 (4)	5.124 (19)
408.1	0.617 (5)	0.617	0.005	0.7			0.182 (2)	0.611 (12)	0.623 (6)
427.9							29.55 (24)	100	100

Energy	Adopted	wtd. avg.	S _{int}	reduced- χ^2	σ_{ext}	σ_{LWM}	P _{γ} (%) \times 0.2955 (24)	90Lo03 eval.	1999Ka26 eval.
443.5	1.033 (7)	1.033	0.007	1.0			0.305 (4)	1.03 (2)	1.035 (6)
463.4	35.47 (4)	35.47	0.04	1.0			10.48 (9)	35.47 (5)	35.45 (10)
497	0.0109 (11)	0.0109	0.0007	2.4	0.0011		0.0032 (3)	0.013 (2)	0.014 (8)
600.6	60.1 (4)	60.07	0.05	6.0	0.13	0.43	17.76 (18)	60.36 (11)	59.62 (16)
606.6	16.997 (27)	19.997	0.027	1.0			5.02 (5)	17.03 (3)	16.83 (6)
635.9	38.31 (14)	38.31	0.05	4.7	0.11	0.14	11.32 (10)	38.36 (15)	37.9 (3)
671.4	6.036 (17)	6.036	0.014	1.5	0.017		1.783 (16)	6.06 (2)	6.049 (19)

^a All values from this reference omitted from analysis since 5 out of 8 were outliers in an initial averaging.

^b All values from this reference omitted from analysis since they do not have uncertainties.

^c All values from this reference omitted from analysis since 9 out of 19 were outliers in an initial averaging.

^d Uncertainty increased from 0.08 to 0.20 by evaluator.

^e No value adopted; data are very inconsistent, namely, 0.091, 0.093, and 0.004.

^f Omitted from average, outlier.

^g Uncertainty increased from 0.07 to 0.20 by evaluator.

^h Typographical error in reference.

ⁱ Equilibrium intensity deduced by evaluator from transition intensity balance.

^j Uncertainty increased in analysis to reduce relative weight to 50%.

Other γ rays have been reported in various papers, but have not been included in the scheme adopted here. For those from 1998Sa55 the energies and relative emission probabilities are listed here and for the other references only the energies are given. These lines are:

1968An15: 122.4, 489.8;

1968Se11: 105.8, 391.5;

1973Gu10: 81.8, 122.4;

1974II02: 81.8, 489.8;

1976Wa13: 146.1;

1979Pr08: 81.8, 122.1, 366.0, 402.0;

1983Si14: 642.1, 693.2, 729.8; and

1998Sa55: [I_γ]: 61.8 [0.0067 (27)]; 81.0 [0.017 (1)]; 132.8 [0.0029 (19)]; 209.3 [0.152 (9)]; 331.8 [0.0085 (8)]; 366.5 [0.027 (2)]; 401.9 [0.0221 (2)]; 489.7 [0.0046 (23)]; 491.2 [0.016 (8)]; 503.1 [0.013 (6)]; 538.6 [0.0047 (25)]; 617.4 [0.018 (2)]; and 652.8 [0.009 (3)].

The decay scheme normalization deduced here has assumed the sum of all the γ -ray transition probabilities (photons + conversion electrons) to the ground state and 35-keV level (not including that of the 35-keV γ ray) to be equal to 100%. The relative equilibrium intensity (0.231 (4)) of the 109-keV γ ray has been reduced by 5.7% in the calculation because of its apparent increase due to the 57-day half-life of the 144-keV isomer from where it decays. Also, its total M4 theoretical conversion coefficient of 363.7 has been reduced by 2.5% to 354.6 as recommended in 1990Ne01. This reduction is usually applied to theoretical M4 conversion coefficients evaluated for the Evaluated Nuclear Structure Data File (ENSDF). This procedure has produced a decay scheme normalization factor of 0.2955 (24). The resulting γ -ray emission intensities are given in the third from the last column of the table given above. The last two columns give the relative probabilities from the evaluations of 1990Lo03 and 1999Ka26. The agreement is very good except for the line at 35 keV, where evaluators have preferred to use a value deduced from a γ -ray probability balance. The relative equilibrium intensity of 19.6 (6) for the 35-keV γ ray has been obtained from a transition probability balance at the 35-keV level. Its absolute emission intensity is then 5.79 (18) %.

The γ ray at 109 keV depopulates the isomeric level at 144 keV (half-life of 58 days), so its intensity depends on any chemical separation and its grow-in time. It takes about 1 year for it to be in equilibrium with the other γ rays to within 1 %. The level at 35 keV is primarily fed from higher-lying levels, but 27% of the 35-keV γ -ray intensity comes via the isomeric level when it is at equilibrium. So, for a chemically separated source, it needs about 8 months grow-in to be at equilibrium at the 1% level.

The population of the isomer was measured to be 24.3 (3) % (1998Gr13) compared to the 22.9 (9) % calculated from this adopted scheme.

4.3 Conversion electrons

From the adopted γ -ray intensities, and the conversion coefficients, one obtains the following conversion electron emission probabilities:

γ energy (keV)	shell	electron energy	emission prob. (%)
19.80	L	14.86	0.184 (7)
	M	18.79	0.0368 (14)
	N	19.63	0.0077 (3)
35.49	K	3.675	70 (3)
	L	30.55	9.5 (4)
	M	34.48	1.9 (1)

γ energy (keV)	shell	electron energy	emission prob. (%)
	N	35.35	0.46 (2)
109.28	K	77.46	12.4 (5)
	L	104.33	9.2 (5)
	M	108.27	2.1 (1)
	N	109.11	0.45 (2)
116.96	K	85.14	0.0287 (11)
	L	112.02	0.00371 (15)
172.72	K	140.90	0.0248 (10)
	L	167.78	0.0032 (1)
176.31	K	144.50	0.95 (4)
	L	171.37	0.150 (6)
	M	175.30	0.031 (1)
178.84	K	147.03	0.0050 (8)
	L	173.90	0.0009 (3)
198.65	K	166.84	0.00161 (10)
204.14	K	172.32	0.0322 (19)
	L	199.19	0.0059 (4)
	M	203.13	0.00120 (7)
208.08	K	176.26	0.0192 (8)
	L	203.13	0.00248 (10)
227.89	K	196.08	0.0090 (15)
	L	222.95	0.0014 (5)
321.04	K	289.23	0.00284 (11)
380.45	K	348.64	0.0231 (9)
	L	375.51	0.0035 (1)
408.06	K	376.25	0.00232 (9)
427.87	K	396.06	0.35 (2)
	L	422.94	0.0450 (18)
	M	426.87	0.0090 (3)
443.56	K	411.74	0.00302 (12)

γ energy (keV)	shell	electron energy	emission prob. (%)
463.36	K	431.55	0.090 (4)
	L	458.43	0.0128 (5)
	M	462.36	0.0026 (1)
600.60	K	568.78	0.074 (3)
	L	595.66	0.0101 (4)
	M	599.59	0.0020 (1)
606.72	K	574.90	0.0206 (8)
	L	601.77	0.0028 (1)
635.95	K	604.14	0.0509 (20)
	L	631.01	0.0063 (2)
671.44	K	639.62	0.00564 (22)
	L	666.50	0.0008

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¹³⁷Cs - Comments on evaluation of decay data by R.G. Helmer and V.P. Chechev

This evaluation was completed by R.G. Helmer in September 1996 with minor editing done in February 1998. Updating ¹³⁷Cs half-life and editing were done by V.P. Chechev in February 2006. The literature available by February 2006 was included.

1 Decay Scheme

There are as many as 2 supposed excited levels in ¹³⁷Ba below the decay energy that have not been reported in the ¹³⁷Cs decay and observed only in ¹³⁶Ba(d, p)-reaction (1997Tu04 evaluation). Since the possible 907 and 1044 levels do not have J^π assignments, and the de-exciting γ rays have not been reported, arguments about their feeding can not be made.

The decay scheme is internally consistent and essentially complete since the total decay energy computed by RADLIST is 1174 (3) keV compared to the Q value of 1175.63 (17) keV, a difference of 1.8 (28) keV.

The J^π values and half-lives of the excited levels in ¹³⁷Ba are from the evaluation of 1997Tu04.

2 Nuclear Data

Q value is from 2003Au03.

The experimental ¹³⁷Cs half-life values available are, in days (values published in years have been converted to days):

12053 (1096)	1951FIAA,	omitted from analysis
10957 (146)	1955Br06,	omitted from analysis
9715 (146)	1955Wi21,	omitted from analysis
10446 (+73-37)	1958MoZY,	omitted from analysis
11103 (146)	1961Fa03	
10592 (365)	1961Gl08	
10994 (256)	1962Fl09	
10840 (18)	1963Go03	
10665 (110)	1963Ri02	
10738 (66)	1964Co35	
10921 (183)	1965Fl01	
11286 (256)	1965Fl01	
11220 (47)	1965Le25	
11030 (110)	1966Re13,	replaced by 1972Em01
11041 (58)	1968Re04,	replaced by 1972Em01
11191 (157)	1970Ha32	
10921 (16)	1970Wa19,	replaced by 1983Wa26
11023 (37)	1972Em01	
11034 (29)	1973Co39	
11020.8 (41)	1973Di01	
10906 (33)	1978Gr08	
11009 (11)	1980Ho17	
10449 (147)	1980RuZX,	replaced by 1990Ma15
10678 (140)	1980RuZY,	replaced by 1990Ma15

10678 (140)	1982RuZV,	replaced by 1990Ma15
11206 (7)	1982HoZJ,	replaced by 1992Un01
10921 (19)	1983Wa26	
10941 (7)	1989KoAA	
10967.8 (45)	1990Ma15	
10940.8 (69)	1992Go24	
11015 (20)	1992Un01,	replaced by 2002Un02
11018.3 (95)	2002Un02	
10970 (20)	2004Sc04	
10976 (30)	Adopted	

If the four values from before 1960 are omitted as well as replaced values, the data set for analysis includes 21 values. The large reduced- χ^2 value (16.3) indicates that these data are quite discrepant; therefore, the adopted value will depend on the method of analysis.

Since no value in this data set contributes more than 50% of the relative weight, the Limitation of Relative Statistical Weight (LRSW) method does not adjust any of the input uncertainties; however, it may expand the final uncertainty to include the more precise value. The Normalized Residual (NORM, 1994Ka08) and RAJEVAL (1992Ra08) methods adjust the input uncertainties for the more discrepant values.

In 1997-1998 R.G. Helmer chose the Normalized Residual (NR) analysis for obtaining the recommended half-life value of 10964(9). That choice was based on a desire for reducing a large relative weight of the value from 1973Di01 and its big contribution to χ^2 value and also to avoid an expansion of the final uncertainty by use of the LRSW analysis. It was stated that the low evaluation result met the tendency of the last measurements (by 1992) and evaluation results to be lower. (Details of Helmer's analysis can be found in the book of 1999BeAA).

The updated NIST value, obtained as a result of continued measurements of six sources (2002Un02), changes the situation. This high value with a small uncertainty (half of that in 1992Un01) has shown that the discrepancy among the most recent and accurate measurements is still kept. Therefore, a small uncertainty of the evaluation result seems to be unrealistic.

Thus, at present we can use the LRSW analysis as one of the methods for the evaluation of the ¹³⁷Cs half-life.

The weighted average of the twenty one values is 10981.8, with an internal uncertainty of 2.3, a reduced χ^2 of 16.3, and an external uncertainty of 9.5. The unweighted average is 10967(37). The LWEIGHT computer program using the LRSW analysis has chosen the weighted average and expanded the final uncertainty to 39 so range includes the most precise value of 11020.8. Hence, use of the LRSW analysis leads to the evaluation of 10982(39) days for the ¹³⁷Cs half-life.

This evaluation agrees well with the recent independent evaluations. Woods and Collins (2004Wo02) used 11 experimental values since 1968 and recommended the value of 10990(40) days by similar evaluation technique. Helene and Vanin (2002He06) presented in their paper a very promising statistical procedure (BOOTSTRAP method) to deduce a best value and its standard deviation for a discrepant set of data. They used 19 experimental ¹³⁷Cs half-life values and obtained the evaluation result as 10987(30) days.

The NORM and RAJEVAL statistical procedures lead to the evaluation results of 10962(7) and 10971(6) days, with the small uncertainties. The Bayesian procedures (BAYS and MBAYS, 1994Ka08) give the equal result of 10982(10) days. Thus, different methods of statistical analysis have led to discrepant results. In such a way the best (the less worst ?) choice is derived from the BOOTSTRAP method. It gives an intermediate result (calculation of Helene and Vanin, 2006) between the unadjusted weighted mean and the adjusted values from different procedures and its uncertainty encompasses all the statistical results.

The adopted value of the ¹³⁷Cs half-life is **10976(30) days, or 30.05(8) years.**

2.1 Beta - Transitions

The emission probability (in %) of the β transition to the ground state has been measured as follows:

4.8 (3)	1957Ri41,	σ increased to 0.6
7.6 (8)	1958Yo01	
6.5 (2)	1962Da05,	σ increased to 0.6
4.8 (10)	1965Me03	
6.0 (5)	1966Hs02	
5.4 (3)	1969Ha05	
6.4 (5)	1978Gr09	
5.57 (7)	1983Be18	
5.69 (19)	Value from LRSW analysis	
5.64 (28)	Adopted value from sect. 4.2	

The uncertainties for early values of 1957Ri41 and 1962Da05 were increased by the evaluator to 0.6 to make them comparable with those of the values measured in the 1966 - 1978 period.

The LRSW analysis gives an internal uncertainty of 0.14, a reduced- χ^2 value of 2.03, and an external uncertainty of 0.19. In this analysis the uncertainty of the 1983Be18 value was increased from 0.07 to 0.19 in order to reduce its relative weight from 78% to 50%.

The average β energies and log ft values have been calculated using the LOGFT computer program.

The shape of the β spectra has been measured by 1983Be18, 1978Ch22, 1978Gr09, 1969Sc23, and 1966Hs02, which is useful in the determination of the relative β branch intensities.

The very detailed treatment of the expression for the shape of the β spectrum for the 2nd forbidden transition to the ground state argues that the measurement of 1983Be18 should replace all of the previous values. If this were done the $P_{\beta}(0)$ would decrease by 0.12% and $P_{\beta}(662)$ would increase by this amount. The $P_{\gamma}(662)$ would then increase by about 0.08%. However, the value of 1983Be18 has only been allowed to contribute 50% of the relative weight, as is our common practice. It should also be noted that this paper has additional influence since its data are also used in determining the $\alpha_T(662)$ value that is used in the calculation of $P_{\gamma}(662)$.

The adopted value $P_{\beta}(662)$ has been computed from the final adopted $P_{\gamma}(662)$ value. [The uncertainty has increased due to the inclusion of the uncertainty in $\alpha_T(662)$ twice.]

2.2 Gamma Transitions

The adopted $\alpha_T(662)$ value of 0.1102 (19) is from a LRSW analysis of the 5 measured values recommended in the 1985HaZA evaluation, except that the value of 1983Be18 is used in place of value of 1978Ch22; these values are 0.1100 (11) (1965Me03), 0.1121 (5) (1969Ha05), 0.1105 (10) (1973LeZJ), 0.1100 (6) (1975Go28), and 0.1083 (5) (1983Be18, where the uncertainty has been increased to match the lowest other value). For this average, internal uncertainty = 0.0003, the reduced- χ^2 = 7.3, and the external uncertainty = 0.0008. The final uncertainty was increased by the LRSW analysis from 0.0008 to 0.0019 to include the 2 most precise values. Due to the large discrepancies among the 12 measured α values reported, 1985HaZA chose not to recommend any value.

The theoretical α_T value interpolated from the tables of 1978Ro21 is 0.1143 34; but 1990Ne01 has suggested that the α_T values for M4's from 1978Ro21 should be multiplied by 0.975 which gives 0.1114; this agrees with the adopted value to 1.1% which is much smaller than the uncertainty in either value. The theoretical total ICC value interpolated from the tables of 1993Ba60 $\alpha_T(662)=0.1116$.

Other measurements of α_T listed in 1985HaZA include 0.114 (2) (1957Ri41), 0.114 (30) (1962Da05), 0.109 (20) (1963Bo31), 0.1167 (15) (1965Pa17), 0.112 (11) (1965Ra12), 0.1092 (8) (1978Ch22), and 0.114 (3) (1978Gr09).

The adopted value $\alpha_K(662)$ of 0.0896 (15) is from the LRSW analysis of the 4 values recommended in the 1985HaZA evaluation, except for the value of 1983Be18 which is used in place of that from 1978Ch22; these values are 0.0894 (10) (1965Me03), 0.0916 (4) (1969Ha05), 0.0901 (9) (1973LeZJ), and 0.0881 (2) (1983Be18). The LRSW analysis increases the uncertainty of the 1983Be18 value from 0.0002 to 0.00034 to reduce its relative weight from 75% to 50%. For this average, the internal uncertainty = 0.0002, the reduced- $\chi^2 = 14.8$, and the external uncertainty = 0.0009. The final uncertainty was increased by the LRSW analysis from 0.0009 to 0.0015 to include the most precise value.

The theoretical value $\alpha_K(662)$ interpolated from the tables of 1978Ro21 is 0.0929 28; but 1990Ne01 has suggested that the α_K values for M4's from 1978Ro21 should be multiplied by 0.975 which gives 0.0906; this agrees with the adopted value to 1.1% which is much smaller than the uncertainty in either value. The theoretical $\alpha_K(662)$ value interpolated from the tables of 1993Ba60 $\alpha_K(662)=0.0907$.

Other measured values of α_K listed in 1985HaZA are 0.097 (3) (1951Wa19), 0.095 (5) (1952He33), 0.11 (1) (1953Do31), 0.096 (5) (1954AZ01), 0.095 (8) (1957Mc34), 0.093 (1957Ri41), 0.092 (6) (1959Wa17), 0.0976 (55) (1958Yo01), 0.093 (6) (1959Hu23), 0.093 (6) (1960De17), 0.095 (4) (1961Hu12), 0.093 (3) (1962Da05), 0.0957 (10) (1965Pa17), 0.092 (9) (1965Ra12), 0.093 (7) (1966Hs01), 0.094 (5) (1966Hu02), 0.093 (9) (1967Ba80), 0.0925 (27) (1967HaZX), 0.0922 (22) (1973Wi10), 0.0901 (10) (1971BrAA), 0.0888 (70) (1978Ch22), and 0.093 (3) (1978Gr09).

3 Atomic Data

The data are from Schönfeld and Janßen (1996Sc06).

3.1 X Radiations

The data are from Schönfeld and Janßen (1996Sc06).

3.2 Auger Electrons

The data are from Schönfeld and Janßen (1996Sc06).

4 Radiation Emissions

4.1 Electron Emission

The β^- data are from RADLIST or LOGFT. The Auger and conversion electron data are from Schönfeld (1996Sc06) calculations. For comparison, these emission probabilities and those from RADLIST (with the atomic data from Schönfeld) are:

Electrons per decay

	Schönfeld	RADLIST
L Auger	0.0728 (12)	0.0728 (22)
K Auger	0.0076 (4)	0.0076 (3)
K-662	0.07644	0.076 (3)
L-662	0.01387	0.0142 (6)

4.2 Photon Emissions

The 662-keV γ -ray energy is from 2000He14 and that for the 283-keV γ is from 1997WaZZ, but more precise values of 283.46 6 and 283.53 4 are available from (n,n' γ) studies.

The intensity of the 662-keV γ ray has been deduced in two ways, (1) the ratio of the measured γ emission

rate and the measured source decay rate and (2) from the probability of β^- decay to the 662-keV level and α_T (662). These two values are independent as long as they involve independent measurements. Of the many papers that quote P_γ values, several are listed in section 2.1 as giving $P_{\beta^-}(0)$ values and are not included here. References 1965Me03 and 1978ChZZ have been replaced by 1978MeZM and 1983Be18, respectively. This leaves the following three values of $P_\gamma(662)$ to consider:

85.3 (10)	1973LeZJ
86.0 (9)	1975Go28
84.7 (7)	1978MeZM
85.2 (5)	Weighted average with reduced- $\chi^2 = 0.65$

[It should be noted that in the evaluation of 1991BaZS the value of 1973LeZJ is quoted as 0.8456 (8), which is the value from 1978Ch22. The evaluation of 1997Tu04 adopts the 1991BaZS result and repeats this error.]

The second value of $P_\gamma(662)$ comes from the average $P_{\beta^-}(0) = 5.69\%$ (19) in section 2.1 and the $\alpha_T(662) = 0.1102$ (19) in section 2.2, $P_{\beta^-}(662)/[1.0+\alpha(662)] = 84.95\%$ (22). Then, the adopted value is taken to be the weighted average of the values 84.95% (22) and 85.2% (5) which is 84.99% (20).

The decay of ¹³⁷Cs to the first excited level in ¹³⁷Ba at 283 keV was observed in 1996Bi23 and 1997WaZZ. The γ -ray intensity relative to that of the 662-keV γ ray is 0.00053 (14) (1996Bi23) and 0.00061 (10) (1997WaZZ) which gives an average of 0.00058 (8) and a corresponding transition intensity of 0.00061 (8).

The final P_{β^-} values are adjusted to be in agreement with this result and are $P_{\beta^-}(662) = 94.36\%$ (28) and $P_{\beta^-}(0) = 5.64\%$ (28). [The uncertainties here are overestimated because the contribution from $\alpha_T(662)$ has been included twice.]

The X-ray emission probabilities are from the γ -ray emission probability, the internal-conversion coefficients, and the atomic data of 1996Sc06. The difference between the Schönfeld values given and the RADLIST values are within the uncertainties:

	Photons per decay	
	Schönfeld	RADLIST
$K_{\alpha 2}$	0.0195 (4)	0.0195 (7)
$K_{\alpha 1}$	0.0358 (7)	0.0359 (13)
K_β	0.0132 (3)	0.0132 (5)
Total K	0.0685 (13)	0.0686 (16)

Double-decay processes which might occur in lieu of the 662-keV γ ray have been studied; two γ 's (1960Be20, 1992BaAA, 1993Ba46); a K shell electron plus a γ (1969Lj01, 1971Lj01); and two electrons (1971Lj02, 1971Po04). The paper of 1993Ba46 suggests an upper limit of the ratio of 2 γ emission to 1 γ emission of 5.10^{-7} .

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**¹⁵³Sm - Comments on evaluation of decay data
by M.M. Bé, R. G. Helmer and E. Schönfeld**

First evaluation was done in 2001 by R.G. Helmer and E. Schönfeld, it has been updated in June 2005, including new half-life and gamma intensity values.

1 Decay Scheme

There are many levels in ¹⁵³Eu below the decay energy, so other levels may be weakly populated in this decay.

2 Nuclear Data

The Q value is from Audi and Wapstra 2003 (2003Au03). Level energy, spin and parity data are from 1998He06.

The half-life values available are, in hours:

1942Ku03	47	1	as quoted in 1990Le13
1946Mi06	46		as quoted in 1990Le13
1952Ru10	46.5	1	as quoted in 1990Le13
1954Le08	47	0.3	as quoted in 1990Le13
1958Co76	47.1	0.1	
1958Gu09	46.7	1.6	
1960Wi10	45	8	outlier
1961Gr18	46.2	0.1	
1961Wy01	46.8	0.1	
1962Ca24	47.1	0.1	
1963Ho15	46.5	0.5	
1970Ch09	46.75	0.09	
1971Ba28	46.44	0.08	
1987Co04	46.27	0.01	superseded by 1992Un01
1989Ab05	46.70	0.05	
1989Po21	45.6	1.6	outlier
1992Un01	46.2853	0.0014	
1998Bo18	46.285	0.004	
1999Sc12	46.274	0.007	superseded by 2004Sc
2004Sc04	46.281	0.007	<i>Corrected value and uncertainty</i>
Adopted	46.2851	0.0013	or 1.92855 (5) d

A mistake appears in the value of the Sm-153 half-life published by 2004Sc04 in Applied Radiation Isotopes 60 (2004) 317 ; after discussion with the author the correct value is 1.92838 (29) d instead of 1.9284 (29) d.

Data are very discrepant, ranging from 46.281 (7) to two values of 47.1 (1), a difference of about 8 σ .

The Limitation of Relative Statistical Weight, LRSW, analysis (1985ZiZY, 1992Ra08), with the Lweight 3 program, shows that the values from 1960Wi10 and 1989Po21 are outlier due to Chauvenet's criterion, the reduced- χ^2 is 18.9 and the uncertainty of 1992Un01 value is increased to 0.0034 to reduce its weight to 50 %. The weighted mean is 46.2874 with a σ_{int} of 0.0024 and a σ_{ext} of 0.011. Then, the program recommends

the unweighted mean and expands the uncertainty to include the most precise value, this leads to a value of 46.64 (36) h.

The average of the measured values has decreased with time and the last three unreplaced values, which are from metrology laboratories, are among the lowest values and they are consistent. The weighted average of these three values is 46.2851 with a σ_{int} of 0.0013, a reduced- χ^2 of 0.18, and a σ_{ext} of 0.0006. This weighted average and the internal uncertainty are adopted.

2.1 β^- Transitions

The probabilities for the β^- branches are primarily from the intensity balances from the γ -ray transition probabilities for all levels including the ground state. This is possible because one has measurements of the absolute emission probabilities for the 69- and 103-keV γ -rays (1987Co04, 1998Bo18, 1999Sc12, 2006Le).

The measured β^- probabilities (in %) from the decomposition of the β^- spectra are:

Level (keV)	Values (%)
0	15 (1952Ba49), 20 (1954Gr19), 21 (1954Le08), 20 (1955Ma62), 22 (1956Du31), 20 (1957Jo24), and 20 (1958Co76) compared to the adopted value of 19.5(15) %.
103	67 (1950Hi17), 35 (1952Ba49), 49 (1954Gr19), 70 (1954Le08), 35 (1955Ma62), 38 (1956Du31), 65 (1957Jo24), and 40 (1958Co76) which have an average of 50(14) compared to the adopted value of 49.2(17)% from the probability balance.
172	50 (1952Ba49), 30 (1954Gr19), 43 (1955Ma62), 40 (1956Du31), 15 (1957Jo24), and 40 (1958Co76) which have an average of 36(11) compared to the adopted value of 30.4(8)% from the probability balance.

2.2 Gamma Transitions

The energies and multiplicities are from the adopted gamma data in Nuclear Data Sheets (1998He06) and they are based on the internal-conversion electron data of 1961Mo07, 1962Su01, 1969Sm04, and 1970PaZI. Gamma transition probabilities are deduced from the gamma emission intensities and the conversion electron coefficients interpolated from the tables of Band *et al.* (2002Ba85).

The 19-keV gamma transition probability is deduced from the probability balance at the 83-keV level.

3 Atomic Data

The fluorescence yields and K x-ray relative intensities are from 1996Sc06.

4 Emissions

4.1 Electron Emission

Data were computed by EMISSION for the Auger electrons and with LOGFT for the average β^- energies.

4.2 Photon Emission

From the evaluation 2000He14, the curved-crystal spectrometer data for the decay of ^{153}Sm and ^{153}Gd give the energies for the γ -rays of 69, 75, 83, 89, 97, 103, and 172 keV on a scale on which the strong line from the decay of ^{198}Au is 411.80205(17). The γ -ray energies from the (n, γ) study of 1970Mu04 have been adjusted to this energy scale to provide values at 54, 68, 96, 118, 151, 166, and 172 keV. The values for 14 and 19 keV are from level energy differences.

The other γ -ray energies are from the data in the following table 1.

Table 1: Gamma-ray energies

1969Un03	1985Ab08	1969Pa03	Adopted	
412.05 (20)	412.26 (30)	411.9 (1)	412.05 (20)	doubly placed
424.38 (20)	424.79 (32)	424.2 (2)	424.4 (3)	
	431.65 (10)			
436.83 (20)	437.10 (30)	436.7 (2)	436.9 (3)	
	443.24 (45)		443.2 (5)	
		462.0 (3)	462.0 (3)	
463.67 (15)	463.93 (35)	463.4 (2)	463.6 (2)	
485.03 (20)	485.12 (40)	484.5 (2)	485.0 (2)	
	487.75 (23)		487.75 (23)	
509.11 (15)	510.36 (35)	509.0 (1)	509.15 (20)	
521.28 (15)	521.62 (26)	521.1 (1)	521.30 (25)	
		523.8 (6)		
531.38 (15)	531.43 (34)	531.6 (3)	531.40 (15)	
533.34 (15)	533.17 (25)	533.1 (1)	533.2 (2)	
539.03 (10)	539.10 (20)	539.2 (3)	539.1 (2)	
542.60 (20)	543.01 (45)	542.7 (6)	542.7 (2)	
545.75 (15)	545.68 (42)		545.75 (15)	
554.94 (10)	554.73 (37)	555.0 (1)	554.94 (10)	
	555.71 (15)			
574.01 (30)	574.32 (51)		574.1 (3)	
578.66 (15)	578.94 (30)	578.8 (1)	578.75 (20)	
584.49 (20)	584.67 (32)	584.8 (5)	584.55 (20)	
587.47 (20)	587.73 (22)	587.7 (6)	587.60 (25)	
	589.3			
590.96 (20)	591.03 (21)	590.7 (6)	590.96 (20)	
596.72 (15)	596.29 (30)	596.9 (2)	596.7 (2)	
598.4 (3)	598.13 (30)		598.3 (3)	doubly placed
603.39 (15)	604.04 (26)	603.5 (2)	603.6 (4)	doubly placed
609.22 (10)	610.21 (42)	609.4 (1)	609.5 (3)	doubly placed
		612 (1)		
615.41 (20)	616.28 (22)	615.5 (6)	615.8 (4)	doubly placed
617.71 (20)	618.07 (24)	618.0 (6)	617.9 (3)	
	623.73 (24)			
630.70 (30)	630.33 (26)	630 (1)	630.5 (4)	
634.61 (30)	634.92 (32)		634.8 (3)	
636.45 (25)	636.73 (30)	636.4 (2)	636.5 (2)	
657.55 (25)	657.68 (25)	657.4 (4)	657.55 (25)	doubly placed
		662.4 (6)	662.4 (6)	
676.9 (5)	677.09 (30)	676 (1)	677.0 (3)	
		682.0 (6)	682.0 (6)	
685.6 (3)	686.64 (21)	685.9 (3)	686.0 (4)	
694.4 (4)	694.02 (25)	694 (1)	694.1 (3)	
701.5 (4)	702.08 (24)	701.7 (10)	701.8 (4)	
706.2 (4)	707.29 (28)	706 (1)	706.8 (5)	
713.6 (3)	713.98 (22)	714.1 (6)	713.9 (3)	
718.5 (4)	719.26 (28)	719.1 (6)	719.0 (4)	
760.2 (3)	760.92 (38)	760.3 (6)	760.5 (4)	
	763.8	763.8 (6)	763.8 (6)	

For the relative γ -ray emission probabilities, the data listed in Table 2 were available. The values of 1969Un03 and 1985Ab08 were not listed since they do not have individual uncertainties and those of 1969Sm04 were not used because the ¹⁵³Sm was just a background in an (n, γ) study.

Some gamma emissions with weak intensities and reported by only one or two authors are not listed in Table 2, they are : 54.1 ; 68.2 ; 96.8 ; 118.1 ; 166.5 ; 487.7 ; 574.1 ; 630.5 ; 677.0 ; 682.0 ; 694.1 ; 701.8 ; 706.8 ; 719.0 ; 763.8 keV.

The emission intensities assigned to each of the components of the doublets at 598, 603, 609, 615 and 657-keV are equal, as there is no information on how to split the total intensity for the doublet.

For all cases with three or more values, the weighted average is computed by the Limitation of Relative Statistical Weight method. If the reduced- χ^2 is $>$ critical χ^2 and one value has a relative weight $>$ 50%, the uncertainty of this value is increased in order to reduce the relative weight to 50% and this is noted in the table. If the reduced- χ^2 is \leq critical χ^2 , no such change is made, but if the relative weight is over 70% this is noted. For all weighted averages the internal uncertainty is given, and if the reduced- χ^2 is $>$ 1.0 the external uncertainty is also given. In some cases the LRSW method expands the uncertainty to include the most precise value; this uncertainty is given as σ_{LRSW} . The adopted values are given in the last row.

The relative γ -ray emission probabilities adopted in Table 2 were normalized to γ 's per 100 decays by consideration of the absolute emission probabilities measured by 1987Co04, 1998Bo18, 1999Sc12 and 2006Le. Of the five γ rays that are given in all papers, the three strongest, at 69, 97, and 103 keV, were considered. Since the weighted average of the data for the 97-keV γ -ray gave a reduced- χ^2 value of 20, it was omitted.

For the 69-keV γ -ray, the weighted average of the four values is 4.668 γ 's per 100 decays with an internal uncertainty of 0.026, a reduced- χ^2 of 3.1, and an external uncertainty of 0.047. The latter uncertainty was adopted.

For the 103-keV γ ray, the weighted average of the four values is 29.19 γ 's per 100 decays with an internal uncertainty of 0.12, a reduced- χ^2 of 1.8, and an external uncertainty of 0.16. The value of 29.19 (16) was adopted and used to convert the relative values into absolute values as listed in the latest line in Table 2.

Table 3. Absolute emission intensities

	103.18 keV		69.6 keV		97.4 keV	
	I %	Uc	I %	Uc	I %	Uc
1987Co04	29.82	0.36	4.85	0.07	0.847	0.011
1998Bo18	28.5	0.5	4.67	0.05	0.794	0.017
1999Sc12	29.23	0.18	4.65	0.05	0.755	0.007
2006Le	29.07	0.2	4.59	0.05	0.738	0.013
chi2	1.8		3.1		19.7	
WM	29.19	0.16	4.668	0.047	0.778	0.024

X-ray emissions

The measured x-ray emission intensities (in %) are compared with the calculated values deduced from the decay scheme :

XK	K α 2	K α 1	K α	K β ' 1	K β ' 2	K β
1992Ch44			44.43 1.31	8.55 0.29	2.23 0.09	
1999Sc12	16.27 0.18	29.4 0.4	45.7 0.5	9.26 0.12	2.444 0.027	11.7 0.13
2006Le	16.03 0.27	28.53 0.20	44.56 0.3	9.03 0.07	2.37 0.06	11.4 0.12
LWM	16.20 0.15	28.70 0.35	44.85 0.35	9.07 0.10	2.417 0.041	11.54 0.15
Calculated	16.6 0.4	30.0 0.7	46.6 1.1	9.45 0.25	2.44 0.08	11.9 0.3

XL	LI	L α	L β	L γ
1992Ch44	0.190 0.018	4.90 0.26	4.20 0.26	0.651 0.044
1999Sc12	0.216 0.011	4.94 0.11	4.26 0.09	0.615 0.01
2006Le	0.245 0.012	5.06 0.15	4.33 0.13	0.0628 0.022
LWM	0.222 0.014	4.97 0.08	4.28 0.07	0.40 0.22
Calculated	0.213 0.007	5.20 0.15	4.63 0.10	0.755 0.017

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Table 2 : gamma relative and absolute emission intensities (1)

keV	69		75		83		89		97		151		172		412 ^(a)	
1964Al09	1730 ^(o)	100	61	4	75	4	58	3	263	13	3.2	0.5	21 ^(o)	2		
1966B106															0.64	0.2
1969Pa03											5.1 ^(o)	1.6	24	5	0.73	0.13
1974HeYW	1620	140	110 ^(o)	12	63	6	32	4	233	20	3	0.5	28	3	0.8	0.1
1987Co04	1626	21	117 ^(o)	5	68	4			284	4			27	0.4		
1992Ch44	1620	50	55	2	63	2	59	2	255	4	3.5	0.1	25	0.4	0.65	0.02
1998Bo18	1639	18	65	4	58	4			279	6			25.3	1.1		
1999Sc12	1591	17	80 ^(o)	7	72	4	53.4	2.4	258.3	2.4	3.93	0.21	24.5	0.24	0.65	0.04
2006Le	1579	17	61	7	69.8	3.4	37	8	253.9	4.5	3.47	0.21	25	0.6	0.38 ^(o)	0.05
Chi2	1.53		2.02		2.55		10.71		8.14		1.34		4.91		0.63	
Chi2 crit	3.02		3.79		2.80		3.32		2.80		3.32		2.80		3.32	
UWM:	1612.5		60.500		66.971		47.880		260.886		3.42		25.543		0.694	
WM:	1606.644		57.839		66.094		53.918		262.783		3.538		25.151		0.656	
Uc (int):	8.865		1.590		1.276		1.277		1.613		0.081		0.175		0.017	
Uc (ext):	10.967		2.258		2.038		4.181		4.603		0.093		0.388		0.014	
LWM :	1607	11	58	2.3	66.1	2	54	5	262.8	4.6	3.54	0.09	25.2	0.7	0.656	0.017
Abs	4.691	0.041	0.169	0.007	0.193	0.006	0.158	0.015	0.767	0.014	0.01033	0.00027	0.0736	0.0021	0.00191	0.00005

Table 2 : gamma relative and absolute emission intensities (2)

keV	424		436		443		462		463		485		509	
1964Al09														
1966B106	0.75	0.2	0.48	0.12					5.1	0.8	0.12	0.06	0.85	0.16
1969Pa03	0.73	0.13	0.5	0.1			0.5	0.1	4.7	0.4	0.12	0.06	0.61	0.2
1974HeYW	0.7	0.1	0.8 ^(o)	0.1					5.3	0.4			1	0.1
1987Co04														
1992Ch44	0.65	0.02	0.53	0.02	0.030	0.005	0.7	0.2	4.3	0.8	0.13	0.01	0.62	0.03 ^(U)
1998Bo18														
1999Sc12	0.62	0.04	0.57	0.03					4.34	0.06	0.12	0.03	0.63	0.06
2006Le	0.758	0.036	0.546	0.038	0.243	0.041			3.93	0.25			0.46	0.10
Chi2	1.80		0.42		13.49		0.80		2.03		0.05		3.61	
Chi2 crit	3.02		3.32		6.63		6.63		3.02		3.79		3.02	
UWM:	0.701		0.525		0.137		0.60		4.612		0.123		0.695	
WM:	0.669		0.541		0.137		0.540		4.349		0.129		0.651	
Uc (int):	0.016		0.015		0.029		0.089		0.057		0.009		0.030	
Uc (ext):	0.021		0.010		0.107		0.080		0.081		0.002		0.058	
LWM :	0.669	0.021	0.541	0.015	0.140	0.11	0.54	0.09	4.35	0.08	0.129	0.009	0.65	0.06
Abs	0.00195	0.00006	0.001579	0.000045	0.00041	0.00032	0.00158	0.00026	0.01270	0.00024	0.000377	0.000026	0.00190	0.00018

Table 2 : gamma relative and absolute emission intensities (3)

keV	521		531		533		539		542		545		554	
1964Al09														
1966B106	3.5 ^(o)	0.7	22.3	2	11.6	1	9.1	1.4					1.93	0.3
1969Pa03	2.5	0.9	23	3	8.8	2.5	8.2	2.5	0.6	0.5			1.6	0.13
1974HeYW	2.8 ^(o)	0.2	23.8	2	11.9	0.8	8.6	0.6	1.4 ^(o)	0.1	0.3	0.1	2	0.2
1987Co04														
1992Ch44	2.3	0.1	18.9	1.3	10.4	0.1	7.2	0.2	0.77	0.08	0.26	0.01 ^(U)	1.61	0.04
1998Bo18			19.3	2.1	9.8	2.1								
1999Sc12	2.31	0.04	18.37	0.21	10.02	0.09	7.04	0.09	0.75	0.06	0.41	0.17	1.62	0.03
2006Le	2.281	0.024	18.74	0.17	9.91	0.07	7.09	0.05	0.85	0.048	0.368	0.027	1.484	0.047
Chi2	0.15		2.38		4.04		1.84		0.69		2.91		2.35	
Chi2 crit	3.79		2.80		2.80		3.02		3.79		3.79		3.02	
UWM:	2.348		20.63		10.347		7.872		0.743		0.335		1.707	
WM:	2.289		18.646		10.066		7.094		0.803		0.312		1.595	
Uc (int):	0.020		0.13		0.048		0.043		0.034		0.018		0.021	
Uc (ext):	0.008		0.20		0.097		0.058		0.028		0.031		0.032	
LWM :	2.29	0.02	18.65	0.2	10.07	0.16	7.09	0.06	0.803	0.034	0.312	0.031	1.595	0.032
Abs	0.00668	0.00007	0.0544	0.0007	0.02939	0.00049	0.02070	0.00021	0.00234	0.00010	0.00091	0.00009	0.00466	0.00010

Table 2 : gamma relative and absolute emission intensities (4)

keV	578		584		587		590		596		598 ^(d)		603 ^(d)	
1964Al09														
1966B106	1.38	0.2	0.54 ^(o)	0.1					4.4 ^(o)	0.7			2	0.4
1969Pa03	1.15	0.23	0.45	0.15	0.1	0.1	0.45	0.15	4.2 ^(o)	0.6			1.8	0.3
1974HeYW	1.3	0.2	0.4	0.1	0.2	0.03	0.5	0.1	4.5 ^(o)	0.3	0.4	0.1	1.9	0.2
1987Co04														
1992Ch44	1.07	0.03	0.36	0.01	0.16	0.04	0.38	0.01	3.8	0.1	0.61	0.09	1.53	0.05
1998Bo18														
1999Sc12	1.17	0.03	0.352	0.027	0.161	0.027	0.421	0.027	3.56	0.1	0.70	0.03	1.49	0.03
2006Le	1	0.019	0.405	0.02	0.154	0.022	0.448	0.009 ^(U)	3.11	0.05 ^(U)	0.725	0.032	1.388	0.031
Chi2	5.19		1.20		0.52		6.38		17.69		3.50		3.26	
Chi2 crit	3.02		3.32		3.32		3.32		4.61		3.79		3.02	
UWM:	1.178		0.393		0.155		0.440		3.490		0.609		1.685	
WM:	1.063		0.368		0.165		0.417		3.395		0.693		1.462	
Uc (int):	0.015		0.008		0.014		0.007		0.050		0.021		0.020	
Uc (ext):	0.034		0.009		0.010		0.017		0.210		0.039		0.035	
LWM :	1.18	0.18	0.368	0.009	0.165	0.014	0.417	0.031	3.4	0.29	0.693	0.039	1.68	0.19
Abs	0.0034	0.0005	0.001074	0.000027	0.000482	0.000041	0.00122	0.00009	0.0099	0.0008	0.00202	0.00011	0.0049	0.0006

Table 2 : gamma relative and absolute emission intensities (5)

keV	609 ^(d)		615 ^(d)		618		634		636		657 ^(d)		662	
1964Al09														
1966B106	5.5	0.8	0.6 ^(o)	0.12					0.81	0.12	0.13	0.03		
1969Pa03	5.2	0.8	0.21	0.1	0.32	0.14			0.74	0.08	0.12	0.03	0.03	0.01
1974HeYW	5.1	0.4	0.3	0.1	0.3	0.1	0.20	0.03	0.7	0.1	0.1	0.03		
1987Co04														
1992Ch44	4.5	0.1	0.14	0.02	0.2	0.02	0.20	0.05	0.7	0.02	0.14	0.01	0.007	0.002
1998Bo18														
1999Sc12	4.04	0.14	0.233	0.024	0.304	0.027	0.15	0.03	0.595	0.027	0.14	0.024		
2006Le	4.59	0.20	0.159	0.020	0.213	0.022	0.168	0.011	0.65	0.06	0.112	0.009	0.197	0.040
Chi2	2.88		2.80		2.82		0.61		2.45		1.09		11.06	
Chi2 crit	3.02		3.32		3.32		3.79		3.02		3.02		4.61	
UWM:	4.822		0.208		0.267		0.180		0.699		0.124		0.078	
WM:	4.420		0.173		0.230		0.171		0.668		0.125		0.023	
Uc (int):	0.073		0.012		0.013		0.010		0.015		0.006		0.007	
Uc (ext):	0.125		0.020		0.022		0.007		0.023		0.006		0.023	
LWM :	4.42	0.12	0.173	0.020	0.230	0.022	0.171	0.01	0.668	0.023	0.125	0.006	0.023	0.023
Abs	0.01290	0.00036	0.00050	0.00006	0.00067	0.00006	0.000499	0.000029	0.00195	0.00007	0.000365	0.000018	0.00007	0.00007

Table 2 : gamma relative and absolute emission intensities (6)

keV	686		713		760	
1964Al09						
1966B106			0.11	0.03	0.013	0.004
1969Pa03	0.09	0.01	0.066	0.02	0.027	0.015
1974HeYW			0.1	0.03		
1987Co04						
1992Ch44	0.077	0.008	0.077	0.008	0.01	0.002
1998Bo18						
1999Sc12	0.072	0.021	0.09	0.04		
2006Le						
Chi2	0.62		0.53		0.81	
Chi2 crit	4.61		3.32		4.61	
UWM:	0.080		0.089		0.017	
WM:	0.081		0.079		0.011	
Uc (int):	0.006		0.007		0.002	
Uc (ext):	0.005		0.005		0.002	
LWM :	0.081	0.006	0.079	0.007	0.011	0.0018
Abs	0.000236	0.000018	0.000231	0.000020	0.000032	0.000005

^(u) Original uncertainty given, was increased in LRSW analysis to reduce the relative weight to 50%.

^(o) Omitted or outlier

^(a) γ is doubly placed, an undivided intensity is given

¹⁵⁹Gd - Comments on evaluation of decay data by R. G. Helmer

This evaluation was completed in 2004. The literature available by March 2005 was included.

1 Decay Scheme

¹⁵⁹Gd decays by β^- emission to levels in ¹⁵⁹Tb.

2 Nuclear Data

Q value is 970.5(7) from Audi et al. 2003 mass evaluation (2003Au03).

For the adopted decay scheme, the total radiation energy per decay is calculated to be 970(12) keV which agrees well with the decay energy of 970.5(7) keV from the 2003 mass evaluation (2003Au03), which confirms the internal consistency of this scheme.

The half-life values available are, in hours:

18.0	1948Kr03
18.0(2)	1949Bu01
18.0(3)	1960Wi10
18.56(8)	1966Da19
18.479(4)	1989Ab05

18.479(7) Adopted value

The weighted average of the last four values in the Limitation of Relative Statistical method, as implemented in the LWEIGHT code, is completely dominated by the value of 1989Ab05 which has 99.7% of the relative weight. The data of 1949Bu01 and 1960Wi10 contribute 2.8 to the reduced- χ^2 value of 3.1, but since this value is less than the critical reduced- χ^2 value of 3.8 used in LWEIGHT for four input values, the relative weight of the dominate input value is not reduced. The internal uncertainty for this average is 0.004 and the external uncertainty is 0.007, which is adopted.

2.1 β^- Transitions

The probabilities for the β^- branches are from the probability balances from the γ -ray transitions for the excited levels and from the measurement of 1975BaXG for the ground state. These values are:

Level (keV)	Value (%)
0	57.8(12)
58	29.6(12)
137	0.012(9)
348	0.315(4)
363	12.19(6)
580	0.0626(8)
617	0.0300(9)
674	0.00388(10)
854	0.0162(5)
891	0.0009(4)

The other measured values from 1975BaXG are 24(4) for the level at 58 keV and 13(2) for the levels at 348 and 363 keV.

2.2 g Transitions

The multiplicities are from the Adopted γ data in the Nuclear Data Sheets (2003He11). See sect. 4.2 for comments on the γ -ray and level energies and the normalization of relative photon emission probabilities to absolute values. The multiplicities are as follows:

() indicates a tentative assignment, based on experimental data;

[] indicates an assignment based on the spins and parities of the associated levels:

Levels and $J\pi$'s	γ energy (keV)	multiplicity	mixing ratio	%E2
58 5/2+ 0 3/2+	58	M1+E2	+0.119(2)	1.40(6)
137 7/2+ 58 5/2+	79	M1+E2	+0.126(8)	1.56(20)
0 3/2+	137	[E2]		
348 5/2+ 137 7/2+	210	[M1,E2]		
58 5/2+	290	[M1,E2]		
0 3/2+	348	M1+E2	+0.43(+10, -9)	16(6)
363 5/2- 137 7/2+	226	E1		
58 5/2+	305	E1		
0 3/2+	363	E1		
580 1/2+ 0 3/2+	580	[M1,E2]		
617 3/2+ 58 5/2+	559	M1+E2	0.67(+58, -1)	31(+30, -1)
0 3/2+	617	(M1)		
674 5/2+ 137 7/2+	536	(M1)		
58 5/2+	616	(M1)		
0 3/2+	674	(M1)		
854 (1/2-) 617 3/2+	237	[E1]		
580 1/2+	274	[E1]		
0 3/2+	854	[E1]		
891 (5/2-) 617 3/2+	273	[E1]		
137 7/2+	753	[E1]		

See section 4.2 for the γ -ray energies and emission probabilities.

3 Atomic Data

3.1 X rays and Auger electrons

The fluorescence yield data are from Schönfeld and Janßen (1996Sc06) and the EMISSION code. These give $\omega_K = 0.935(4)$, the average $\omega_L = 0.186(8)$, and $\eta_{KL} = 0.847(4)$.

The Auger electron emission intensities are from the EMISSION code and based on the adopted γ -ray emission probabilities and conversion coefficients. These values are KLL 0.94(7)%, KLX 0.49(4)%, and KXY 0.063(5)%.

4 Emissions

4.1 K x-rays

The K x-ray electron emission probabilities are from the EMISSIONS code and based on the adopted γ -ray emission probabilities and conversion coefficients.

4.2 Photon Emission

Values for the γ -ray energies are available from 1968Hi03, 1969Br05, and 1995Mo08. Any weighted average would be dominated by the values of 1995Mo08, so the values from the latter reference are adopted.

The γ -ray energies from these references are:

1968Hi03	1969Br05	1995Mo08
58.00(1)	58.00(5)	58.0000(22)
79.45(2)	79.52(2)	79.5132(27)
137.7(3)	137.4(2)	137.515(5)
210.8(3)	210.9(5)	210.783(3)
226.00(4)	226.2(2)	226.0406(18)
236.9(4)	237.5(2)	237.341(5)
		273.62(12)
274.2(6)	274.2(2)	274.163(19)
290.2(3)	290.3(2)	290.2865(25)
305.6(2)	305.5(2)	305.5492(20)
348.17(8)	348.1(2)	348.2807(18)
363.56(3)	363.3(2)	363.5430(18)
		479.84(6)
536.7(4)	536.8(2)	536.730(12)
559.9(3)	559.56(15)	559.623(6)
581.1(3)	580.84(15)	580.808(6)
	616.5(3)	616.233(18)
617.7(3)	617.7(2)	617.615(18)
	674.3(5)	674.26(5)
		753.74(6)
854.5(4)	854.9(2)	854.947(20)

For the relative γ -ray emission probabilities, the following data were used. All the values of 1965Fu14 are omitted since the normalization value of 100 has a 30% uncertainty.

g ray (keV)	1964Pe07	1965Fu14	1968Hi03	1969Br05	1985Da31	1994St05	1995Mo08	2001Ma01	Adopted	Reduced c ²
58			18.0(30)	21(2)	19.1(8)	22.7(4)	18.9(9)	20.7(3) ^{ac}	21.1(6)	6.2
79		0.44(8)	0.38(7)	0.38(4)	0.37(6)	0.36(2)	0.417(11)	0.388(14)	0.397(9)	1.52
137		0.10(3)	0.042(26)	0.06(1)	0.05(1)	0.05(1)	0.0550(13) ^f		0.0549(13)	0.25
210			0.090(35)	0.165(25)	0.16(3)	0.192(23)	0.178(4) ^c		0.170(12)	1.66
226			1.8(1)	1.96(10)	1.80(4)	1.92(10)	1.89(4)	1.83(1)	1.842(18)	0.99
237			0.055(36)	0.072(11)	0.059(12)	0.064(12)	0.0652(14) ^f		0.0653(14)	0.33
246					0.012(7)		< 0.0008			
269					0.013(9)		< 0.0004			
273		0.065(3) ^b	0.065(40) ^b	0.054(13) ^b	0.056(11) ^b	0.055(12) ^b	0.0065(25)		0.006(3)	
274							0.0478(25)		0.048(3)	
290			0.24(3)	0.28	0.23(5)	0.27(3)	0.275(5)	0.274(8)	0.274(4)	0.43
305			0.54(4)	0.55(4)	0.51(2)	0.52(2)	0.527(10)	0.527(9)	0.526(6)	0.25
348	2.0(3)		2.0(1)	2.00(15)	1.99(8)	2.04(10)	2.05(4)	1.99(1) ^{cc}	2.031(21)	1.86
363	≡ 100(5)	100(30)	100	100(5)	100	100	100	100	100	
371					0.006(4)		< 0.0003			
429					0.005(4)		< 0.0003			
536	0.07 (4)	< 0.02	0.018(12)	0.010(3)	0.018(9)	0.013(3)	0.0137(4) ^f		0.0136(4)	0.48
559	0.25(10)	0.23(4)	0.17(3)	0.20(2)	0.19(2)	0.19(1)	0.187(6)		0.188(5)	0.20
581	0.70(15)	0.5(2)	0.55(4)	0.57(4)	0.60(4)	0.57(2)	0.578(19)	0.581(5) ^f	0.588(5)	0.24
616	0.20(8) ^d	0.02(1)	0.009(6)	0.020(5)	0.016(6)	0.026(8)	0.0159(7) ^f		0.0160(7)	0.90
617		0.15(5)	0.13(4)	0.13(2)	0.15(3)	0.14(1)	0.134(5) ^f		0.135(4)	0.15
674				0.0034(10)	< 0.008	0.0034(13)	0.00263(20) ^f		0.00268(19)	0.044
753							0.00153(17)		0.00153(17)	
854		0.015(7)	0.014(8)	0.021(3)	0.020(6)	0.021(2)	0.0212(18)		0.0209(12)	0.20

^a Authors also give value of 20.1(8). The most precise value is adopted.

^b Value is for sum of 273 and 274 lines.

^c Authors also give value of 2.11(3), both values are included in the calculation of the average.

^d Value is for sum of 616 and 617 lines.

^e This uncertainty was increased in the averaging process to reduce the relative weight to 50%.

^f Value contributes over 70% of the relative weight in the calculation of the average, but since the input values are consistent this weight is not reduced.

These relative γ -ray emission probabilities have been scaled by 0.1178(5) to obtain absolute values based on the measured emission probability of 11.78(5)% from 2001Ma01.

5. Electron emissions

The internal-conversion electron emission probabilities are from the adopted γ -ray emission probabilities and the associated conversion coefficients. These values for the stronger lines are:

g-ray energy (keV)	shell, energy	emission probability (%)
58	K, 6.004	22.8(9)
	L, 49.292	3.86(16)
	M, 56.032	0.85(4)
	N+, 57.602	0.235(10)
79	K, 27.518	0.17(7)
	L, 70.805	0.0273(11)
	M, 77.546	0.00604(23)
	N+, 70.115	0.00167(5)
137	K, 85.519	0.00307(12)
	L, 128.807	0.00179(7)
210	K, 158.787	0.0036(11)
226	K, 174.045	0.00629(19)
290	K, 238.291	0.0024(8)
348	K, 296.285	0.0134(5)
	L, 339.573	0.00201(6)
363	K, 311.547	0.104(3)
	L, 354.835	0.0145(4)
	M, 361.576	0.00313(9)
581	K, 528.812	0.00084(25)

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²⁰³Pb - Comments on evaluation of decay data by V. Chisté and M. M. Bé

1 Decay Scheme

²⁰³Pb disintegrates by electron capture to ²⁰³Tl via excited levels. Spin and half-life of the 680-keV level are from the mass-chain evaluation of F. G. Kondev (2005Ko20).

2 Nuclear Data

The Q(EC) value is from the atomic mass adjustment of Audi et al. (2003Au03).

Experimental ²⁰³Pb half-life values (in hours) are given in Table 1:

Table 1: Experimental values of ²⁰³Pb half-life.

Reference	Experimental value (h)	Comments
K. Fajans (1941Fa04)	52,0 (5)	
J. R. Prescott (1954Pr04)	52 (1)	
A. A. Barlett (1958Bart)	52,1 (2)	
L. Persson (1961Pe12)	52,1 (2)	
G. A. Chackett (1971Ch54)	52,02 (10)	Original uncertainty increased (x 2) for missing details (systematic uncertainty).
H. Houtermans (1979Ho17)	51,88 (2)	
D. D. Hoppes (1982HoZJ)	51,92 (4)	Superseded by 2002Un02.
K. Lindenberg (2001Li17)	51,94 (1)	
M. P. Unterweger (2002Un02)	51,923 (37)	
Recommended value	51,929 (10)	$\chi^2 = 1,37$

The evaluators have chosen to take into account the eight values with associated uncertainty for the calculation. The original uncertainty given by Chackett (1971Ch54) has been multiplied by 2, in order to take into account the systematic uncertainties not considered by 1971Ch54. Then a weighted average of the eight values above has been calculated using LWEIGHT computer program (version 3). The largest contribution comes from the value of Lindenberg (2001Li17), amounting to 75 %.

The recommended value is the weighted average of 51,929 h, with an external uncertainty of 0,010 and a reduced χ^2 of 1,37.

Experimental 279-keV level half-life values (in ps) are given in Table 2.

Table 2: Experimental 279-keV level half-life.

Reference	Experimental value (ps)
R.E. Azuma (1955Az33)	300 (100)
E. E. Berlovich (1957Be57)	290 (30)
E. Bashandy (1960Ba16)	290 (20)
S. Gorodetzky (1960Go15)	283 (17)
B. Johansson (1960Jo15)	220 (30)
E.C. Pederson (1960Pe16)	282 (8)
A. Schwarzschild (1961Sc04)	281 (6)
J. de Boer (1962De14)	340 (3)
R. Rougny (1964Ro19)	283 (7)
J.C. Palathingal (1967Pa09)	280 (40)
Recommended value	282,3 (37)

The half-life weighted average has been calculated by the LWEIGHT program (version 3).

The evaluators have chosen to take into account for the calculation the ten experimental values shown in Table 2. The Azuma (1955Az33), Johansson (1960Jo15) and de Boer (1962De14) values were rejected by the LWEIGHT program, based on the Chauvenet's criterion, thus they were not used for averaging.

The recommended value is the weighted average of 282,3 ps, with an internal uncertainty of 3,7 and a reduced χ^2 of 0,05.

2.1 Electron Capture Transitions

The electron capture probabilities have been deduced from gamma-ray transition intensity imbalance for each level of the decay scheme.

P_K , P_L , P_M values have been calculated for 1st forbidden and 1st forbidden unique electron-capture transitions in the decay of ²⁰³Pb to the excited states in ²⁰³Tl using the LOGFT computer program.

2.2 g Transitions

Probabilities

The absolute transition probabilities have been deduced from the relative γ -ray emission intensities (see **5.2 Gamma ray emission**), the internal conversion coefficients and the normalization of the decay scheme to an absolute radiation intensity scale.

Multipolarity and internal conversion coefficients

Multipolarities of γ -ray transitions in decay of ²⁰³Tl are from 2005Ko20:

279-keV γ -ray : M1 + E2, with $\delta = +1,17$ (6)

401-keV γ -ray : M1 + E2, with $\delta = 0,030$ (3) (1965Ka02)

680-keV γ -ray : E2

The internal conversion coefficients (ICC's) for these γ -ray transitions have been calculated using the BRICC computer program, which interpolates the new values in 2006Ra03.

For the 279-keV γ -ray, the evaluators have chosen to follow the recommendations of H. H. Hansen (1985HaZA). The 279-keV γ -ray transition is M1(1 -forbidden) + E2. It takes place between the $d_{3/2}$ and $s_{1/2}$ shell model proton configurations. Thus nuclear penetration is significant (see 1979Ha21). The forbidness applies only to the M1 component. Therefore, the evaluators have chosen to use experimental values for α . The experimental data set given by 1985HaZA to determine α_T and α_K are included in Tables 3 and 4, respectively.

Table 3: Experimental values of α_T used by 1985HaZA.

Reference	Original value	Revised by Hansen (1985HaZA) and used value.	Comments
1960Pe22	0,227 (8)		Not used.
1962Ta06	0,2262 (19)	0,2273 (24)	The authors revised their values.
1965Ra12	0,210 (30)		Not used.
1965Wa13	0,222 (15)		Not used.
1971WaYL	0,2267 (7) 0,2240 (9)	0,2267 (16)	The author gives 2 results without explaining the reason of the discrepancy. Hansen has chosen the higher one, with the sum of their uncertainties quoted for both results.
1974Ha29	0,2279 (24)	0,2279 (24)	
2000Sc05	0,2250 (12)	0,2250 (12)	
Recommended value		0,2261 (8)	$\chi^2 = 0,60$.

Hansen's study provides, together with three experimental values, an α_T average of 0,2271 (12). The evaluators have included the most recent measurement of 2000Sc05 (0,2250 (12)) in their evaluation and, with four experimental values (1962Ta06, 1972WaYL, 1974Ha29, 2000Sc05), a weighted average has been calculated using the LWEIGHT computer program (version 3). The recommended value is the weighted average of 0,2261, with an internal uncertainty of 0,0008 and a reduced χ^2 of 0,60.

Table 4: Experimental values of α_K and α_L .

Reference	Original value of α_K	Revised by Hansen (1985HaZA) and used value.	Original value of α_L (10^{-2})	Comments
1952He18	0,23 (10)			Not used.
1954Th17	0,154 (15)			Not used.
1954Wa12	0,15 (1) 0,141 (15)			Not used.
1955Do12	0,147 (2)			Not used.
1955Ma40	0,205 (20)			Not used.
1956No26	0,159 (4)			Not used.
1956Of03	0,150 (10)		4,8 (3)	Not used.
1956Wa30	0,164 (5)	0,164 (5)	4,90 (17)	
1956Wo09	0,130 (10)			Not used.
1958Ni28	0,163 (3)	0,163 (3)	4,87 (12)	
1960Pe22	0,163 (6)	0,163 (6)		
1960Ra04	0,195 (14)			Not used.
1960St21	0,160 (15)			Not used.
1961Hu15	0,1750 (36)			Not used.
1961Su10	0,164 (4)	0,164 (4)	4,49 (34)	
1962Ta06	0,1633 (17)	0,1642 (21)		The authors revised their values.
1963Bu09	0,168 (8)	0,165 (9)		Result had to be corrected for ω_K .
1963Cr14	0,162 (3)	0,162 (3)		
1964He19	0,163 (3)	0,163 (3)	4,84 (6)	
1965Ra12	0,158 (24)			Not used.
1967Bo47	0,14 (3)			Not used.
1968Ra26	0,179 (13)			Not used.
1968Sa22	0,156 (7)			Not used.
1974Ha29	0,1653 (17)	0,1653 (17)	4,75 (13)	
Recommended values		0,1640 (10)	4,837 (48)	$\chi^2 = 0,16$; $\chi^2 = 0,22$

For the α_K recommended value, the evaluators, following the recommendations of H. H. Hansen (1985HaZA), used only nine experimental values with their associated uncertainties in the weighted average calculation, using the LWEIGHT computer program (version 3). A recommended value of 0,1640 for α_K (279-keV γ -ray) is a weighted average, with an internal uncertainty of 0,0010 and a reduced χ^2 of 0,16.

Evaluators' recommended α_L is 4,837 (48) 10^{-2} (reduced $\chi^2 = 0,22$), weighted average of values from: A. H. Wapstra (1956Wa30), G. J. Nijgh (1958Ni28), Z. Sujkowski (1961Su10), C. J. Herrlander (1964He19) and H. H. Hansen (1974Ha29).

3 Atomic Data

Atomic values, ω_K , ω_L and n_{KL} , are from Schönfeld and Janssen (1996Sc06).

3.1 X rays and Auger electrons

The X-ray and Auger electrons relative probabilities have been calculated from γ -ray data by using the EMISSION computer program.

4 Electron Emissions

The Auger electrons emission probabilities have been calculated from γ -ray data using the EMISSION computer program.

5 Photon emissions

5.1 K x-rays

X-ray emissions probabilities have been calculated from γ -ray data using the EMISSION computer program.

5.2 Gamma-ray emissions

The measured energies of γ -ray emissions are given in Table 6.

Table 6 : The measured energies of γ -ray emissions, in keV.

γ -ray	1954Pr04	1954Wa12	1958Ni28	1964He19	1969Cl11	1978He21	2000He14 (evaluated)	Recommended values (keV)
$\gamma_{1,0}$	280 (5)	279 (1)	279,12 (5)	279,16 (2)	279,16 (2)	279,1967 (12)	279,1952 (10)	279,1952 (10)
$\gamma_{2,1}$	400 (7)	400 (2)	403,8 (3)	401,27 (5)	401,28 (40)	401,325 (10)	401,320 (3)	401,320 (3)
$\gamma_{2,0}$	685 (10)	678 (3)			680,7 (6)	680,514 (10)	680,515 (3)	680,515 (3)

The evaluators have adopted the recommended values of R. G. Helmer (2000He14).

The measured relative emission intensities listed in Table 7 are given in values relative to 100 for the 279-keV γ ray.

Table 7: Measured relative γ emission intensity in %.

Energie (keV)	1954Pr04	1954Wa12	1989Ne05	Recommended value
279	100	100	100	100
401	4,7 (3)	4,30 (8)	4,14 (8)	4,24 (8)
680	0,87 (10)	0,80 (1)	0,932 (22)	0,932 (22)

For the 401-keV γ -ray, the recommended value is a weighted average (with an external uncertainty) calculated using the LWEIGHT computer program with these three experimental values. For the 680-keV γ -ray, the calculation using the LWEIGHT computer program showed that the data are discrepant, so the evaluators have chosen to use the most recent and precise result of Zs. Németh (1989Ne05).

The normalization factor to convert the relative emission intensities to absolute emission intensities is calculated using the formula:

$$N = \left(\frac{100}{(\sum (1 + \alpha_T) P_{rel})} \right) \times 100$$

where the sum is over all the γ transitions to the ground state and α_T is the relevant coefficient. In this case, the contributions are from the 279- and 680-keV γ transitions. The uncertainty was calculated through the propagation on the formula given above.

From the recommended α_T (Table 5) and the evaluated relative emission intensities (Table 7), the deduced normalization factor is **80,94 (5)**.

The evaluated relative and absolute γ -ray emission intensities are given in Table 8.

Table 8 : Evaluated relative and absolute γ -ray emission intensities, in %.

Energy (keV)	Relative emission intensity	Absolute emission intensity
279	100	80,94 (5)
401	4,24 (8)	3,43 (6)
680	0,932 (22)	0,754 (18)

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²³³Pa – COMMENTS ON EVALUATION OF DECAY DATAby **V. P. Chechev and N. K. Kuzmenko**

This evaluation was completed in September 2004 and corrected in December 2004. The literature available by May 2004 was included. Additional small corrections have been done by the evaluators in March 2006.

1. DECAY SCHEME

Decay scheme is based on the work of Kouassi et al. (1990Ko41). See also 1990Ak02 and 2005Si15.

2. NUCLEAR DATA

Q^- value is from 2003Au03.

The evaluated half-life of ²³³Pa is based on the experimental results given in Table 1.

Table 1. Experimental values of the ²³³Pa half-life (in days)

Reference	Author(s)	Value	Measurement method
1941Gr03	Grosse et al.	27,4 (4)	β -counting
1956Mc60	Mc Isaac and Freiling	27,0 (1)	$4\pi\gamma$ ionization chamber (4 $T_{1/2}$) and β proportional counter (2 $T_{1/2}$)
1957Wr37	Wright et al.	26,95 (6)	Gamma ionization chamber and β proportional counter (2 $T_{1/2}$)
1986Jo07	Jones et al.	26,967 (2)	Gamma ionization chamber (11 $T_{1/2}$)
1999Popov	Popov and Timofeev	26,9 (1)	Ge(Li) γ -ray spectrometer
2000Us01	Usman and MacMahon	27,02 (3)	HPGe gamma-ray spectrometer (8 gamma lines, 5 $T_{1/2}$)

The weighted mean of the six values from Table 1 of 26,967 (2) is dominated by the very accurate value of 1986Jo07. The LWEIGHT computer program uses a limitation of relative statistical weights (LRSW method), and increased the uncertainty of 1986Jo07 from 0,002 to 0,025 to give a weighted mean of 26,984(18). The evaluation technique from 2000Ch01 also uses the LRSW method and some additional criteria to give the same value of 26,984 (18). The Rajeval data evaluation technique (1992Ra08) uses different criteria to adjust the uncertainties, and has increased the uncertainties of 1986Jo07 and 2000Us01 to give the same value of 26,984 (18).

Huang et al. (2005Hu06) used the analogous procedures for their statistical analysis, and adopted the mean of the normalized residuals and Rajeval technique for the ²³³Pa half-life: 26,971 (13) d. However, they did not take into account the measurement of Popov and Timofeev (1999Popov).

Thus, taking into account the accuracy of most of available measurements, the best estimate of the ²³³Pa half-life is believed to be a recommended value of 26,98 (2) days.

2.1. Beta Transitions

The energies of β^- transitions have been calculated from the Q^- value and the level energies given in Table 2.

Table 2. ²³³U levels populated in the ²³³Pa β^- -decay

Level	Energy, keV	Spin and Parity	Half-life	Probability of β^- -transitions ($\times 100$)
0	0,0	5/2+		~ 3,3
1	40,349(5)	7/2+		~ 3,4
2	92,1(5)	9/2+		-
3	298,81(2)	5/2-		0,12 (5)
4	301,99(10)	5/2-		0,010 (2)
5	311,904(5)	3/2+	0,120 (15) ns	26,7 (29)
6	320,73(10)	7/2-		0,020 (2)
7	340,476(10)	5/2+	52 (10) ps	25,6 (29)
8	380,28(10)	7/2+		0,020 (3)
9	398,492(5)	1/2+	55 (20) ps	15,5 (9)
10	415,764(5)	3/2+	≤ 30 ps	25,3 (11)
11	455,96(10)	5/2+		0,0011 (2)

The evaluated probabilities of β^- -transitions have been obtained from the $P(\gamma+ce)$ balance for each level of ²³³U except for β^- -transitions to the ground and first excited states.

The sum of intensities of β^- -transitions to these states [$P(\beta_{0,0})+P(\beta_{0,1})$] has been deduced as $(100 - \sum P_i(\gamma+e)(i=3 - 10)) = (100 - 93,3 (10)) = 6,7 (10) \%$, where the latter value includes only the intensities of the gamma transitions feeding the ground state and the 40,3- and 92,2-keV levels. The 92,1-keV level (9/2+) cannot be fed directly in the β^- -decay of ²³³Pa ground state (3/2). This forbiddenness allows $P(\beta_{0,0})+P(\beta_{0,1})$ to be evaluated as 6,7 (10) % to be compared with a value of 8,8 (14) % as measured by Browne et al. (1989Br24) and deduced from the decay scheme in 1990Ko41 (6,9 (15) %) and in 2005Hu06 (7,4 (6) %). Individual $P(\gamma+ce)$ balances for the ground state (“0”) and for the 40,3-keV level (“1”) lead to the β^- -transition intensity values of 3,3 (31) % and 3,4 (28) % to these levels, respectively.

Only approximate intensity values are given in the final tables for each of the above β^- -transitions are given because of the large uncertainties that arise from the large and inaccurate total ICC ($\alpha_T = 584 (54)$) for the 40,3-keV γ -ray transition ($\gamma_{1,0}$).

Measured and evaluated energies and β^- -transition probabilities are given in Tables 3 and 4, respectively.

Table 3. Measured and evaluated energies of β^- -transitions (keV)

	1954Br37	1955On05	1960Un01	1963Bj03	Evaluated
$\beta_{0,10}$	140 (14)	145 (10)	155 (7)	154 (5)	154,3 (20)
$\beta_{0,9}$	-	-	175 (8)	-	171,5 (20)
$\beta_{0,5}$	256 (4)	257 (5)	250 (5)	254 (5)	258,2 (20)
$\beta_{0,0}$	568 (5)	568 (5)	-	578 (10)	570,1 (20)

Table 4. Measured and evaluated probabilities (x100) of β^- -transitions

	1954Br37	1955On05	1963Bj03	Evaluated
$\beta_{0,10}$	50	37	32	25,3 (11)
$\beta_{0,5}$	45	58	56	26,7 (29)
$\beta_{0,0}$	5	5	12	~ 3,3

2.2. Gamma-ray Transitions and Internal Conversion Coefficients

The evaluated energies of gamma-ray transitions are virtually the same as the gamma-ray energies because nuclear recoil is negligible.

The gamma-ray transition probabilities have been calculated from the gamma-ray emission probabilities and the total internal conversion coefficients (ICC) from 1978Band and 1993Ba60. The relative uncertainties of α_K , α_L , α_M , α_T for pure multipolarities have been taken as 2 %.

The gamma transition multipolarities have been adopted from 1961Al19, 1962Sc03, 1963Bi03, 1966Ze02, 1988Wo01 and 1989Br24.

The E2/M1 mixing ratio (0,0166) for the 17,2-keV gamma ray ($\gamma_{10,9}$) has been taken from 1962Sc03. The best set of E2/M1 mixing ratios for the 75,3- ($\gamma_{10,7}$), 86,6- ($\gamma_{9,5}$), and 103,9-keV ($\gamma_{10,5}$) gamma rays reported by 1986Kr10 have been adopted. This set is in accordance with the angular correlation data (1986Kr10) and conversion electron data from 1961Al19, 1962Sc03, 1963Bi03, 1966Ze02, and 1988Wo01. Their adopted E2/M1 mixing ratios have been used to calculate ICC for these transitions (Table 5).

We have adopted the value of 0,54 (4) for the 40,3-keV gamma ray ($\gamma_{1,0}$) E2/M1 mixing ratio from 1962Sc03, 1966Ze02 and 1986Kr10 (Table5). This mixing ratio produces a better P(γ +ce) balance for level "1". If we used a smaller value for the E2/M1 mixing ratio (reported by 1961Al19 and 1963Bi03) the intensity of the β^- -transition to level "1" deduced from the balance would have been < 0.

For the most intense, predominantly M1, 300,1- ($\gamma_{7,1}$), 311,9- ($\gamma_{5,0}$), and 340,5-keV ($\gamma_{7,0}$) transitions the ICC values measured in 1989Br24 were adopted. The α_M values for the 300,1- ($\gamma_{7,1}$), 311,9-keV ($\gamma_{5,0}$) and α_{NO} values for the 300,1- ($\gamma_{7,1}$), 311,9- ($\gamma_{5,0}$), and 340,5-keV ($\gamma_{7,0}$) transitions, needed for estimating α_T , have been obtained from theory using the E2/M1 mixing ratios reported in 1986Kr10.

The E2/M1 mixing ratio for the 52,0-keV gamma ray ($\gamma_{2,1}$) has been taken from 1990Ak02.

Table 5. Experimental and adopted E2 γ -ray admixtures

E γ	1961Al19	1962Sc03	1963Bi03	1966Ze02	1986Kr10	1988Wo01	Adopted
28,6	0,030 (5)	0,0102 (8)	0,02 (1)	0,024 (2)	-	0,03 (1)	0,024 (2)
40,3	0,30 (10)	0,54 (4)	0,31 (2)	0,54 (5)	0,54 (8)	-	0,54 (4)
75,3	0,01 (1)	< 0,0005	0	< 0,005	0,022 (16)	0	0,022 (16)
86,6	0,020 (5)	< 0,002	0,01 (1)	< 0,006	0,0031(3)	0,033 (6)	0,0031 (3)
103,9	0,04 (1)	< 0,03	0,01 (1)	0,020 (15)	0,010 (14)	0,074 (9)	0,010 (14)
300,1	0,12 (10)	0,03	0	0	0,006 (2)	0	0,006 (2)
311,9	< 0,02	< 0,03	0	< 0,016	0,010 (1)	0	0,010 (1)
415,8	0,82 (7)	0,96 (4)	0,78 (8)	0,76 (3)		-	0,80 (2)

3. ATOMIC DATA

3.1. Fluorescence yields

The fluorescence yield data are taken from 1996Sc06 (Schönfeld and Janßen).

3.2. X Radiations

The X-ray energies are based on the wavelengths given in the compilation of 1967Be65 (Bearden). The relative K X-ray emission probabilities are calculated using the adopted absolute emission probabilities.

3.3. Auger Electrons

The energies of Auger electrons are from 1977La19 (Larkins) and 1987Lagoutine.

The ratios $P(\text{KLX})/P(\text{KLL})$, $P(\text{KXY})/P(\text{KLL})$ are taken from 1996Sc06.

4. ELECTRON EMISSIONS

The energies of the conversion electrons have been calculated from the gamma transition energies and the electron binding energies.

The emission probabilities of the conversion electrons have been calculated using evaluated P_γ and ICC values.

The total absolute emission probabilities of K Auger electrons have been calculated using total $P(\text{ce}_K)$ values and the adopted ω_K given in section 3.

The total absolute emission probabilities of L Auger electrons have been calculated using total $P(\text{ce}_K)$ and $P(\text{ce}_L)$ values and the adopted $\bar{\omega}_L$, n_{KL} given in section 3.

β^- average energies have been calculated using the LOGFT program.

5. PHOTON EMISSIONS

5.1. X-Ray Emissions

The absolute emission probabilities of U K X-rays have been calculated using the adopted value of ω_K (U) and the total evaluated absolute emission probability of K conversion electrons in the $^{233}\text{Pa} \rightarrow ^{233}\text{U}$ decay. In Table 6 some of these calculated values are compared to measured results. A total calculated absolute U K X-ray emission probability of 30,7 (11) % agrees with the experimental value of 30,0 (4) % from 2004Sh07.

The absolute emission probabilities of U LX-rays have been calculated with the EMISSION computer program using the adopted values of $\bar{\omega}_L$ (U), ω_K (U), n_{KL} (U) and the evaluated absolute emission probabilities of L_1 , L_2 , L_3 -, and K- conversion electrons in the $^{233}\text{Pa} \beta^-$ -decay.

5.2. Gamma-Ray Emissions

The energies of gamma rays have been adopted from 1990Ko41. In Table 7 a comparison is given with other experimental results.

In Table 8 the experimental and evaluated absolute gamma ray emission probabilities (P_γ) are presented. All measurement results given in Table 8 are absolute (P_γ) except those in 1973Va33 and 1990Ko41, which have been renormalized by evaluator to $P_\gamma(312) = 0,3825$ (23). Values given in the last column are weighted averages (LRSW) of individual results.

$P_{\gamma_{10,9}}$ (17,2 keV) has been deduced from $P_{\text{ce}}(\text{M1}) = 0,0054$ (1962Sc03) and $\alpha_{\text{M1}} = 132$ (1993Ba60) calculated for this conversion line using an E2/M1 mixing ratio of 0,017 from 1990Ak02.

$P_{\gamma_{2,1}}$ (52,0 keV) and $P_{\gamma_{2,0}}$ (92,2 keV) have been obtained from the $P(\gamma+\text{ce})$ balance at the 92-keV level and the ratio $P_{\gamma_{2,1}}/P_{\gamma_{2,0}} = 0,21$ (4) from 1990Ak02.

Table 6. Experimental and adopted (calculated) absolute U KX- ray emission probabilities in the decay of ²³³Pa

	Energy, keV	1979Ge08	1984Va28	1990Ko41	2000Smith	2000Sc04	2002Lu01	2004Sh07	Adopted (calculated)
Kα ₂	94,666	8,8 (5)	8,8 (4)	8,3 (4)		8,78 (10)	8,77 (9)	8,78 (10)	9,09 (4)
Kα ₁	98,440	14,4 (8)	14,3 (5)	13,4 (7)	14,3 (3)	14,4 (4)	14,17 (14)	14,22 (17)	14,6 (4)
Kβ ₃	110,421	} 5,2 (3)	1,78 (9)	1,60 (8)	1,89 (4)	1,90 (5)	1,708 (25)	1,708 (38)	1,73 (7)
Kβ ₁	111,298		3,27 (15)	3,11 (15)		3,35 (5)	3,34 (8)	3,39 (14)	
Kβ ₅	111,964		0,15 (1)			0,1230 (17)	0,1239 (28)	0,130 (5)	
Kβ ₂	114,407(11)			0,52 (7)		} 1,59 (9)	1,293 (23)	1,34 (5)	1,37 (6)
Kβ ₄	115,012	} 1,74 (8)	} 1,71 (8)	0,78 (7)	} 1,73 (8)		0,0380 (6)	0,0388 (13)	0,039 (2)
KO _{2,3}	115,377							0,332 (10)	} 0,391 (9)
KP _{2,3}	115,580			} 0,39 (2)				0,051 (2)	

Table 7. Experimental and adopted gamma-ray energies in the decay of ²³³Pa

	1952Br84	1961Al19	1967Br20	1968Ma13	1971Vo02	1972De67	1973Va33	1988Wo01	1990Ko41	Adopted
$\gamma_{10\ n}$						17,2 (1)				17,2 (1)
$\gamma_{7\ 5}$	28,67 (2)					28,6 (1)		28,375 (5)	28,559 (10)	28,559 (10)
$\gamma_{1\ n}$	40,47 (10)	40,35 (1)				40,5 (1)			40,349 (5)	40,349 (5)
$\gamma_{7\ 3}$		41,65 (2)							41,663 (10)	41,663 (10)
$\gamma_{10\ 7}$	75,4 (2)	75,28 (1)				75,27 (3)		75,354 (4)	75,269 (10)	75,269 (10)
$\gamma_{9\ 5}$	87,0 (3)	86,59 (1)				86,58 (3)		86,814 (3)	86,595 (10)	86,595 (10)
$\gamma_{2\ n}$							92,0 (5)		92,1 (5)	92,1 (5)
$\gamma_{10\ 5}$		103,86 (2)						103,971 (9)	103,860 (10)	103,860 (10)
$\gamma_{6\ 2}$									228,57 (5)	228,57 (5)
$\gamma_{7\ 2}$			248,3 (3)	248,69 (24)			248,0 (2)		248,38 (4)	248,38 (4)
$\gamma_{3\ 1}$							258,29 (2)		258,45 (2)	258,45 (2)
$\gamma_{5\ 1}$		271,62 (23)			271,48 (8)				271,555 (10)	271,555 (10)
$\gamma_{6\ 1}$									280,61 (5)	280,61 (5)
$\gamma_{8\ 2}$									288,42 (10)	288,42 (10)
$\gamma_{3\ n}$									298,81 (2)	298,81 (2)
$\gamma_{7\ 1}$		300,20 (24)						300,34 (2)	300,129 (5)	300,129 (5)
$\gamma_{4\ n}$									301,99 (10)	301,99 (10)
$\gamma_{5\ n}$		311,91 (13)						312,17 (12)	311,904 (5)	311,904 (5)
$\gamma_{6\ n}$									320,73 (10)	320,73 (10)
$\gamma_{7\ n}$		340,51 (18)						340,81 (3)	340,476 (5)	340,476 (5)
$\gamma_{10\ 1}$		375,35 (32)			375,45 (4)				375,404 (5)	375,404 (5)
$\gamma_{8\ n}$									380,28 (10)	380,28 (10)
$\gamma_{9\ n}$		398,57 (40)			398,62 (8)				398,492 (5)	398,492 (5)
$\gamma_{10\ n}$		415,87 (42)			415,76 (4)				415,764 (5)	415,764 (5)
$\gamma_{11\ n}$									455,96 (10)	455,96 (10)

Table 8. Experimental and evaluated absolute gamma-ray emission probabilities ($\times 100$) in the decay of ²³³Pa

E γ	1973Va33	1978Poenitz	1979Ge09	1984Va27	1988Wo01	1990Ko41	2000Wo01	1988Wo01	2000Sc04	2002Lu01 2000Lu01	2004Sh07	Evaluated
17,2												
28,56	0,069 (8)			0,15 (1)	0,068 (9)	0,074 (8)		0,068 (9)		0,034 (10)	0,019 (2)	0,071 (8) ^a
40,35	0,039 (8)					0,024 (4)	0,0215 (16)			0,028 (4)	0,032 (4)	0,029 (4)
41,66	0,013 (4)					0,014 (3)						0,014 (3)
75,27	1,25 (8)		1,39 (8)	1,30 (4)	1,25 (9)	1,25 (9)	1,401 (25)	1,25 (9)	1,38 (4)	1,270 (8)		1,30 (3)
86,60	1,87 (23)		1,97 (12)		1,87 (25)	1,93 (11)		1,87 (25)		2,61 (23)		1,99 (11)
92,1	< 0,004					< 0,002						0,002 (1)
103,86	0,73 (8)		0,87 (3)	0,87 (3)	0,73 (9)	0,847 (60)	0,853 (8)	0,73 (9)	0,844 (17)	0,855 (6)	0,825 (25)	0,853 (6)
228,57						0,0042 (7)						0,0042 (7)
248,38	0,039 (12)		0,059 (2)	0,06 (1)		0,058 (4)	0,0607 (12)		0,0618 (11)	0,057 (6)		0,0609 (11)
258,45	0,0039 (16)					0,027 (2)			0,0274 (6)			0,0274 (6)
271,56	0,30 (3)		0,33 (1)	0,32 (1)		0,334 (17)	0,3227 (29)		0,323 (4)	0,323 (5)	0,290 (56)	0,323 (3)
280,61						0,011 (2)						0,011 (2)
288,42						0,016 (3)						0,016 (3)
298,81	0,035					0,085 (7)				0,147 (29)		0,12 (5)
300,13	6,57 (31)		6,62 (10)	6,64 (6)	6,57 (46)	6,76 (7)	6,66 (6)	6,57 (46)	6,55 (7)	6,39 (6)		6,60 (21)
301,99						0,010 (2)						0,010 (2)
311,90		38,6 (15)	38,6 (5)	38,65 (39)			38,7 (4)		38,5 (4)	37,80 (23)	37,5 (24)	38,25 (23)
320,73						0,0051 (4)						0,0051 (4)
340,48	4,47 (46)		4,47 (6)	4,52 (5)	4,48 (51)		4,52 (4)	4,48 (51)	4,50 (5)	4,41 (3)	4,36 (44)	4,47 (3)
375,40			0,68 (1)	0,69 (1)			0,690 (6)		0,686 (7)	0,687 (6)	0,58 (8)	0,684 (7)
380,28						0,0037 (9)						0,0037 (9)
398,49			1,39 (2)	1,43 (2)			1,407 (11)		1,406 (15)	1,39 (1)	1,33 (10)	1,408 (14)
415,76			1,74 (2)	1,74 (2)			1,771 (14)		1,765 (18)	1,740 (7)	1,59 (10)	1,747 (7)
455,96						0,0011 (2)						0,0011 (2)

^a Weighted average of the values from 1988Wo01 and 1990Ko41.

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²³³Th- COMMENTS ON EVALUATION OF DECAY DATA
by V.P.Chechev and N.K.Kuzmenko

This evaluation was completed in September 2004 and revised in December 2004. The literature available by April 2004 was included.

1. DECAY SCHEME

The decay scheme is based on 1990Ak02. There are no precise measurements of P_β , $P_{\gamma+ce}$ and P_γ , P_X values available in the decay of ²³³Th. The available experimental data (without uncertainties) are based on the unpublished works of 1957Fr55, 1969HoZY, 1972SeZI and 1976JeZU (see 1990Ak02). New measurements are needed to construct a ²³³Th decay scheme with more accurate characteristics.

2. NUCLEAR DATA

Q^- value is from 2003Au03.

The evaluated half-life of ²³³Th is based on the experimental results given in Table 1.

Table 1. Experimental values of the ²³³Th half-life (in minutes)

Reference	Author(s)	Value	Measurement method
1952Ru10	Rutledge et al.	23,6(6)	β -counting
1955Je26	Jenkins	22,12(5)	β -counting, good purification of the thorium sample
1957Dr46	Dropesky and Langer	22,4(1)	β -counting
1969HoZY	Hoekstra	22,3(1)	Gamma counting, Ge(Li), one gamma-ray
1989Ab05	Abzouzi et al.	22,30(2)	Gamma counting
1998Us01	Usman, MacMahon and Kafala	21,83(4)	Gamma counting, Ge(Li), 14 gamma rays, very careful data analysis

The value from 1952Ru10 has been omitted as it is an outlier. The weighted mean of the 5 remaining values from the Table 1 is equal 22,15; the internal uncertainty is 0,02. The LWEIGHT program has increased the uncertainty of 1998Us01 by 1,43 times and used the weighted mean of 22,15, having expanded the uncertainty to 0,15 so the range includes the most precise value of 22,30(2).

The adopted value of the ²³³Th half-life is 22,15(15) minutes.

2.1. Beta-transitions

The energies of β^- transitions have been computed from the Q^- value and the ²³³Pa level energies in Table 2 taken from 1990Ak02. The adopted level energy values also include the available data on ²³⁷Np alpha-decay. (The energies of the levels "10" and "12" have been obtained directly from the energies of gamma-rays $\gamma_{10,0}$ (237,86 (2) keV) and $\gamma_{12,0}$ (447,762 (20) keV), respectively).

The adopted probabilities of β^- transitions have been obtained from the $P(\gamma+ce)$ balance for each level of ²³³Pa. The obtained summed β^- intensity is $\approx 103\%$. More precise measurements of the absolute P_γ and P_{ce} are needed.

Table 2. ²³³Pa levels populated in the ²³³Th decay

Level	Energy, keV	Spin and Parity	Half-life	Probability of β^- -transitions ($\times 100$)
0	0	3/2 ⁻	26,975(13) d	34
1	6,65(5)	1/2 ⁻		46
2	57,10(2)	7/2 ⁻		-
3	70,49(10)	5/2 ⁻		-
4	86,477(10)	5/2 ⁺		-
5	94,65(5)	3/2 ⁺		16
6	103,8(1)	7/2 ⁺		
7	169,159(10)	1/2 ⁺		0,9
8	201,62(5)	3/2 ⁺		0,04
9	212,34(5)	5/2 ⁺		-
10	237,86(2)	5/2 ⁺		-
11	257,30(15)	5/2 ⁻		0,08
12	447,762(20)	3/2 ⁻		1,18
13	454,40(7)	3/2 ⁺		0,27
14	553,88(6)	1/2 ⁺ , 3/2 ⁺		1,7
15	585,50(5)	3/2 ⁺		0,22
16	669,9(5)	(3/2 ⁻)		0,02
17	764,55(6)	1/2 ⁺ , 3/2 ⁺		1,58
18	811,6(2)	(3/2 ⁺)		0,54
19	984,8(5)	(3/2 ⁺)		0,32
20	1018,7(5)	(3/2)		0,056

2.2. Gamma Transitions and Internal Conversion Coefficients

The evaluated energies of gamma-ray transitions include the recoil energy of $E_\gamma^2/2Mc^2$, where M is mass of the daughter nucleus.

The gamma-ray transition probabilities have been calculated using the gamma-ray emission probabilities and the total conversion coefficients (ICC) from 1978Ro22. The ICC for $\gamma_{1,0}$ (6,65 (5) keV) have been deduced from 1978Band. For $\gamma_{4,0}$ (86,477 (10) keV) the ICC have been taken from 1988Wo01.

Multipolarities and the E2/M1 mixing ratios have been adopted (following 1990Ak02) from conversion electron measurements of 1972SeZI, 1976JeZU and data on ²³⁷Np alpha-decay.

3. ATOMIC DATA

3.1. Fluorescence yields

The fluorescence yield data are from 1996Sc06 (Schönfeld and Janßen).

3.2. X Radiations

The X-ray energies are based on the wavelengths given in the compilation of 1967Be65 (Bearden). The relative KX-ray emission probabilities are from 1999Schönfeld.

3.3. Auger Electrons

The energies of Auger electrons are from 1977La19 (Larkins) and 1987Lagoutine.

The ratios P(KLX)/P(KLL), P(KXY)/P(KLL) are from 1996Sc06.

4. ELECTRON EMISSIONS

The energies of the conversion electrons have been calculated using the gamma-ray transition energies and the electron binding energies.

The emission probabilities of the conversion electrons have been calculated using the evaluated P_γ and ICC.

The total absolute emission probability of K Auger electrons has been computed using the evaluated total $P(\text{ce}_K)$ and the adopted ω_K from section 3.

The total absolute emission probability of L Auger electrons has been computed using the evaluated total $P(\text{ce}_K)$ and $P(\text{ce}_L)$ and the adopted ω_L , n_{KL} from section 3.

β^- average energies have been calculated using the LOGFT program.

5. PHOTON EMISSIONS

5.1. X-Ray Emissions

The absolute emission probabilities of Pa KX-rays have been computed using the adopted value of ω_K (Pa) and the evaluated total absolute emission probability of K conversion electrons in $^{233}\text{Th} \rightarrow ^{233}\text{Pa}$ decay.

In Table 3 the comparison of measured and calculated emission probabilities for specific groups of Pa KX-rays is given.

Table 3. Experimental and recommended (calculated) values of absolute KX- ray emission probabilities in the decay of ^{233}Th

	Energy, keV	1969HoZY (measured)	Recommended
$K\alpha_2$	92,288	0,54(7)	0,48
$K\alpha_1$	95,869	1,01(7)	0,78
$K\beta'_1$	107,6-109,1	0,28	0,28
$K\beta'_2$	111,4-111,9	0,09	0,095

The absolute emission probabilities of Pa LX-rays have been calculated with the program EMISSION using the adopted values of $\omega_L(\text{Pa})$, $\omega_K(\text{Pa})$, $n_{KL}(\text{Pa})$ and the evaluated total absolute emission probabilities of L- and K- conversion electrons.

5.2. Gamma-Ray Emissions

The energies of the gamma-rays $\gamma_{7,5}$ (74 keV), $\gamma_{9,6}$ (109 keV), $\gamma_{8,4}$ (115 keV), $\gamma_{11,6}$ (153 keV), $\gamma_{7,0}$ (169 keV), $\gamma_{17,15}$ (179 keV), $\gamma_{10,2}$ (181 keV), $\gamma_{11,3}$ (187 keV), $\gamma_{8,1}$ (195 keV), $\gamma_{17,14}$ (211 keV), $\gamma_{13,10}$ (216 keV), $\gamma_{12,8}$ (246 keV), $\gamma_{11,1}$ (251 keV), $\gamma_{13,8}$ (253 keV), $\gamma_{18,14}$ (258 keV), $\gamma_{13,7}$ (285 keV), $\gamma_{15,10}$ (348 keV), $\gamma_{12,4}$ (361 keV), $\gamma_{13,4}$ (368 keV), $\gamma_{12,3}$ (377 keV), $\gamma_{14,4}$ (467 keV), $\gamma_{17,10}$ (527 keV), $\gamma_{17,9}$ (552 keV), $\gamma_{7,8}$ (563 keV), $\gamma_{17,7}$ (595 keV), $\gamma_{18,9}$ (599 keV), $\gamma_{18,7}$ (642 keV), $\gamma_{16,0}$ (670 keV), $\gamma_{18,6}$ (708 keV), $\gamma_{18,5}$ (717 keV), $\gamma_{18,4}$ (725 keV), $\gamma_{18,3}$ (741 keV), $\gamma_{17,1}$ (758 keV), $\gamma_{19,8}$ (783 keV), $\gamma_{18,1}$ (805 keV), $\gamma_{20,7}$ (849 keV), $\gamma_{19,4}$ (898 keV), $\gamma_{20,3}$ (948 keV), $\gamma_{19,1}$ (978 keV) have been deduced from the adopted ^{233}Pa level energies (Table 2).

The energies of the gamma-rays $\gamma_{7,1}$ (162 keV), $\gamma_{12,11}$ (190 keV), $\gamma_{13,5}$ (360 keV), $\gamma_{12,1}$ (441 keV), $\gamma_{12,0}$ (448 keV), $\gamma_{14,5}$ (459 keV), $\gamma_{15,5}$ (491 keV), $\gamma_{17,5}$ (670 keV), $\gamma_{17,4}$ (678 keV) are from the precise measurements with crystal spectrometer (1969Bo30).

Gamma-rays $\gamma_{6,2}$ (46 keV), $\gamma_{3,0}$ (70 keV), $\gamma_{8,4}$ (115 keV), $\gamma_{10,6}$ (134 keV), $\gamma_{9,3}$ (141 keV), $\gamma_{9,2}$ (155 keV), $\gamma_{10,2}$ (181 keV), $\gamma_{9,0}$ (212 keV), $\gamma_{10,0}$ (238 keV) have not been observed in ^{233}Th decay. These gamma-rays have been adopted from the decay scheme on the basis of the available data on ^{237}Np a-decay.

In Table 4 experimental energies for a number of prominent gamma-rays in the decay of ^{233}Th are compared with evaluated results.

The recommended energies of the remaining gamma-rays are from 1969HoZY, 1972SeZI, 1972Vo08 following the evaluation by Akevali (1990Ak02). See also 1968Br25, 1968Da24, 1969Va06, 1970Se06 and 1972De67.

Table 4. Experimental and evaluated gamma-ray energies in the decay of ²³³Th

	1976Sk01	1979Bo30	1979Go12	1988Wo01 (Ge detector)	1988Wo01 (LEPS detector)	Evaluated (recommended)
$\gamma_{4,2}$	29,373(10)		29,374(20)	29,5(17)	29,18(21)	29,373(10)
$\gamma_{6,2}$	46,534(40)		46,53(6)	46,7(11)	46,28(18)	46,53(4)
$\gamma_{2,0}$	57,15(4)	57,11(5)	57,104(20)	57,15(80)	56,88(17)	57,10(2)
$\gamma_{4,0}$	86,503(20)	86,48(6)	86,477(10)	86,50(48)	86,26(14)	86,477(10)
$\gamma_{5,1}$	88,04(16)		87,988(30)			87,99(3)
$\gamma_{5,0}$	94,66(5)		94,638(50)			94,65(5)
$\gamma_{8,4}$	115,40(35)		115,40(35)			115,14(5) ^a
$\gamma_{9,5}$	117,681(30)		117,702(20)	117,72(50)	117,41(15)	117,692(20)
$\gamma_{8,3}$	131,043(30)		131,101(25)	131,09(52)	130,62(15)	131,101(25)
$\gamma_{10,6}$	134,23(4)		134,285(20)	134,27(53)		134,285(20)
$\gamma_{9,3}$			141,74(10)			141,74(10)
$\gamma_{10,5}$	143,208(25)		143,249(20)	143,27(56)	142,96(16)	143,230(20)
$\gamma_{10,4}$	151,375(35)		151,414(20)	151,42(60)	151,06(17)	151,409(20)
$\gamma_{9,2}$	155,22(4)		155,239(20)	155,28(63)		155,239(20)
$\gamma_{7,1}$	162,50(6)	162,504(12)	162,41(8)	162,45(68)		162,504(12)
$\gamma_{7,0}$	169,17(5)	169,162(10)	169,156(20)	169,18(73)		169,159(10)
$\gamma_{11,4}$	170,63(8)		170,59(6)			170,60(6)
$\gamma_{10,2}$	180,80(8)		180,81(10)	180,87(85)		180,76(3) ^a
$\gamma_{11,3}$	186,8(5)		186,86(35)			186,80(18) ^a
$\gamma_{12,11}$		190,552(14)				190,552(14)
$\gamma_{8,0}$	201,72(5)		201,62(5)	201,8(11)		201,62(5)
$\gamma_{9,0}$	212,415(25)	212,4(12)	212,290(50)			212,34(5) ^a
$\gamma_{10,0}$	238,04(4)		237,862(60)	238,0(14)		237,86(2)
$\gamma_{13,5}$		359,745(40)				359,74(4)
$\gamma_{12,1}$		440,943(40)				440,94(4)

a- deduced from level energies

The gamma-ray transitions with energies (keV) of 80, 105, 278, 409, 418, 435, 454, 497, 505, 513, 517, 531, 555, 681, 698, 704, 745, 752, 774, 784, 832, 847, 871, 874, 919, 935, 942, 955, 961, 968, 994, 1001, 1007, 1011, 1026, 1092, 1144 and 1201 keV have not been placed in the ²³³Th decay scheme. The gamma-ray transitions $\gamma_{7,1}$ (162 keV) and $\gamma_{11,5}$ (162 keV), $\gamma_{11,0}$ (257 keV) and $\gamma_{18,14}$ (257 keV), $\gamma_{16,0}$ (670 keV) and $\gamma_{17,7}$ (670 keV) have been placed twice in the decay scheme; their intensities have been suitably divided (1990Ak02).

The absolute gamma-ray emission probability of $\gamma_{4,0}$ (86,5 keV), $P(\gamma_{4,0}) = 2,7$ (1957Fr55) has been used to normalize relative values (1969HoZY, 1972SeZI) recommended in 1990Ak02, to absolute emission probabilities.

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²³⁴U - Comments on evaluation of decay data by V. Chisté and M.M. Bé

This evaluation was completed in 2005. Literature available by September 2005 was included.

1 Decay Scheme

²³⁴U disintegrates by alpha emission to excited and ground state levels of ²³⁰Th. Spin and half-lives of excited states are from the mass-chain evaluation of Y.A. Akovali (1993Ak02 to A = 230, and 1994Ak05 to A = 234).

2 Nuclear Data

The Q value is from atomic mass evaluation of Audi et al. (2003Au03).

The experimental ²³⁴U half-life values (in years) are given in Table 1:

Table 1: Experimental values of ²³⁴U half-life.

Reference	Original value (10 ⁵ a)	Revised Value by Holden (1981HoZI and 1989Ho24)	Comments
Nier (1939Ni03)	2.70 (27)		Not used.
Chamberlain (1946Ch02)	2.29 (14)		Not used. Measurements of relative abundance of ²³⁴ U and ²³⁸ U.
Chamberlain (1946Ch02)	2.35 (14)		Not used. Measurements of α-activity of ²³⁴ U.
Baldinger (1949Ba41)	2.33 (10)		Not used.
Goldin (1949Go18)	2.67 (4)		Not used.
Kienberger (1949Ki26)	2.552 (8)		Not used. Superseded 1952Ki19
Fleming (1952Fl20)	2.475 (16)	2.475 (24)	Not used. Uncertainty increased for missing details.
Kienberger (1952Ki19)	2.520 (8)		Not used.
White (1965Wh05)	2.47 (3)		Not used.
Meadows (1970MeZN)	2.439 (14)	2.439 (18)	Not used. Uncertainty increased for missing details.
de Bievre (1972DeYN)	2.446 (7)	2.450 (9) *	Revised by author (see 1989Ho24)
Lounsbury (1972LoZL)	2.444 (6)	2.458 (13) *	Revised by author (see 1989Ho24)
Geidel'man (1980Ge13)	2.4604 (45)	2.459 (9) *	4π α - x coincidence. Revised uncertainty for missing details.
	2.4570 (45)		Liquid scintillator. Revised uncertainty for missing details.
Poenitz (1983 and 1985 Poenitz)	2.457 (5)		Not used.
Davideenam (1984Davideenam)	2.457 (5)		Not used. Evaluated value.
Recommended value		2.455 (6)	reduced $\chi^2 = 0.28$

The first six and less precise values (1940's) were omitted from analysis. For remaining values, the evaluators have chosen to take into account the recommendations given by N.E. Holden (1989Ho24), thus the only three experimental values (*) with associated uncertainties used to the weighted average are 1972DeYN, 1972LoZL and 1980Ge13. For the data in 1980Ge13, the evaluators have chosen to use the average value of 2.459 (9) 10⁵ a, calculated from two experimental values given in the paper to produce a single DDEP value from each laboratory. A weighted average has been calculated using LWEIGHT computer program (version 3). However, the treatment of uncertainties in 1989Ho24 ("... when detailed information on the uncertainties was available in each of these experiments, the standard deviation for the experiment was combined with one third of the systematic error to provide the uncertainty quoted in the table: $\sigma_{\text{tot}} = \sigma_{\text{statistical}} + 1/3 \sigma_{\text{systematic}}$ ") seemed more realistic, so the evaluators recommend a half-life of 2.455 10⁵ a with a final uncertainty of 0.006 10⁵ a. The reduced - χ^2 value is 0.28.

The experimental ^{230}Th half-life values (in years) are given in Table 2:

Table 2: Experimental values of ^{230}Th half-life.

Reference	Value (a)	Uncertainty (a)
M. Curie (1930Cu02)	82300	2469
E.K. Hyde (1949Hy03)	80000	3000
R.W. Attree (1961At01)	75200	1600
J.W. Meadows (1980Me10)	75381	295
Recommend value	75500	500

The recommended value is the weighted average (calculated with LWEIGHT computer program) of $75.5 \cdot 10^3 a$ with an external uncertainty of $0.5 \cdot 10^3 a$. The reduced χ^2 value is 3.3.

The evaluated spontaneous fission partial half-life of ^{234}U is based on the experimental results given in Table 3.

Table 3: Experimental values of ^{234}U spontaneous fission half-life (in 10^{16} years).

Reference	Value	Uncertainty	Comments
A. Ghiorso (1952Gh27)	2	1	Not used.
H.R. von Gunten (1981Vo02)	1.42	0.08	
S. Wang (1987Sh27)	1.90	0.15	
Recommend value	1.5	0.2	reduced $\chi^2 = 5.12$

The evaluators have not use the value given in 1952Gh27, as recommended in 1989Ho24. Evaluators' recommended value is the weighted average of the two remaining values : $1.5 \cdot 10^{16} a$ with an external uncertainty of $0.2 \cdot 10^{16} a$. The reduced χ^2 value is 5.12.

This value produces a spontaneous fission branching of $1.6 (2) \cdot 10^{-9} \%$.

2.1 a Transitions

The energies of the α -particle transitions given in Section 2.1 have been calculated from the Q_α (2003Au03) and level energies deduced by the evaluators from a least-squares fit to γ -ray energies.

2.2 g Transitions

The transition probabilities have been calculated using the γ -ray emission intensities and the relevant internal conversion coefficients (see **4.2 Gamma Emissions**).

For the 634-keV γ -ray (E0 transition), $P_{(\gamma+ce)} = 1.4 (7) \cdot 10^{-5} \%$ has been deduced from decay scheme balance.

Multipolarities of γ -ray transitions in decay of ^{230}Th are from 1993Ak02:

53-keV γ -ray : E2	581-keV γ -ray: E2
120-keV γ -ray : E2	624-keV γ -ray: E0 + E2 + M1
454-keV γ -ray : E1	634-keV γ -ray: E0
503-keV γ -ray: [E2]	677-keV γ -ray: [E2]
508-keV γ -ray: E1	

The internal conversion coefficients (ICC's) have been calculated using the Icc99v3a computer program (GETICC dialog), which uses interpolated values from new tables of Band et al (2002Ba85). The evaluators have used a fractional uncertainty of 3 % for all conversion coefficients.

3 Atomic Data

Atomic values, ω_K , ω_L and n_{KL} , X-ray and Auger electrons relative probabilities are from Schönfeld and Janßen (1996Sc06).

4 a Emissions

α -particle energies are from Q_α (2003Au03) and level energies (see section 2.1). For the $\alpha_{0,0}$ and $\alpha_{0,1}$ emissions, the energies are from A. Rytz (1991Ri01).

The measured α -emission intensities are given in Table 4.

Table 4: Measured α -emission intensities, in %.

Energy (keV)	1955Go57	1960Ba44	1961Ko11	1963Bj03	1984Va41	1987Bo25	Recommended Value
4774.6 ($\alpha_{0,0}$)	72	72.5 (30)	73		71.38 (5)	71.37 (2)	71.37 (2)
4722.4 ($\alpha_{0,1}$)		27.15 (15)	27		28.42 (5)	28.42 (2)	28.42 (2)
4603.5 ($\alpha_{0,2}$)		= 0.37 (11)	0.3		0.206 (4)	0.199 (2)	0.210 (2)
4275.2 ($\alpha_{0,3}$)				4 (1) 10^{-5}			4 (1) 10^{-5}
4150.6 ($\alpha_{0,4}$)				1.2 (5) 10^{-5}			2.6 10^{-5}
4108.6 ($\alpha_{0,5}$)				0.3 10^{-5}			7.0 10^{-6}

The U-234 spectrum was recorded by 1984Va41, a second analysis of the same data was done by 1987Bo25, these latest values are the adopted results for the 4774- and 4722-keV α -emissions intensity. The 4603-keV intensity is deduced from the decay scheme, the tree others being negligible.

The 4275-, 4150-, 4108- keV emission intensities are deduced from 1963Bj03 and decay scheme transition probability balance (§6.2).

6 Photon Emissions

6.1 X-rays

The X-ray and Auger electrons absolute intensities have been calculated from γ -ray data and ICC by using the EMISSION computer program.

In the Table 5 the recommended values of ^{230}Th X-ray emission probabilities are compared with the experimental results. Good agreement was found between the experimental results given by 1977Bemis, 1984Va41 and 1995Jo23 and the recommended values calculated from the decay scheme data set. This agreement confirms the completeness and consistency of the decay scheme.

Table 5: Experimental and recommended (calculated) values of ^{230}Th X-ray emission intensities.

Reference	1977Bemis	1984Va41	1995Jo23	Recommended value
11.118 – 19.504 (L X-ray)	9.81 (13)	10.35 (14)	10.02 (7)	10.2 (4)
L λ - 11.118			0.206 (3)	0.209 (12)
L α - 12.808 – 12.967			3.42 (2)	3.48 (17)
L η - 14.509				0.118 (7)
L β - 14.972 – 16.425			5.17 (4)	5.16 (26)
L γ - 18.363 – 19.504			1.22 (1)	1.21 (6)

Reference	1977Bemis	1984Va41	1995Jo23	Recommended value
89.95 (X K _{α2})		2.53 (7) 10 ⁻³		2.69 (25) 10 ⁻³
93.35 (X K _{α1})		4.15 (10) 10 ⁻³		4.4 (4) 10 ⁻³

6.2 Gamma emissions

The energies of the γ-ray emissions given in Section 6 are from Y.A. Akovali (1993Ak02). The experimental intensity of the 120-keV γ emission given in Table 6 is relative to the 53-keV γ-ray.

Table 6: Experimental relative γ emission intensity (P_{rel}) in %.

γ Energy (keV)	1966Ah02	1974HeYW	1984Va41	Recommended value
53.20	100	100 (5)	100	100.0 (25)
120.90	34 (4)	34.2 (18)	27.5 (5)	30.8 (24)

The recommended values are the weighted averages of the three values given with uncertainties. The normalization factor to convert the relative emission intensities to absolute emission intensities is calculated with the formula:

$$\text{Normalization factor} = \frac{(100\% - 71.371(19)\%)}{\sum [(1 + a_T)P_{rel}]} = 0.001253 (40),$$

where the sum is over all the γ transitions to the ground state and α_T is the relevant conversion coefficient. In this case, the contribution of 508- (see next), 634- and 677-keV γ transitions are considered negligible. The uncertainty was calculated through the propagation on the formula given above.

For the 454- and 508-keV absolute emission probabilities, the evaluators have following relations: P_γ(454) + P_γ(508) = 4 (1) 10⁻⁵ (from 1963Bj03) and P_γ(508) = 0.60 (4) × P_γ(454) (from average value of measured ratios in ²³⁰Pa and ²³⁰Ac decays. See 1993Ak02). Then the evaluator obtains P_γ(454) = 0.000025 (6) % and P_γ(508) = 0.0000150 (39) %. For the others γ rays, the evaluators present the experimental absolute emission values given in 1993Ak02. The evaluated relative and absolute γ-rays emission intensities are given in Table 7.

Table 7: Evaluated relative and absolute γ-ray emission intensities.

Energy (keV)	Relative emission intensity (%)	Absolute emission intensity (%)
53.20 (2)	100.0 (25)	0.1253 (40)
120.90 (4)	30.8 (24)	0.0386 (32)
454.96 (5)		0.000025 (6)
503.5 (1)		0.00000095
508.16 (5)		0.0000150 (39)
581.7 (1)		0.000012 (5)
624.4 (1)		0.00000082
677.6 (1)		0.000001

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²³⁶Np – COMMENTS ON EVALUATION OF DECAY DATA

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This evaluation was completed in June 2006. The literature available by May 2006 was included.

1. DECAY SCHEME

From the systematics of the isomer levels it has been assumed in 1981Li30 (see also the analysis carried out in 1991Sc08) that the short-lived state of ²³⁶Np (22,5 h) lies higher in energy than the long-lived state of ²³⁶Np (1,55 × 10⁵ y). In line with this assumption we consider the long-lived state of ²³⁶Np as the ground state. Using Q values for electron capture decay of the isomer and ground state and a close energy cycle we can estimate the energy level spacing between these states as 60(50) keV.

The decay scheme of the long-lived ²³⁶Np includes three decay modes: β⁻ decay to ²³⁶Pu, electron capture decay (EC) to ²³⁶U and α decay to ²³²Pa (see evaluations in 1991Sc08, 1996FiZX). A favored α-particle branch to the (6-) level at ~ 400 keV is expected in ²³²Pa from α systematics (1972El21, 1980Sc26, 1991Sc08). However, this decay was not observed experimentally.

The β⁻-decay branching, ΣP(β⁻), and alpha-decay branching, ΣP(α), have been deduced from the partial half-lives T_{1/2}(β⁻) and T_{1/2}(α), respectively. The EC -decay branching, ΣP(EC), has been obtained as the difference of 1 – ΣP(β⁻) – ΣP(α).

2. NUCLEAR DATA

Q⁻, Q_{EC}, Q(α) values are from 2003Au03.

The total half-life of ²³⁶Np is based on the evaluated partial half-lives T_{1/2}(α), T_{1/2}(β⁻), T_{1/2}(EC) measured in 1981Li30.

The evaluated T_{1/2}(α) = 9,5(35) × 10⁷ years has been obtained as an average of the two measurements of 1981Li30 (specific activity, ²³²U gamma-ray of 894 keV was measured): 9,4(35) × 10⁷ and 9,6(35) × 10⁷ years. A standard deviation of the individual measurement has been adopted for the uncertainty of the evaluated alpha-decay half-life using a rule that the uncertainty assigned to the recommended value should be greater than or equal to the smallest uncertainty in any experimental value. T_{1/2}(β⁻) = 1,29(3) × 10⁶ years has been adopted here from the ²³⁶Pu growth measurement of 1981Li30. The result of this measurement is independent of the decay scheme, and it is equal to the weighted average of 1,34(15), 1,29(3), 1,32(9), 1,69(30), 1,29(3), 1,31(8) (in 10⁶ years) given in 1981Li30. The uncertainties of these measurements do not include any estimation of uncertainties from the decay scheme parameters. It agrees well with an earlier measurement in 1972En06 (1,29 + 0,07 - 0,05 × 10⁵ yr).

The evaluated T_{1/2}(EC) = 1,77(10) × 10⁵ years has been obtained as an average of the two ²³⁶U/²³⁵U mass ratio measurements in 1981Li30: 1,75(10) × 10⁵ and 1,79(10) × 10⁵ years. These ²³⁶U growth measurement results are independent of the decay scheme. A standard deviation of the individual measurement has been adopted for the uncertainty of the evaluated partial EC-decay half-life. The specific gamma-ray activity method (²³⁶U 160,3 -keV gamma-ray was measured) was used in other measurements presented in 1981Li30 (in 10⁵ years): 1,60(4), 1,73(2), 1,77(11), 1,75(10), 1,79(10), 1,74(1), 1,78(10). The uncertainties of these measurements do not include an estimation of uncertainties from the decay scheme parameters.

Thus, the recommended value of the total ²³⁶Np half-life obtained from the relation T_{1/2} = [(T_{1/2}(α))⁻¹ + (T_{1/2}(β⁻))⁻¹ + (T_{1/2}(EC))⁻¹]⁻¹ is equal to 1,55(8) × 10⁵ years.

2.1.1. Electron Capture Transitions

The energies of the electron capture transitions have been obtained from the Q_{EC} value and the level energies (Table 1) based on the evaluated gamma-ray energies.

Table 1. ²³⁶U levels populated in the ²³⁶Np electron capture decay

Level number	Energy, keV	Spin and parity	Half-life	Probability of e - transition (x100)
0	0,0	0 ⁺	2,342·10 ⁷ yr	-
1	45,242(3)	2 ⁺	234 ps	-
2	149,476(15)	4 ⁺	124 ps	0,0(44)
3	309,783(8)	6 ⁺	58 ps	87,8(43)
4	687,60(5)	1 ⁻	3,8 ns	-
5	744,15(8)	3 ⁻	<0,1 ns	-
6	848,3(8)	5 ⁻		~0,09

The probabilities of the electron capture transitions P(EC_{0,2}) and P(EC_{0,3}) have been obtained from P(EC_{0,2}) + P(EC_{0,3}) = 100% – ΣP(β⁻) – ΣP(α) = 87,8(6)% and P(EC_{0,3}) = P(γ_{3,2} + ce)(160-keV). The upper limit of P(EC_{0,2}) < 4,4% has been obtained from P(EC_{0,2}) = 0,0(44)%. The estimate of P(EC_{0,6}) ~ 0,1% is from 1996FiZX.

2.1.2. Beta Transitions

The energies of the β⁻ - transitions have been calculated from the Q⁻ value and the level energies (Table 2) based on the evaluated gamma-ray energies.

Table 2. ²³⁶Pu levels populated in ²³⁶Np β⁻ -decay

Level number	Energy, keV	Spin and parity	Half-life	Probability of β ⁻ - transition (x100)
0	0,0	0 ⁺	2,858 yr	-
1	44,63(10)	2 ⁺		-
2	147,45(10)	4 ⁺		0,2(14)
3	305,80(11)	6 ⁺		11,8(12)

The β⁻ transition probability P(β_{0,3}) = P(γ_{3,2} + ce)(158 -keV), and P(β_{0,2}) = 12,0(6) % – P(β_{0,3}) = 0,2(14) %. From this result follows an upper limit of P(β_{0,2}) < 1,6%.

2.2. Gamma Transitions and Internal Conversion Coefficients

The evaluated energies of gamma-ray transitions are virtually the same as the photon energies because nuclear recoil is negligible.

The gamma-ray transition probabilities have been obtained from the gamma-ray emission probability and the total internal conversion coefficients (ICC's). Multipolarities of gamma-ray transitions have been taken from 1991Sc08 and 1996FiZX. Internal conversion coefficients (ICC) have been interpolated using the BRICC computer program, except for γ_{4,1} (642,3 -keV) and γ_{4,0} (687,6 -keV). The fractional uncertainties in α_K, α_L, α_M, α_T for pure multipolarities have been taken as 2%.

α_K and α_L for γ_{4,1}(642,3 -keV) and γ_{4,0}(687,6 -keV) are experimental values from ²⁴⁰Pu α-decay (1969Le05 and 1977Po05, see also the evaluation of 2004Be). α_M and α_T for these transitions have been evaluated using α_M/α_L and α_{NO}/α_M from 1971Dr11. More accurate ICC measurements for these transitions are required.

3. ATOMIC DATA

3.1. Fluorescence yields

The fluorescence yield data are from 1996Sc06 (Schönfeld and Janßen).

3.2. X Radiations

The LX-ray energies are from 1996FiZX. The KX-ray energies and the relative KX-ray emission probabilities are from 1999Schönfeld.

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

The relative KX-ray emission probabilities have been taken from 1999Schönfeld.

3.3. Auger Electrons

The ratios P(KLX)/P(KLL), P(KXY)/P(KLL) are taken from 1996Sc06.

4. ELECTRON EMISSIONS

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

The emission probabilities of the conversion electrons have been obtained using evaluated P(γ) and ICC values.

The absolute emission probabilities of K and L Auger electrons have been obtained using the EMISSION computer program.

β^- average energies have been obtained using the LOGFT computer program.

5. PHOTON EMISSIONS

5.1. X-Ray Emissions

The absolute emission probabilities of KX- and LX-rays have been deduced from experimental data and theoretical internal conversion coefficients using the EMISSION computer program.

For LX-ray calculations the theoretical ratios $P_{EC}(L2)/P_{EC}(L1) = 0,115$ and $P_{EC}(L3)/P_{EC}(L1) = 0$ have been obtained for the level “3” (309 keV) of ²³⁶U (1972Dzhelepov). The calculated relative intensities of KX- rays accompanying the electron capture of ²³⁶Np are in a good agreement with the experimental results (Table 3).

Table 3. Intensities of KX- rays (relatively P($\gamma_{3,2}$)) accompanying ²³⁶Np electron capture

	1983Ah03 (experimental)	Adopted (deduced)
X _K		
K α_2	0,61(2)	0,66(7)
K α_1	0,99(3)	1,0(1)
K β_1'	0,38(2)	0,38(4)
K β_2'	0,131(7)	0,13(1)

5.2. Gamma Ray Emissions

5.2.1. Gamma Ray Energies (²³⁶U)

The energies of gamma rays accompanying the ²³⁶Np electron capture decay have been adopted from the evaluated DDEP data on the ²⁴⁰Pu α -decay (2004Be).

5.2.2. Gamma Ray Energies (²³⁶Pu)

The energies of gamma rays $\gamma_{1,0}$ (44,6 keV), $\gamma_{2,1}$ (102,8 keV), $\gamma_{3,2}$ (158,3 keV) accompanying β^- decay of ²³⁶Np have been adopted from measurements given in 1983Ah02.

5.2.3. Gamma-Ray Emission Probabilities (²³⁶U)

The evaluated gamma ray emission probabilities P(γ) have been deduced using the relative gamma ray intensities from 1983Ah02 (Table 4), the quantity $\Sigma P(\beta^-) = 12,05(60)\% = P(\gamma_{2,1} + ce)$ (102,8 keV) and the intensity balance at each level. We have assumed that the populations to the two lower levels ("0" and "1") in β^- decay are negligible and have taken into account the intensity balance of the gamma-ray transitions to these levels, that is $P(\gamma_{1,0} + ce)$ (44,6 keV) = $P(\gamma_{2,1} + ce)$ (102,8 keV).

Table 4. Gamma rays in the decay of the long-lived ²³⁶Np measured in 1983Ah02

	Energy, keV	Relative intensity
$\gamma_{1,0}$ (²³⁶ U)	45,23(3)	0,4(1)
$\gamma_{2,1}$ (²³⁶ Pu)	102,82(2)	2,9(2)
$\gamma_{2,1}$ (²³⁶ U)	104,23(2)	23(1)
$\gamma_{3,2}$ (²³⁶ Pu)	158,35(2)	13,5(7)
$\gamma_{3,2}$ (²³⁶ U)	160,33(2)	100

5.2.3. Gamma-Ray Emission Probabilities (²³⁶Pu)

The evaluated gamma ray emission probabilities P(γ) have been deduced using the relative gamma ray intensities from 1983Ah02 (Table 4), the relation of $\Sigma P(EC_{0,i}) = 87,8(6)\% = P(\gamma_{2,1} + ce)$ (104,23 keV) and the intensity balance at each level. We have assumed that the populations to the two lower levels ("0" and "1") in the electron capture decay are negligible and have taken into account the intensity balance relation for the gamma-ray transitions to these levels, that is $P(\gamma_{1,0} + ce)$ (45,2 keV) = $P(\gamma_{2,1} + ce)$ (104,2 keV).

The evaluated gamma ray emission probabilities for γ -rays de-exciting level "4" ($\gamma_{4,2}$ (538,1 keV), $\gamma_{4,1}$ (642,3 keV), and $\gamma_{4,0}$ (687,5 keV)) have been deduced from the relation $P(\gamma_{5,4} + ce)$ (56,6 keV) = $P(\gamma_{4,2} + ce)$ (538,1 keV) + $P(\gamma_{4,1} + ce)$ (642,3 keV) + $P(\gamma_{4,0} + ce)$ (687,5 keV) using the relative intensities for these γ -rays evaluated from the ²⁴⁰Pu α -decay (Table 5) and assuming $P(EC_{0,4}) = 0$.

Table 5. Experimental and evaluated absolute emission probabilities of gamma rays de-exciting the ²³⁶U level with energy of 687,6 keV in the decay of ²⁴⁰Pu (per 10⁸ a-decays) and the deduced relative intensities of these gamma rays

	Energy, keV	1969Le05	1971GuZY	1975OtZX	1975Dr05	1976GuZN	Evaluated	Evaluated relative intensities
$\gamma_{4,2}$	538,1	$\approx 0,23^a$		0,147(12)			0,147(12)	1,17(10)
$\gamma_{4,1}$	642,4	14,5 ^a	14,5(5) ^b	12,6(4)	13(1)	12,45(30)	12,6(3) ^c	100 (3)
$\gamma_{4,0}$	687,6	3,77(11)	3,70(15) ^b	3,30(13)		3,55(9)	3,56(15) ^d	28,3(13)

^a Omitted from averaging as uncertainty is not quoted

^b Omitted from averaging as the data of 1971GuZY have been revised in 1976GuZN

^c Weighted mean of 3 experimental values; the uncertainty is the smallest quoted uncertainty

^d Weighted mean of 3 experimental values; the uncertainty is external

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²³⁶Np^m – COMMENTS ON EVALUATION OF DECAY DATA

by V.P.Chechev and N.K.Kuzmenko

This evaluation was completed in June 2006. The literature available by May 2006 was included.

1. DECAY SCHEME

From the systematics of isomer levels it was assumed in 1981Li30 (see also the analysis carried out in 1991Sc08) that the short-lived state of ²³⁶Np (22,5 h) lies higher in energy than the long-lived state of ²³⁶Np (1,55 10⁵ y). In line with this assumption we have considered the long-lived state of ²³⁶Np as the ground state. Using Q values for electron capture decays of the isomer and ground states together with closed energy cycles we can estimate the energy level spacing between these states as 60(50) keV.

The decay scheme of the isomer ²³⁶Np^m includes two decay modes: β⁻ decay to ²³⁶Pu and electron capture decay (EC) to ²³⁶U (see evaluations of 1991Sc08, 1996FiZX). The β⁻-decay branching, ΣP(β⁻), has been adopted from 1969Le05. The EC -decay branching, ΣP(EC), has been obtained as the difference of 1-ΣP(β⁻).

2. NUCLEAR DATA

Q⁻ (²³⁶Np^m) is from 1969Le05 (the end-point energy of the β⁻ spectrum was measured). Q_{EC} (²³⁶Np^m) has been calculated from the closed energy cycle of decays ending in ²³²Th. The values of Q⁻ (²³⁶Np^m), Q_α (²³⁶Pu), Q⁻ (²³²Pa), Q_{EC} (²³²Pa) and Q_α (²³⁶U) from 2003Au03 were used in this calculation.

The half-life of ²³⁶Np^m is from 1969Le05. This result agrees with other (less accurate) measurements (1949Ja01 – 22 h, 1984Gr33 – 22,5 h).

2.1. Electron Capture Transitions

The energies of the electron capture transitions have been deduced from the Q_{EC} value and the level energies (Table 1) obtained from the evaluated gamma-ray energies.

Table 1. ²³⁶U levels populated in the ²³⁶Np^m electron capture decay

Level number	Energy, keV	Spin and parity	Half-life	Probability of EC - transition (×100)
0	0,0	0 ⁺	2,342·10 ⁷ yr	43,1(32)
1	45,242(3)	2 ⁺	234 ps	8,3(30)
2	149,476(15)	4 ⁺	124 ps	-
4	687,60(5)	1 ⁻	3,8 ns	1,64(9)

The individual EC- transition probabilities P(EC_{1,i}) have been deduced from the intensity balance for each level and the total EC -decay probability ΣP(e_{1,i}).

2.2. Beta Transitions

The β⁻- transition energies have been deduced from the Q⁻ value and the level energies (Table 2) obtained from the evaluated gamma-ray energies.

Table 2. ²³⁶Pu levels populated in the ²³⁶Np^m β⁻-decay

Level number	Energy, keV	Spin and parity	Half-life	Probability of β ⁻ - transition (× 100)
0	0,0	0 ⁺	2,858 yr	36(4)
1	44,63(10)	2 ⁺		11(4)

The β^- transition probabilities $P(\beta_{1,0})$, $P(\beta_{1,1})$ have been obtained from the ratio $P(\beta_{1,0})/P(\beta_{1,1}) = 38(7)/12(5)$ measured in 1959Gi58 and the total β^- -decay probability $\Sigma P(\beta_{1,i})$.

2.3. Gamma Transitions and Internal Conversion Coefficients (²³⁶U)

The evaluated transition energies are virtually the same as the photon energies because nuclear recoil is negligible.

The gamma-ray transition probabilities have been obtained from the gamma-ray emission probabilities and the total internal conversion coefficients (ICC's). Multipolarities of gamma-ray transitions have been taken from 1991Sc08 and 1996FiZX. The gamma-ray transition probability $P(\gamma_{1,0} + \text{ce})(44,6\text{-keV})$ has been deduced from the relation of $P(\gamma_{1,0} + \text{ce})(44,6\text{-keV}) = P(\beta_{0,1})$.

ICC's have been interpolated using the BRICC computer program, except for $\gamma_{4,1}$ (642,3-keV) and $\gamma_{4,0}$ (687,6-keV) because of nuclear penetration effects. The relative uncertainties of α_K , α_L , α_M , α_T for pure multipolarities have been taken as 2%.

α_K and α_L for $\gamma_{4,1}$ (642,3-keV) and $\gamma_{4,0}$ (687,6-keV) are experimental values from data in ²⁴⁰Pu α -decay (1969Le05 and 1977Po05, see also the evaluation of 2004Be). α_M and α_T for these transitions have been evaluated using α_M/α_L and α_{NO}/α_M from 1971Dr11. More accurate ICC measurements for these transitions are required.

3. ATOMIC DATA

3.1. Fluorescence yields

The fluorescence yield data are from 1996Sc06 (Schönfeld and Janßen).

3.2. X Radiations

The LX-ray energies are from 1996FiZX. The KX-ray energies and the relative KX-ray emission probabilities are from 1999Schönfeld.

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

The relative KX-ray emission probabilities have been taken from 1999Schönfeld.

3.3. Auger Electrons

The ratios $P(\text{KLX})/P(\text{KLL})$, $P(\text{KXY})/P(\text{KLL})$ are taken from 1996Sc06.

4. ELECTRON EMISSIONS

The energies of the conversion electrons have been deduced from the gamma transition energies and the electron binding energies.

The emission probabilities of the conversion electrons have been deduced using evaluated P_γ and ICC values.

The absolute emission probabilities of K and L Auger electrons have been obtained with the EMISSION computer program.

β^- average energies have been obtained using the LOGFT computer program.

5. PHOTON EMISSIONS

5.1. X-Ray Emissions

The absolute emission probabilities of KX- and LX-rays have been obtained with the EMISSION computer program.

For U LX-ray calculations the ratios $P_{\text{EC}}(\text{L2})/P_{\text{EC}}(\text{L1}) = 0,115$ and $P_{\text{EC}}(\text{L3})/P_{\text{EC}}(\text{L1}) = 0$ from the theoretical calculations of 1972Dzhelepov were used for all levels populated in the ²³⁶Np^m electron capture decay.

5.2. Gamma Ray Emissions

5.2.1. Gamma Ray Energies (²³⁶U)

The energies of gamma rays accompanying the ²³⁶Np^m electron capture decay have been adopted from the evaluated DDEP data in ²⁴⁰Pu α -decay (2004Be).

5.2.2. Gamma Ray Energies (²³⁶Pu)

The energy of $\gamma_{1,0}$ (44,6 keV) accompanying the β^- - decay of ²³⁶Np^m has been adopted from measurements in 1983Ah02.

5.2.3. Gamma-Ray Emission Probabilities (²³⁶U)

The gamma-ray emission probability $P(\gamma)$ for $\gamma_{1,0}$ (45,2 keV) has been obtained from the ratio $\Sigma P(e_i)(45,2 \text{ keV}) / P(\gamma_{4,1})(642,3 \text{ keV}) = 9(3)$ measured in 1969Le05.

The evaluated gamma ray emission probability $P(\gamma_{4,1})(642,3 \text{ keV}) = 0,96(20)\%$ has been deduced using the following values:

- 1) $\Sigma P(e_{1,i})=53(1)\%$;
- 2) measured ratio $P(XK\alpha) / P(\gamma_{3,1})(642,3 \text{ keV})=27,6(10)$ from 1969Le05;
- 3) theoretical value of the ratio $P(XK\alpha)/P(XK\beta)=0,298(5)$;
- 4) relative (partial) intensities of gamma rays de-exciting level "4" [$\gamma_{4,2}$ (538,1 keV), $\gamma_{4,1}$ (642,3 keV), $\gamma_{4,0}$ (687,5 keV)], which have been deduced from the absolute gamma-ray emission probabilities evaluated in the ²⁴⁰Pu α -decay (Table 5), and a_K for these gamma-rays;
- 5) the measured ratio $\Sigma P_K(i) P(EC_{1,i}) / \Sigma P(\beta_{1,i})=0,75(15)$ from 1956Gr11, which can be represented as $P_K^{(\text{average})} = \Sigma P_K(i) P(EC_{1,i}) / \Sigma P(\beta_{1,i})=0,67(13)$.

The most accurate evaluation of $P_K^{(\text{average})}$ (and also the new evaluation of $P(\gamma_{4,1})$ (642,3 keV) and other values) may be obtained by using the theoretical $P_K(i)$, the values of $P(EC_{1,i})$ deduced from $P(\gamma_{4,1})(642,3 \text{ keV}) = 0,96(20)\%$, and the fact that a contribution of the third term (with $P(EC_{1,4})$) to $P_K^{(\text{average})}$ comprises $\sim 2,5\%$. This value has been taken as a fractional uncertainty for the $P_K^{(\text{average})} = 0,75(2)$. Using the latter and the relations 1) - 4) we have deduced a more accurate evaluation of $P(\gamma_{4,1})(642,3 \text{ keV}) = 1,08(6)\%$, and correspondingly a more accurate evaluation for other decay data.

The gamma-ray emission probability $P(\gamma_{2,1})$ (104,2 keV) has been calculated from $P(\gamma_{2,1} + ce)$ (104,2 keV) = $P(\gamma_{4,2} + ce)(538,1 \text{ keV})$ assuming that the electron capture feeding of level "2" is negligible.

Table 5. Experimental and evaluated absolute emission probabilities of gamma rays de-exciting the ²³⁶U level with energy of 687,6 keV in the decay of ²⁴⁰Pu (per 10⁸ a-decays) and the deduced relative intensities of these gamma rays

	Energy, keV	1969Le05	1971GuZY	1975OtZX	1975Dr05	1976GuZN	Evaluated	Evaluated relative intensities
$\gamma_{4,2}$	538,1	$\approx 0,23^a$		0,147(12)			0,147(12)	1,17(10)
$\gamma_{4,1}$	642,3	14,5 ^a	14,5(5) ^b	12,6(4)	13(1)	12,45(30)	12,6(3) ^c	100 (3)
$\gamma_{4,0}$	687,6	3,77(11)	3,70(15) ^b	3,30(13)		3,55(9)	3,56(15) ^d	28,3(13)

^a Omitted from averaging as uncertainty is not quoted

^b Omitted from averaging as the data of 1971GuZY have been revised in 1976GuZN

^c Weighted mean of 3 experimental values; the uncertainty is the smallest quoted uncertainty

^d Weighted mean of 3 experimental values; the uncertainty is external

5.2.4. Gamma-Ray Emission Probability (²³⁶Pu)

The gamma-ray emission probability $P(\gamma)$ for $\gamma_{1,0}$ (44,6 keV) has been obtained from $P(\beta_{1,1})$ and the adopted α_T for this gamma-ray transition.

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**²³⁷U - Comments on evaluation of decay data
by V. P. Chechev and N. K. Kuzmenko.**

This evaluation was completed in September 2005. The literature available by August 2005 was included.

1 Decay Scheme

The decay scheme has been adopted from 1996Firestone. See also 1995Ak01.

2 Nuclear Data

Q⁻ value is from 2003Au03.

The evaluated half-life of ²³⁷U is based on the experimental results given in Table 1.

Table 1. Experimental values of the ²³⁷U half-life (in days)

Reference	Author(s)	Value
1949Me43	Melander and Slatis	6,63 (5)
1953Wa05	Huizenga and Flynn	6,75 (1)
1958Ca16	Cabell <i>et al.</i>	6,752 (2)

The weighted mean of the 3 values from the Table 1 of 6,752 (2) is dominated by the very accurate value of 1958Ca16. The EV1NEW computer program, which uses the limitation of relative statistical weights by 0,5 (LRSW method), increased the 1958Ca16 uncertainty from 0,002 to 0,0098 and gave 6,749 (16). The adopted value of the ²³⁷U half-life is 6,749 (16) days.

2.1 b- Transitions

The energies of β⁻ transitions have been computed from the Q⁻ value and the level energies given in Table 2.

Table 2. ²³⁷Np levels populated in the ²³⁷U β⁻-decay

Level	Energy, keV	Spin and Parity	Half-life	Probability of β ⁻ -transitions (× 100)
0	0,0	5/2+	2,144 10 ⁶ y	-
1	33,1963 (3)	7/2+	54 ps	-
2	59,5409 (1)	5/2-	67 (5) ns	7 (6)
3	75,92 (4)	9/2 ⁺	~ 56 ps	-
4	102,96 (2)	7/2 ⁻	80 ps	-
5	267,54 (2)	3/2 ⁻	5,2 ns	40,7 (32)
6	281,35 (2)	1/2-	-	48,1 (25)
7	332,36 (3)	1/2 ⁺	< 1,0 ns	2,9 (6)
8	368,59 (3)	5/2 ⁺	-	-
9	370,93 (3)	3/2 ⁺	-	1,3 (7)

The probabilities of β⁻-transitions have been deduced from the P(γ + ce) balance for each level of ²³⁷Np. The

probability $P_{0,2}(\beta^-) = 7 (4) \%$ has been obtained as $100 - \sum P_{0,i}(\beta^-)$ where $i = 5 - 7,9$. For comparison $P_{0,2}(\beta^-)$ obtained from the $P(\gamma + ce)$ balance for level "2" is equal 7 (6) %.

Some experimental estimations of energy and probability of β^- transitions are given in 1949Me43, 1953Wa05 and 1957Ra04. More precise measurements are needed.

2.2 g Transitions

The evaluated energies of gamma-ray transitions are virtually the same as the gamma-ray energies because nuclear recoil is negligible.

The gamma-ray transition probabilities have been calculated from the gamma-ray emission probabilities and the total internal conversion coefficients (ICC) interpolated from 1978Ba60 and 1993Ba60. The relative uncertainties of $\alpha_K, \alpha_L, \alpha_M, \alpha_T$ for pure multipolarities have been taken as 2%.

The gamma transition multipolarities have been adopted from 1966Ya05, 1966Le13, 1959Sa10, 1964Wo03, 1966Ko06 and from the analysis of the ^{237}Np level scheme in 1995Ak01 and 1996Jo28.

ICC's for the anomalously converted gamma-transitions $\gamma_{2,1}$ (26,3- keV), $\gamma_{2,0}$ (59,5- keV) have been adopted from 1996Jo28, see also 1960As02 and 1966Ya05. The E2/M1 mixing ratio of 1,66 (25) % for $\gamma_{4,2}$ (43,4- keV) has been obtained by averaging the four measurement results from 1964Wo03, 1966Ko06, 1966Ya05 and 1998Ko61.

The E2/M1 mixing ratio of 15 (8) % for $\gamma_{9,7}$ (38,5 keV) has been deduced using the ratio $P_{ce}(L_2; \gamma_{9,7}) / P_{ce}(M_3; \gamma_{9,7}) = 10 (5)$ from 1966Ya05 and the theoretical values from 1993Ba60. $P_{\gamma+ce}(\gamma_{9,8} 2,3\text{-keV})$ has been calculated assuming that there is no β^- feeding to the 368,59-keV level.

$P_{\gamma+ce}(\gamma_{3,1} 42,7\text{-keV})$ and $P_{\gamma+ce}(\gamma_{3,0} 75,8\text{-keV})$ have been calculated from $P_{\gamma_{3,0}}/P_{\gamma_{3,1}} = 3/28$ (see 1995Ak01) assuming that there is no β^- feeding to the 75,92-keV level.

The gamma transitions with energies 114,09 keV and 340,45 keV are not placed in the level scheme.

3 Atomic Data

3.1. Fluorescence yields

The fluorescence yield data are from 1996Sc06 (Schönfeld and Janßen).

3.2 X rays and Auger electrons

The X L-ray energies are from 2001Sc08. The K X-ray energies and the relative K X-ray emission probabilities are from 1999 Schönfeld.

The energies of Auger electrons are from 1977La19 (Larkins) and 1987Lagoutine.

The ratios $P(\text{KLX})/P(\text{KLL})$, $P(\text{KXY})/P(\text{KLL})$ are from 1996Sc06.

4 Electron Emissions

The energies of the conversion electrons have been calculated from the gamma transition energies and the electron binding energies.

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

β^- average energies have been calculated using the LOGFT program.

5 Photon emissions

5.1 X-ray Emissions

The absolute emission intensities of U K X and L X-rays have been calculated using the EMISSION program. In Table 3 some of these calculated values are compared to experimental data.

Table 3. Experimental and adopted (calculated) absolute Np K X- ray emission intensities in the decay of ^{237}U

	Energy, keV	1966Ya05	1976GuZN	Adopted
$\text{K}\alpha_2$	97,069	16,2 (17)	15,8 (7)	14,7 (4)
$\text{K}\alpha_1$	101,059	22,6 (24)	25,2 (8)	23,4 (6)
$\text{K}'\beta_1$	113,944	9,8 (10)	9,22 (24)	8,50 (27)
$\text{K}'\beta_2$	117,463	3,1 (4)	2,3 (5)	2,92 (10)

Np L X- ray emission intensities in the decay of ^{237}U calculated from the decay scheme data set are :

	Energy, keV	Adopted
XL	11,89 – 22,20	51,3 (3)
Ll	11,89	1,22 (5)
$\text{L}\alpha$	13,76 – 13,93	19,5 (5)
$\text{L}\eta$	15,88	0,44 (4)
$\text{L}\beta$	16,13 – 17,99	24,2 (12)
$\text{L}\gamma$	20,12 – 22,2	5,8 (3)

5.2 Gamma-rays emissions

The energies of gamma rays $\gamma_{2,1}$ (26,3-keV) and $\gamma_{2,0}$ (59,5-keV) are from 2000He14. $E_{\gamma_{1,0}}$ (33,2 keV) has been calculated as the difference $E_{\gamma_{2,0}} - E_{\gamma_{2,1}}$. The energies of gamma rays $\gamma_{4,3}$, $\gamma_{3,1}$, $\gamma_{4,2}$ have been taken from 1998Ko61. The rest gamma-ray energies have been adopted from 1996Firestone based on experimental data of 1996Ya05, and 1976GuZN. Other measurements: 1957Ra04, 1963Ak04, 1968Da24, 1971Cl03.

In Table 4 the experimental and evaluated absolute gamma ray emission probabilities (P_γ) are presented.

Table 4. Experimental and evaluated absolute gamma-ray emission probabilities ($\times 100$) in the decay of ^{237}U .

E_γ , keV	1966Ya05	1971Cl03	1976GuZN	1982BuZF	1984BaYS	1985He02	1985Wi04	Evaluated
51,01	0,21 (10)		0,340 (14)		0,44 (6)			0,36 (7)
59,54	32,9 (40)	32,8 (25)	34,5 (8)		33,8 (9)			34,1 (8)
64,83	1,15 (16)	1,19 (9)	1,30 (3)		1,31 (5)		1,282 (17)	1,286 (17)
164,61	1,80 (9)	1,82 (14)	1,84 (5)		1,85 (5)	1,865(23)	1,853 (23)	1,855 (23)
208,00			21,7 (5)	21,5 (14)		21,2 (3)	21,2 (3)	21,28 (30)
221,80	0,0199 (18)	0,0182 (14)	0,0212 (8)		0,0199 (25)			0,0204 (8)
234,40	0,0190 (18)	0,0273 (20)	0,0205 (8)		0,0224 (40)			0,0216 (18)
267,54	0,698 (30)	0,755 (20)	0,740 (18)		0,723 (25)	0,714 (22)	0,711 (10)	0,721 (10)
332,36	1,18 (8)	1,19 (9)	1,21 (3)		1,18 (4)		1,200 (16)	1,199 (16)
335,38	0,094 (9)	0,109 (9)	0,097 (3)		0,092 (5)		0,0951 (22)	0,0958 (22)
368,59	0,045 (4)	0,044 (3)	0,043 (2)		0,042 (3)		0,0392 (17)	0,0416 (17)
370,94	0,109 (9)	0,125 (10)	0,110 (4)		0,109 (6)		0,1073 (17)	0,109 (2)

Measurement results for gamma ray emission probabilities given in 1976GuZN, 1982BuZF, 1985He02, 1985Wi04 are absolute. Measurements results given in 1966Ya05, 1971Cl03, 1984BaYS are relative. The latter have been renormalized by evaluators at $P_\gamma(208 \text{ keV}) = 21,3 (3) \%$.

$P_{\gamma_{6,5}}$ has been calculated from $P_{ce}(M1) = 29,9 (3) \%$ and $\alpha_{M1} = 280 (9)$.

$P_{\gamma_{4,1}}$ has been calculated from $P_{\gamma_{4,1}}/P_{\gamma_{4,2}} = 2,9 (4)/73 (8)$, as measured in ^{241}Am α -decay (see 1995Ak01).

$P_{\gamma_{4,0}}$ has been calculated from $P_{\gamma_{4,0}}/P_{\gamma_{4,2}} = 19,5 (1)/73 (8)$, as measured in ^{241}Am α -decay (see 1995Ak01).

$P_{\gamma_{8,2}}$ has been calculated from $P_{\gamma_{8,2}}/P_{\gamma_{8,1}} = 10,14/49,6$ as measured in ^{241}Am α -decay (see 1995Ak01).

$P_{\gamma_{8,3}}$ has been calculated from $P_{\gamma_{8,3}}/P_{\gamma_{5,2}} = 0,00012 (3)$, as measured by 1966Ya05.

$P_{\gamma_{9,7}}$ has been calculated by evaluators from the ratio $P_{ce}(L_2; \gamma_{9,7})/P_{ce}(K; \gamma_{5,2}) = 0,0056 (20)$ from 1966Ya05 and total ICC's.

$P_\gamma(340,4\text{-keV})$ has been adopted from 1976GuZN.

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²³⁸U - Comments on evaluation of decay data by V. Chisté and M.M. Bé

This evaluation was completed in January 2006, and the literature available at this date has been included here.

1 Decay Scheme

²³⁸U disintegrates by alpha emission to two excited levels and to the ground state of ²³⁴Th. Spin and half-lives of excited states are from the mass-chain evaluation of Y.A. Akovali (1983E111 and 1994Ak05 for A = 234) and F.E. Chukreev (2002Ch52 for A = 238).

2 Nuclear Data

The Q value is from the atomic mass evaluation of Audi *et al.* (2003Au03).

Experimental ²³⁸U half-life values (in years x 10⁹) are given in Table 1:

Table 1: Experimental values of ²³⁸U half-life.

Reference	Original value (10 ⁹ a)	Revised Value by Schön (2004Sc03)	Comments
Kovarik (1932Ko01)	4.52		Not used. Natural U.
Schiedt (1935Schiedt)	4.42 (3)	4.46 (3) (a) 4.41 (5) (b)	Not used. Natural U. Corrected for ²³⁵ U. (a) ²³⁴ U and ²³⁸ U assumed to be in equilibrium. (b) ²³⁴ U and ²³⁸ U assumed to be not in equilibrium.
Curtis (1941Curtis)	4.514 (9)		Not used. Natural U. Lacking details.
Kienberger (1949Ki26)	4.490 (10)	4.495 (18)	Not used. Enriched U.
Kovarik (1955Ko13)	4.507 (9)	4.51 (2) (a) 4.46 (5) (b)	Not used. Natural U. (a) ²³⁴ U and ²³⁸ U assumed to be in equilibrium. (b) ²³⁴ U and ²³⁸ U assumed to be not in equilibrium.
Lechman (1957Le21)	4.56 (3)		Not used. Enriched U.
Steyn (1959St45)	4.460 (10)	4.457 (4) (a) 4.41 (4) (b)	Not used. Natural U. (a) ²³⁴ U and ²³⁸ U assumed to be in equilibrium. (b) ²³⁴ U and ²³⁸ U assumed to be not in equilibrium.
Jaffey (1971Ja07)	4.4683 (24)	4.468 (5)	Highly enriched U.
Recommended value		4.468 (5)	

The evaluators have chosen to follow the recommendations given by R. Schön (2004Sc03), who studied in detail various problems with the measurements of the half-life of ²³⁸U. So, the recommended value is the half-life obtained by Jaffey (1971Ja07), but its original uncertainty was multiplied by 2 (as suggested by Schön (2004Sc03)) in order to take into account the systematic uncertainties which were not considered by 1971Ja07.

Experimental ²³⁴Th half-life values (in days) are given in Table 2:

Table 2: Experimental values of ^{234}Th half-life.

Reference	Value (d)	Uncertainty (d)
M. Curie (1931Cu01)	24.5	
B.W. Sargent (1939Sa11)	24.1	0.2
G.B. Knight (1948Kn23)	24.101	0.025
Recommended value is (from 1994Ak05)	24.10	0.03

The recommended value is $24.10 d$ with an uncertainty of $0.03 d$, from Y. A. Akovali (1994Ak05).

The evaluated spontaneous fission partial half-life of ^{238}U is based on the experimental results given in Table 3.

Table 3: Experimental values of spontaneous fission decay rate of ^{238}U (λ^{238} , in 10^{-17} years $^{-1}$).

Reference	Value	Uncertainty	Comments by Holden (2000Ho27)
W.J. Withehouse (1950Whitehouse)	8.38	0.52	Ionization chamber.
E. Sègres (1952Se67)	8.60	0.29	Ionization chamber.
R.L. Fleischer (1964Fl07)	6.85	0.20	Not used. Mica-uranium sandwich.
A. Spadavecchia (1967Sp12)	8.42	0.10	Rotating bubble chamber.
J.H. Roberts (1968Ro15)	7.03	0.11	Not used. Mica-uranium sandwich.
H.R. von Gunten (1969Vo24)	8.66	0.22	Fission products of ^{238}U .
D. Galliker (1970Ga27)	8.46	0.06	Rotating bubble chamber.
D. Storzer (1970Storzer)	8.49	0.76	Fission tracks in dated uranium glass.
J.D. Kleeman (1971Kl14)	6.8	0.6	Not used. Lexam-uranium sandwich.
W.M. Thury (1971Th17)	8.66	0.43	Third order coincidence.
M.P.T. Leme (1971Le11)	7.30	0.16	Not used. Mica-uranium sandwich.
H.A. Khan (1973Kh10)	6.82	0.55	Not used. Mica-uranium sandwich.
K.N. Ivanov (1974Iv01)	7.12	0.32	Not used. Mica-uranium sandwich.
V. Emma (1975Em03)	7.2	0.2	Not used. Mica-uranium sandwich.
G.A. Wagner (1975Wa37)	8.7	0.6	Fission tracks in dated uranium glass.
K. Thiel (1976Th12)	8.57	0.42	Fission tracks in dated uranium glass.
M. Kase (1978Ka40)	8.22	0.20	Ionization chamber.
A.G. Popeko (1980Po09)	7.9	0.4	Multiple neutron coincidence.
E.R.V. Spaggiari (1980Sp10)	9.26	0.17	Not used. Mica-uranium sandwich.
Z.N.R. Baptista (1981Ba70)	6.6	0.2	Not used. Mica-uranium sandwich.
J.C. Hadler (1981Hadler)	8.6	0.4	Not used. Mica-uranium sandwich.
H.G. de Carvalho (1982De22)	11.8	0.7	Not used. Fission tracks in ordinary glass.
S.N. Belenky (1983Be66)	8.35	0.40	Multiple neutron coincidence.
B. Vartanian (1984Va34)	8.23	0.43	Not used. Fissions tracks (plastic, uranium foils).
M.P. Ivanov (1985Iv01)	8.29	0.27	Double ionization chamber.
S.S. Liu(1991Liu)	7.03	0.21	Not used. Solid-state track detectors.
Recommended value of λ^{238} (in 10^{-17} years $^{-1}$)	8.451	0.060	reduced $\chi^2 = 0.30$
Recommended half-life value (in 10^{15} years)	8.202	0.060	

The evaluators, following the recommendations of N.E. Holden (2000Ho27), have not used in their calculations the measurements with fission tracks in mica-uranium, lexan-uranium sandwiches or ordinary glass, because they significantly disagree with the rest (for more details see 2000Ho27). Thus the experimental values with associated uncertainties used in the weighted average calculation are those from 1950Whitehouse, 1952Se67, 1967Sp12,

1969Vo24, 1970Ga27, 1970Storzer, 1971Th17, 1975Wa37, 1976Th12, 1978Ka40, 1980Po09, 1983Be66 and 1985Iv01. A weighted average has been calculated using LWEIGHT computer program (version 3). Based on the Chauvenet's criterion, Popeko's value (1980Po09) has been shown to be an outlier.

The recommended value of λ^{238} is the weighted average (calculated with LWEIGHT computer program) of $8.451 \cdot 10^{-17} a^{-1}$ with an internal uncertainty of $0.046 \cdot 10^{-17} a^{-1}$. However, evaluators have adopted an uncertainty of $0.060 \cdot 10^{-17} a^{-1}$, minimum input value.

Using this value of λ^{238} and the formula:

$$t_{1/2} = \frac{\ln(2)}{\lambda^{238}},$$

the evaluators have deduced a partial spontaneous fission half-life of $8.202(60) \cdot 10^{15} a$ for ^{238}U and a spontaneous fission branching of $5.45(4) \cdot 10^{-05} \%$.

2.1 a Transitions and Emissions.

The energies of the α -particle transitions given in Section 2.1 have been calculated from Q_α (2003Au03) and level energies.

The energies of $\alpha_{0,0}$, $\alpha_{0,1}$ and $\alpha_{0,2}$ emissions given in Section 4 are from A. Rytz (1991Ri01).

Measured α -emission intensities are given in Table 4.

Table 4: Measured α -emission intensities, in %.

Energy (keV)	1959Ko58	2000Ga05	Recommended Value
4198 ($\alpha_{0,0}$)	77 (4)	77.54 (50)	77.54 (50)
4151 ($\alpha_{0,1}$)	23 (4)	22.33 (50)	22.33 (50)
4038 ($\alpha_{0,2}$)	0.23 (7)	0.13 (3)	0.13 (3)

The results of these two intensity measurements (1959Ko58 and 2000Ga05) are consistent with each other. Evaluators have adopted the most recent and precise results of Garcia-Toraño (2000Ga05).

2.2 g Transitions

The γ -ray probabilities of the 49- and 113-keV transitions have been deduced from decay-scheme balance by using the recommended experimental alpha emission intensity values (2000Ga05). (see **2.1 a Transitions and Emissions**).

Multipolarities of γ -ray transitions in the decay of ^{234}Th are from 1994Ak05:

49-keV γ -ray : E2

113-keV γ -ray: [E2]

The internal conversion coefficients (ICC's) have been calculated using the Icc99v3a computer program (GETICC dialog), which uses the new tables of Band et al (2002Ba85) (results of calculation for "hole" and "no hole" are the same). The evaluators have used a fractional uncertainty of 3 % for all conversion coefficients.

3 Atomic Data

Values of atomic values quantities ω_K , ω_L and n_{KL} , are from Schönfeld and Janßen (1996Sc06).

3.1 X rays and Auger electrons

The relative probabilities of X-ray and Auger electrons have been calculated from γ -ray data using the EMISSION computer program.

4 a Emissions

See **2.1 a Transitions and Emissions**.

5 Electron emissions

The Auger electrons emission probabilities have been calculated from γ -ray data using the EMISSION computer program.

6 Photon Emissions

6.1 K x-rays

X-ray emission probabilities have been calculated from γ -ray data using the EMISSION computer program.

6.2 g-ray emissions

The energies of the γ -ray emissions given in Section 6 are from Y.A. Akovali (1994Ak05).

The absolute γ -ray emission intensities have been deduced from the absolute γ -ray transition probabilities and the internal conversion coefficients (ICC's). (see **2.2 g Transitions**).

Table 5 shows the recommended absolute γ -ray (photon) emission intensities of the 49- and 113-keV emissions as well as the experimental results obtained from direct measurements of emission intensities.

The agreement is not good, maybe due to experimental difficulties (many peaks of different contaminant isotopes in this energy region) when measuring these weak γ -ray intensities.

Table 5: Experimental absolute γ emission intensity in %.

γ Energy (keV)	1984Ro21	1990Ko40	1996Ru11	Recommended value
49.55	0.064 (8)	0.059 (2)		0.0698 (26)
113.5	0.0102 (15)		0.07 (1)	0.0174 (47)

A fair agreement has been found between the results given by J-C. Roy (1984Ro21) and the evaluators' recommended value for the 49-keV γ -ray.

For the 113-keV γ -ray, there is no good agreement either between results of direct experimental measurements or between those latter and the recommended value. In this energy region the experimental difficulties are associated with presence of many small peaks from different isotopes in the γ -ray spectrum.

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²⁴²Cm - Comments on evaluation of decay data by V. P. Chechev

This evaluation was completed in December 2004 and corrected in February 2005. The literature available by November 2004 was included.

1 Decay Scheme

The decay scheme is based on the evaluation of Chukreev *et al.* (2002Ch52) and can be considered essentially complete although some weak gamma-ray transitions have not been observed in ²⁴²Cm alpha decay. Such gamma rays were taken from ²³⁸Am→²³⁸Pu, ²³⁸Np→²³⁸Pu decays and have been included in the decay scheme.

2 Nuclear Data

Q(α) is from 2003Au03.

The evaluated half-life of ²⁴²Cm is based on the experimental results given in Table 1. Re-estimated values were used for averaging when needed.

Table 1. Experimental values of the ²⁴²Cm half-life (in days)

Reference	Author(s)	Original value	Re-estimated value	Measurement method
1950Ha14	Hanna et al.	162.5(20)	-	α-counting with low geometry counter
1954G137	Glover and Milsted	162.46(14) ^a	162.46(32) ^c	α-counting with low geometry counter
1954Hu32	Hutchinson and White	163.0(18)	-	Calorimetry
1957Treiman	Treiman et al.	162.7(1)	-	Calorimetry
1965F102	Flynn et al.	164.4(4)	163.1(4) ^d	2π α counting
1975Ke02	Kerrigan and Banick	163.2(2) ^b	-	Calorimetry
1977Di04	Diamond et al.	162.76(4)	162.76(8) ^c	Intermediate geometry α-counting
1979Ch41	Chang et al.	163.02(11)	163.02(18) ^c	α-counting with low geometry counter
1980Jadhav	Jadhav et al.	162.13(215)	162.13(225)	α-spectrometry with solid state detector
1981Us03	Usuda and Umezawa	161.35(20)	161.35(30) ^c	α-counting with 2π proportional counter
1982Ag02	Aggarwal et al.	163.17(6)	163.17(11) ^c	α-counting with proportional counter
1982Ag02	Aggarwal et al.	162.82(21)	162.82(26) ^c	α-spectrometry with solid state detector
1984Wi14	Wiltshire et al.	163.0(2)	-	α-counting with low geometry counter

^a The uncertainty of 0.27 quoted by authors, which corresponds to 95% confidence level, has been reduced by a factor 2.

^b The uncertainty of 0.04 quoted by authors, which corresponds to 95% confidence level, has been reduced by a factor 2.

^c Quoted uncertainties have been re-estimated in 1986LoZT.

^d The value has been recalculated in 1977Di04.

The LWIGHT and EV1NEW computer programs identified two outliers in the above data set. These are the values from 1981Us03 and 1980Jadhav. Omitting these values in the calculation and using the remaining 11 results produced a weighted mean of 162.86 with an internal uncertainty of 0.05 and an external uncertainty of 0.06 ($\chi^2/\nu = 1.6$). The EV1NEW program has chosen the smallest experimental uncertainty of 0.08 as the uncertainty of the weighted average.

Thus the adopted value of the ²⁴²Cm half-life is 162.86(8) days.

The evaluated spontaneous fission partial half-life of ²⁴²Cm is based on the experimental results given in Table 2. Re-estimated values were used for averaging when needed.

Table 2. Experimental values of the ²⁴²Cm spontaneous fission half-life (in 10⁶years)

Reference	Author(s)	Original value	Re-estimated value ^a	Measurement method
1951Ha87	Hanna et al.	7.2(2)	-	Fission fragment counting, ionization chamber
1967Ar09	Armani and Gold	6.09(18)	6.82(18)	Fission neutron counting, LiI detector
1979Ch41	Chang et al.	7.46(6)	-	Mica fission track detector
1982Ra33	Raghuraman et al.	7.15(15)	-	Solid state detector
1982UmZZ	Umezawa et al.	6.89(17)	-	Mica fission track detector
1986Ze06	Zelenkov et al.	6.9(3)	6.98(33)	α /SF, Si(Au) detectors
1989Us04	Usuda et al.	6.96(18)	-	Absolute fission track counting

^a Recalculated in 2000Ho27

Omitting the value of 1979Ch41 (outlier) the weighted mean of the six remaining values becomes 7.005 with an internal uncertainty of 0.076 and an external uncertainty of 0.063 ($\chi^2/\nu = 0.69$).

The adopted value of the ²⁴²Cm spontaneous fission half-life is 7.01(15) 10⁶ years, where the uncertainty is the smallest quoted uncertainty of 6 experimental results.

2.1 a Transitions

The energies of the alpha-particle transitions given in Section 2.1 have been calculated from the Q value and the level energies given in Table 3 from 2002Ch52.

Table 3. ²³⁸Pu levels populated in the ²⁴²Cm α-decay

Level number	Energy, keV	Spin and parity	Half-life	Probability of α-transition (x100)
0	0.0	0 ⁺	87.74(3) yr	74.06(7)
1	44.08(3)	2 ⁺	177(5) ps	25.94(7)
2	146.00(5)	4 ⁺		0.034(2)
3	303.42(7)	6 ⁺		0.0046(5)
4	513.62(16)	8 ⁺		2×10 ⁻⁵
5	605.08(7)	1 ⁻		2.5(5)×10 ⁻⁴
6	661.28(11)	3 ⁻		1.3(3)×10 ⁻⁵
7	763.22(12)	5 ⁻		£ 2.2×10 ⁻⁷
8	941.44(9)	0 ⁺		3.5(7)×10 ⁻⁵
9	962.72(8)	1 ⁻		1.13(21)×10 ⁻⁶
10	983.00(9)	2 ⁺		1.7(5)×10 ⁻⁶
11	1018.6(3)	1 ⁻		≤ 2×10 ⁻⁷
12	1028.62(5)	2 ⁺		3.7(10)×10 ⁻⁶
13	1125.79(17)	(4 ⁺)		3.1(10)×10 ⁻⁷
14	1228.69(22)	0 ⁺		5.5(15)×10 ⁻⁷
15	1264.29(22)	2 ⁺		5.2(14)×10 ⁻⁷

The emission probabilities of the most intensive transitions α_{0,i} (i = 0 to 4) have been obtained by averaging experimental data (Table 4). The emission probabilities of the remaining α-particle transitions have been deduced either from the P(γ+ce) decay-scheme balances or by averaging experimental and deduced values (for example, α_{0,5}).

Table 4. Experimental, calculated and evaluated α-transition probabilities (×100) in ²⁴²Cm decay

	a-particle energy, keV	1953As14	1958Ko87	1963Dz07	1966Ba07	1998Ya17	Deduced from decay-scheme balance ^c	Evaluated
α _{0,0}	6113	73.7(5)	73.5(5)	74(2)	74.2(5) ^a	74.08(7)		74.06(7) ^d
α _{0,1}	6069	26.3(5)	26.5(5)	26.0(9)	25.8(5) ^a	25.92(6)		25.94(7) ^d
α _{0,2}	5969	0.035(2) ^a	0.030(2) ^b	0.035(2)	0.036(2) ^a			0.034(2) ^e
α _{0,3}	5816		0.0046(5)		0.0046			0.0046(5) ^f
α _{0,4}	5608			1963Bj01	2·10 ⁻⁵			2·10 ^{-5g}
α _{0,5}	5518			2.8(5)·10 ⁻⁴	2.5(6)·10 ⁻⁴		2.6(7)·10 ⁻⁴	2.5(5)·10 ^{-4e}
α _{0,6}	5462						1.3(3)·10 ⁻⁵	1.3(3)·10 ^{-5c}
α _{0,7}	5366						2.2·10 ⁻⁷	2.2·10 ^{-7c}
α _{0,8}	5187			3.4(8)·10 ⁻⁵	2.5(8)·10 ⁻⁵		3.5(7)·10 ⁻⁵	3.5(7)·10 ^{-5c}
α _{0,9}	5166						1.13(21)·10 ⁻⁶	1.13(21)·10 ^{-6c}
α _{0,10} ^h	5146				≤ 5·10 ⁻⁶		1.7(5)·10 ⁻⁶	1.7(5)·10 ^{-6c}

^a No uncertainties are quoted by the authors. The uncertainties have been adopted by the evaluator based on the similarity of the spectra measured with magnetic spectrometers in 1953As14, 1958Ko87 and 1966Ba07.

^b The uncertainty of 0.001 quoted by authors has been increased by a factor of 2 by the evaluator (see ^a).

^c Calculated from P($\gamma + ce$) decay-scheme balances for corresponding ²³⁸Pu levels.

^d Weighted average of experimental values. The experimental data of 1998Ya17 have been obtained by the most accurate method (using a semiconductor detector).

^e Weighted average of experimental and deduced values.

^f Adopted experimental value from 1958Ko87.

^g Adopted experimental value from 1966Ba07.

^h The probabilities of remaining alpha-transitions ($\alpha_{0,11}$ and $\alpha_{0,15}$) have been calculated from P($\gamma + ce$) decay-scheme balances.

2.2 g Transitions and Internal Conversion Coefficients

The evaluated energies of gamma-ray transitions are essentially the same as the gamma-ray energies because nuclear recoil is negligible.

The probabilities, P($\gamma + ce$), for gamma-ray transitions of 44-($\gamma_{1,0}$), 102-($\gamma_{2,1}$), 157-($\gamma_{3,2}$), and 210-keV ($\gamma_{4,3}$) have been deduced from transition- probability balances, using the emission probabilities of α -transitions directly measured.

For E0- gamma transitions 941-($\gamma_{8,0}$) and 1229-keV ($\gamma_{14,0}$) the P($\gamma+ce$) values have been taken from data on the electron capture decay ²³⁸Am \rightarrow ²³⁸Pu (see 2002Ch52 and references therein).

The remaining P($\gamma+ce$) values have been calculated from the gamma-ray emission probabilities and the total internal conversion coefficients (ICC's). The experimental values of ICC's have been adopted for (E0+E2)gamma-ray transitions 939-($\gamma_{10,1}$) and 1220-keV ($\gamma_{15,1}$). The remaining ICC's have been interpolated from tables of 1978Band and 1993Ba60 using the computer program "ICC99v3.a". The relative uncertainties of α_K , α_L , α_M , α_T for pure multipolarities have been taken as 2%.

The multipolarities and E2/M1, M2/E1 mixing ratios have been taken from 2002Ch52. These are based on conversion electron measurements of 1952Du12, 1956Ba95, 1956Sm18, 1960As10, and 1965Ak02 made in the ²⁴²Cm α -decay.

3 Atomic Data

3.1 Fluorescence yields

Fluorescence yield data are from 1996Sc06 (Schönfeld and Janßen).

3.1.1 X rays

The Pu KX-ray energies and relative emission probabilities have been taken from 1999Schönfeld, where the calculated energy values are based on X-ray wavelengths from 1967Be65 (Bearden). In Table 5 the adopted values of Pu KX-ray energies are compared with experimental results.

Table 5. Experimental and adopted (calculated) values of Pu KX-ray energies (keV)

	1980Di13	1982Ba56	Adopted
K α_2	99.55(3)	99.530(2)	99.525
K α_1	103.76(3)	103.741(2)	103.734
K β_3	116.27	116.242(2)	116.244
K β_1	117.26	117.233(2)	117.228
K $\beta_{2,4}$	120.60(15)	-	120.553
KO $_{2,3}$	121.55(6)	-	121.543

The Pu KX-ray energies in 1980Di13 were measured in the alpha decay of ²⁴⁵Cm. The relative emission probabilities of KX-rays were given as:

$$K\alpha_2:K\alpha_1:K\beta_3:K\beta_1:K\beta_{2,4} = 64.7(23):100.0(33):12.9(7):23.1(10):8.9(5).$$

3.1.2 Auger Electrons

The energies of Auger electrons have been calculated from atomic electron binding energies.

The P(KLX)/P(KLL), P(KXY)/P(KLL) ratios have been taken from 1996Sc06.

4 a Emissions

The energy of the alpha-particle group to the ground state of ²³⁸Pu, E($\alpha_{0,0}$) is from the absolute measurement of 1971Gr17, with a correction of -0.20 keV recommended by A.Rytz in 1991Ry01.

The energies of all other α particles have been calculated from Q_α and the various ²³⁸Pu level energies including the recoil energy corrections (see 2002Ch52).

In Table 6 the calculated (evaluated) values of α -particle energies are compared with the experimental results obtained with magnetic alpha spectrometers.

Table 6. Experimental^a and evaluated α -emission energies in the decay of ²⁴²Cm, keV

	1953As14	1958Ko87	1963Dz07	1966Ba07 1971Bb10	1971Gr17	Evaluated
$\alpha_{0,0}$	6113	6114	6113(1)	6112.9(3)	6112.72(8)	6112.72(8)
$\alpha_{0,1}$	6069	6070	6069(1)	6069.5(5)	6069.43(12)	6069.37(9)
$\alpha_{0,2}$	5968	5968(2)	5969(3)	5970		5969.24(9)
$\alpha_{0,3}$	-	5816(2)	-	5817		5816.39(11)
$\alpha_{0,4}$	-	-	-	5609		5607.76(16)
$\alpha_{0,5}$	-	-	-	5514		5517.75(11)
$\alpha_{0,8}$	-	-	-	5189		5186.95(12)
$\alpha_{0,10}$	-	-	-	5146		5146.07(12)

^a Authors' values have been adjusted for changes in calibration energies (see 1991Ry01)

5 Electron Emissions

The energies of conversion electrons have been calculated using gamma-ray transition energies and electron binding energies. The emission probabilities of conversion electrons have been deduced from the evaluated $P(\gamma)$ and ICC values.

The total absolute emission probability of K Auger electrons has been calculated using the evaluated total emission probability of K– conversion electrons $P(\text{ce}_K) = 0.00027$ (5) % and the adopted ω_K given in section 3. The total absolute emission probability of L Auger electrons has been calculated using the evaluated total absolute emission probability of L – conversion electrons $P(\text{ce}_L) = 18.8$ (4) % and the adopted ω_L given in section 3.

6 Photon emissions

6.1. X-Ray Emissions

The absolute emission probabilities of Pu KX-rays have been calculated using the adopted value of $\omega_K(\text{Pu})$, the evaluated total absolute emission probability of K conversion electrons (see above) and relative intensities of KX-ray components from 1999Schönfeld.

The absolute emission probabilities of Pu LX-rays have been calculated with the program EMISSION using the adopted values of $\omega_L(\text{Pu})$, $\omega_K(\text{Pu})$, $n_{KL}(\text{Pu})$ and the evaluated total absolute emission probabilities of L- and K- conversion electrons. The calculated total absolute emission probability of LX-rays $P(\text{XL}) = 9.8$ (5)% agrees well with the experimental value of 9.70 (14) % from 1970By01 and disagrees with the value of 11.7(3)% measured in 1971Swinth.

The relative Pu LX-ray emission probabilities in ²⁴²Cm α -decay measured in 1990Po14 [4.9(8)-L1 ; 66(7)-L α ; 100-L $\eta\beta$; 23(3)-L γ] agree well with the values calculated using the computer program EMISSION with the exception of $L\alpha/L\eta\beta^{\text{calc.}} = 79(4)/100$. The latter agrees well with the experimental result from 1995Jo23 $L\alpha/L\eta\beta(\text{Pu}) = 80.9(9)/100$, obtained for LX-rays in the decay of other even-even curium isotope – ²⁴⁴Cm.

6.2 Gamma Emissions

6.2.1. Gamma Ray Energies

The energy of the 44-keV gamma ray ($\gamma_{1,0}$) is from ²³⁸Np → ²³⁸Pu β^- decay (1972Wi22); it agrees with the less accurate measurements in ²⁴²Cm α -decay (44.11(5) keV - 1956Sm18) and in ²³⁸Am ϵ -decay (44.1(1) keV - 1972Ah04).

The energies of the 102-($\gamma_{2,1}$), 157-($\gamma_{3,2}$), 336-($\gamma_{8,5}$), 358-($\gamma_{9,5}$), 605-($\gamma_{5,0}$), 940-($\gamma_{10,1}$), and 941-keV($\gamma_{8,0}$) gamma rays have been obtained from the available experimental data of 1981Le15 (²⁴²Cm α -decay and ²³⁸Np β^- decay), 1972Wi22, 1972Ah04, 1956Sm18, and 1971Po09 (²³⁸Am ϵ -decay) using the adopted ²³⁸Pu level energies.

The energies of the 210-($\gamma_{4,3}$), 617-($\gamma_{7,2}$), and 883-keV ($\gamma_{12,2}$) gamma rays, which were not observed in the ²⁴²Cm α -decay, have been deduced from the adopted level energies. The energies of the remaining gamma rays have been taken from the measurements of 1981Le15 (²⁴²Cm α -decay).

6.2.2. Gamma-Ray Emission Probabilities

The absolute emission probabilities for gamma-rays of 44-($\gamma_{1,0}$), 102- ($\gamma_{2,1}$), 157-($\gamma_{3,2}$), and 210-keV ($\gamma_{4,3}$)

have been deduced from decay-scheme intensity balances using the probabilities of α -transitions evaluated directly from experimental data.

The absolute emission probabilities of > 300 keV gamma-rays (except for 883- and 1229-keV γ rays) have been obtained from relative gamma-ray emission probabilities $P(\gamma)/P(\gamma 561\text{keV})$ measured in 1981Le15. The normalization factor $P(\gamma 561\text{keV}) = 1.5 \cdot 10^{-4}$ per 100 disintegrations, which was used here, was estimated in 1981Le15 using a previous $\alpha\gamma$ coincidence measurement of the sum of the absolute emission probabilities of the 515-, 561-, 605-, and 617-keV($\gamma_{7,2}$) gamma rays (1963Le17).

$P(\gamma 883\text{keV})$ and $P(\gamma 1229\text{keV})$ are from 2002Ch52, using the experimental data on ²³⁸Np β^- -decay and ²³⁸Am ϵ -decay, respectively.

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Evaluation Procedures

The *Limitation of Relative Statistical Weight* (LWM) [1985ZiZY] method, used for averaging numbers throughout this evaluation, provided a uniform approach for the analysis of discrepant data. The uncertainty assigned in this evaluation to the recommended value is always greater than or equal to the smallest uncertainty in any of the experimental values used in the calculation. Most of the experimental data available for this evaluation was of limited quality.

1 Decay Scheme

²⁴³Am decays 100 % by emission of α particles, with a minute branch of $3.8(7) \times 10^{-9}\%$ (2002Sa53) by spontaneous fission. Other value: $3.7(9) \times 10^{-9}\%$ (1966Gv01). The α -particle probabilities (in percent) to individual levels presented in the decay scheme are experimental values from α -spectroscopic measurements. α -hindrance factors given in the decay scheme have been calculated by using a radius parameter $r_0(^{239}\text{Np}) = 1.505$, average of $r_0(^{238}\text{U}) = 1.5143(9)$, $r_0(^{240}\text{U}) = 1.5062(10)$, $r_0(^{238}\text{Pu}) = 1.5013(10)$, and $r_0(^{240}\text{Pu}) = 1.4979(7)$ (1998Ak04). The level energies, spins, parities, as well as γ -ray multiplicities and mixing ratios shown in the decay scheme are recommended values from the evaluation 2003Br12.

Levels at 71- and 122 keV are based on α - γ coincidence experiments with γ rays (169-, 50.6-, and 195 keV) that feed such levels. The de-excitations of these two levels, however, have not been observed. The expected γ rays may have been masked by more intense ones, which de-excite other levels.

2 Nuclear Data

The recommended half-life of ²⁴³Am is 7370 y, a weighted average (LWM) ($\chi^2/\nu = 0.64$) of the values given in Table 1. The calculated internal uncertainty is 14 y. However, the recommended uncertainty is the smallest uncertainty in the input values, i.e., 17 y. This half-life compares well with other recommended values such as 7370 (40) y (1992Ak06), 7366 (20) y (1991BaZS), and 7370 (15) y (1986LoZT).

$Q_\alpha = 5438.8(10)$ keV is from the atomic mass adjustment 2003Au03.

Table 1. ²⁴³Am measured half-life values

Reference	Method	$T_{1/2}({}^{243}\text{Am})/T_{1/2}({}^{241}\text{Am})$	$T_{1/2}({}^{243}\text{Am})$ (years)	Remarks
1959Ba22	Relative activity	16.85 (35)	7283 (152)*	
1960Be10	Relative activity	16.70 (10)	7218 (100)*	An uncertainty of 1.4% (100 y) from 1960Be10 is mostly systematic. Thus, dividing this value by the square root of the number of measurements (5) is questionable and was not done either in the evaluation 1986LOZT or here.
1968Br22	Relative activity	16.96 (13)	7330 (57)*	
	Specific activity		7390 (50)	
1974Po17	Relative activity	17.08	7382 (190)*	Uncertainty is from 1974Po17 as quoted in 1980Ag05.
	Specific activity		7380 (17)	
1980Ag05	Relative activity	17.010 (95)	7352 (42)*	
	Recommended value		7370 (17)	Weighted average. Uncertainty is minimum value from input.

* Relative to $T_{1/2}({}^{241}\text{Am})=432.2$ (6) years (1991BaZS).

3 Atomic Data

X-ray and Auger (relative and absolute) electron emission probabilities given in Sections 3 and 5, respectively, have been calculated by means of the computer code EMISSION (version 3.01, Nov. 3, 1999) [2], which makes use of the atomic data from 1996Sc06, from reference [3], and from the evaluated γ -ray data given in Sections 2.1 and 4.2. In addition, internal conversion electron energies and absolute emission probabilities for the strongest lines are presented in Section 5. Electron energies have been calculated using electron binding energies from 1977La19, and γ -ray energies from Section 2.1. Absolute electron emission probabilities have been calculated using absolute γ -ray emission probabilities given in Section 4.2 and conversion coefficients from Section 2.1.

4 Alpha Particles

a-Particle Energies

Most of the recommended α -particle energies in this evaluation are weighted averages (*Limited Relative Statistical Weight* method, LWM) of values from 1964Ba26 and 1968Ba25 (magnetic spectrograph), and from 1996Sa24 and 2002Da21 (semiconductor detectors). Values reported by 2002Da21 are from the analysis of an α -particle spectrum measured by 1992Ga01.

A. Rytz (1991Ry01) has critically evaluated the α -particle groups at 5233, 5275, and 5379 keV. His energies, also recommended in this evaluation, are virtually the same as the weighted average energies given in Table 2. This table shows the results of various measurements as well as the values recommended in this evaluation.

Table 2. ²⁴³Am Alpha-Particle Energies

1964Ba26	1968Ba25	1996Sa24	2002Da21 ^{&}	W. Average	Rec. Values
4695 (3)			[4697]#		4695 (3)
4919 (3)					4919 (3)
4930 (3)			[4936]#		4930 (3)
4946 (3)			[4951]#		4946 (3)
4997 (3)			[5001]#		4997 (3)
5008 (3)		5002(5)	5012 (5)	5008 (3)	5008 (3)
5029 (3)		5030 (5)		5029 (3)	5029 (3)
5035 (3)			5037 (5)	5035 (3)	5035 (3)
5088 (3)		5083 (5)	5091 (5)	5088 (5)	5088 (5)
5113 (1)		5109 (5)	5113 (5)	5113 (1)	5113 (1)
5181 (1)		5177 (5)	5178 (5)	5181 (1)	5181 (1)
5234 (1)	5232.9 (10)	5232 (5)	5233 (5)	5233.4 (10)	5233.3 (10)*
5276 (1)	5274.8 (10)	5275 (5)	5275 (5)	5275.3 (10)	5275.3 (10)*
5321 (1)		5319 (5)	5318 (5)	5321 (1)	5321 (1)
5350 (1)		5350 (5)	5349 (5)	5350 (1)	5349.4 (23)*

2002Da21 did not measure the alpha spectrum of ²⁴³Am. The alpha spectrum used was from 1992Ga01, who had not identified these very weak peaks. 2002Da21 reported for these peaks, intensities ranging from 2 to 13 times those given by 1964Ba26. Evaluators have interpreted this discrepancy as possibly caused by *spurious peaks* produced in the spectral peak-shape analysis of 2002Da21. Thus, they did not use these α -particle energies in the averaging process.

* From 1991Ry01.

& Rounded values. Uncertainties assigned by evaluators are typical values for spectra measured with semiconductor detectors.

a-Particle Emission Probabilities

Table 3 shows the emission probabilities measured by various authors. The uncertainties given by all of them (except one, 1996Sa24) are statistical values deduced from spectral peak-shape analysis. Such uncertainties do not include a constraint imposed by normalizing the sum of the emission probabilities to 100, that is, to absolute emission probabilities ($p_i(\%)$) per 100 α -particle disintegrations of the parent nuclide. The following formula (1988Br07) may be used to convert uncertainties (dI_i) in relative α -particle emission probabilities (I_i) to values in the absolute emission probabilities ($dp_i(\%)$):

$$dp_i(\%)/p_i(\%) = [(dI_i/I_i)^2 (1 - 2 I_i/\Sigma I_k) + \Sigma dI_k^2/(\Sigma I_k)^2]^{1/2} \quad (1)$$

The uncertainties given by 1996Sa24 (see Table 3) are those in the absolute α -emission probabilities ($dp_i(\%)$), whereas the other authors give uncertainties only in the relative α -emission probabilities (dI_i). This situation significantly affects only the two most intense α -particle groups for which 1996Sa24 give the same uncertainty of 0.03.

The energies and absolute emission probabilities recommended in this evaluation are given in Section 2.2. The following description shows the procedure used here for determining these recommended absolute emission probabilities:

1. Changing the uncertainty in the 5275-keV α -particle group before averaging from its absolute value of $dp(\%) = 0.03$ (1996Sa24) to a relative value (estimated by evaluators) of $dI = 0.06$.
2. Averaging (i.e., weighted averages, LWM) the relative emission probabilities given by various authors (1955St98, 1956Hu96, 1964Ba26, 1966Le13, 1992Ga01, 1996Sa24, 2002Da21) and depicted in Table 3. Relative emission probabilities from 1998Ya17 (also shown in Table 3) are in disagreement with those from these authors, thus significantly increasing χ^2/ν for most averages. Their uncertainties include a “non-statistical component.” Unfortunately, 1998Ya17 give neither their values for these components nor the criteria used for estimating them. Therefore, data from 1998Ya17 have not been used for averaging.
3. Converting uncertainties in the recommended emission probabilities (Table 3, column 9) to uncertainties in the absolute α -particle emission probabilities by using formula (1). It should be noticed that only the uncertainties in the two most intense α -particle groups have been affected by this procedure.

Table 3. ²⁴³Am Alpha particle emission intensities

Ea(keV)	1955St98	1956Hu96	1964Ba26	1966Le13	1992Ga01	1998Ya17	1996Sa24 ^{##}	2002Da21 ^{\$}	Ia(avg) ^{&&}	c ² /h	Rec. Ia ^{&&&}
4695			0.0006	0.0017 (5) ^{***}				0.0038 (4) ^{^^}			0.0017 (5)
4919			0.000085								0.000085
4930			0.00018					0.0026 (3) ^{^^}			0.00018
4946			0.00034					0.0028 (3) ^{^^}			0.00034
4997			0.0016 [#]		0.0016 (5) [#]		0.0020 (4) [#]	0.0031 (4) ^{^^}	0.0018 (3)	0.39	0.0018 (4) [#]
5008								0.0052 (4) ^{^^}			
5029			0.0022 [^]		0.0033 (5) [^]		0.0044 (5) [^]	0.0082 (5) ^{^^}	0.0039 (4)	2.4	0.0039 (6) [^]
5035											
5088			0.004		0.0056 (7)		0.0055 (6)	0.0112 (6) ^{^^}	0.0055 (5)	0.01	0.0055 (6)
5113			0.0054		0.010 (1)		0.0101 (10)	0.019 (1) ^{^^}	0.0100 (7)	0	0.010 (1)
5181	1.1 (3) ^{&}	1.3 (2)	1.1		1.36 (1)	0.98 (2)	1.388 (8)	1.391 (7)	1.383 (5)	2.0	1.383 (7)
5233	11.5 (3) [*]	11.5 (3)	10.6 (2) ^{**}		11.46 (3)	11.04 (7)	11.37 (3)	11.52 (2)	11.46 (6)	7.1	11.46 (5) ^{\$\$}
5275	87.1 (4) [*]	86.9 (4)	87.9 (3) ^{**}		86.74 (6)	87.42 (8)	86.79 (3)	86.60 (7)	86.74 (4)	4.1	86.74 (5) ^{\$\$}
5321	0.16	0.16	0.12		0.190 (7)	0.270 (6)	0.194 (3)	0.190 (3)	0.192 (2)	0.48	0.192 (3)
5349	0.17	0.17	0.16		0.230 (7)	0.298 (8)	0.243 (3)	0.240 (3)	0.240 (2)	1.5	0.240 (3)

^{\$} 2002Da21 analyzed an α spectrum of 1992Ga01.

[&] Uncertainty assumed by evaluator.

^{*} From 1955St98, quoted in 1991Ry01; uncertainties are from 1991Ry01.

[#] 4997 α + 5008 α

[^] 5029 α + 5035 α

^{**} From 1964Ba26, quoted in 1991Ry01; uncertainties are from 1991Ry01.

^{##} Uncertainties include the effect of covariances when normalizing $\Sigma I\alpha = 100$.

^{^^} α -particle intensities are at least about twice those found by other authors, which suggest a possible systematic bias in the analysis of the spectrum. These values were not used for averaging.

^{***} Agrees well with $I\alpha=0.00148$ 3% from γ -ray transition intensity balance.

^{&&} Weighted average using the Limitation of Relative Statistical Weights method. Data from 1998Ya17 have not been included. See text.

^{\$\$} Normalization of $I\alpha$ to $\Sigma I\alpha=100$ requires same values for these uncertainties. See text.

^{&&&} Uncertainty is always greater than or equal to the smallest uncertainty in any of the experimental values used in the calculation

5 Gamma Rays

Energies

The recommended γ -ray energies given in Sections 2.1 and 4.2 are weighted averages (LWM) of values given in 1982Ah04 and 1975Pa04, complemented with values from 1996Sa23, 1969En02, and 1968Va09 (See table 4).

Table 4. ²⁴³Am Gamma-ray Energies

E_γ (keV)	E_γ (keV)	E_γ (keV)	E_γ (keV)	E_γ (keV)	E_γ (keV)	E_γ (keV)	E_γ (keV)
1996Sa23	1982Ah04	1975Pa04	1969En02	1968Va09	W. Avg.*	χ^2/ν	Rec. E_γ
31.13	31.14 (3)	31.10 (15)		31.2	31.14 (3)	0.068	31.14 (3)
		43.1	43.1				43.1#
43.53	43.53 (2)	43.53 (15)		43.6	43.53 (2)		43.53 (2)
50.6				50.6			50.6&\$
55.18			55.4	55.4			55.18&
74.66	74.66 (2)	74.67 (15)	74.7	74.8	74.66 (2)	0.004	74.66 (2)
86.71	86.71 (2)	86.79 (15)	86.7	86.7	86.71 (2)	0.27	86.71 (2)
98.5			98.5				98.5^
117.84		117.60 (15)	117.8	117.8			117.60 (15)#
141.89	141.89 (3)	142.18 (15)	142	142	141.90 (3)	3.6	141.90 (6)
169				169			169\$
195				195			195\$

* Weighted average of values in 1982Ah04 and 1975Pa04.

From 1975Pa04

& From 1996Sa23

\$ From 1968Va09

^ From 1969En02

The recommended absolute γ -ray emission (photons) and transition (photons + electrons) probabilities given in Sections 4.2 and 2.2, respectively, are weighted averages (LWM) of values in 1996Sa23, 1996Wo05, 1984Va41, 1982Ah04, 1979Po20, 1977St35, 1975Pa04, 1972Ah02, 1969Al14 and 1960As02 (see Table 5). The conversion coefficients used for deducing absolute transition probabilities (see section 2.2) are theoretical values from 1978Ro22 interpolated by using the computer ICC [1] for the recommended γ -rays energies and multipolarities (2003Br12) given in section 2.

Table 5. ²⁴³Am g-ray Absolute Emission Probabilities

E _g (keV)	I _g	I _g [@]	I _g	I _g	I _g	I _g	I _g	I _g	I _g	I _g	I _g	I _g	W. Avg.	c ² /n	I _g ^a
Rec. Value [*]	1960As02	1968Va09	1969Al14	1972Ah02	1975Pa04	1977St35	1979Po20	1982Ah04	1984Va41	1996Wo05	1996Sa23				Rec. Value
31.14 (3)								0.069 (7)				0.0477 (13)	0.0484 (13)	9	0.048 (4)
43.1		0.03													0.065 [^]
43.53 (2)	4 (1)	5.3	5 (1)	5.5 (3)			5.3 (12)	6.20 (30)	6.04 (13)	5.93 (10)	5.72 (17)	5.89 (7)	1.4	5.89 (10)	
50.6		0.0027									0.0062 (10)			0.0062 (10)#	
55.18		0.0094									0.0168 (11)			0.0168 (11)#	
74.66 (2)	69 (3)	61		66 (3)		59 (4)	60 (4)	68.0 (20)	68.5 (15)	66.7 (12)	68.4 (13)	67.2 (7)	1.4	67.2 (12)	
86.71 (2)		0.37						0.340 (15)	0.35 (1)	0.342 (15)	0.344 (9)	0.346 (6)	0.2	0.346 (9)	
98.5											0.0151 (21)			0.0151 (21)#	
117.60 (15)		0.75			0.56 (8)						0.57 (5)			0.57 (5)#	
141.90 (6)		0.13						0.128 (6)	0.13 (1)	0.117 (5)	0.1068 (26)	0.115 (2)	3.8	0.115 (8)	
169		0.0012												0.0012 [^]	
195		0.00085												0.00085 [^]	

a Recommended absolute emission probabilities are weighted averages (LWM) of experimental values, unless otherwise noted.

Uncertainty is always greater than or equal to the smallest uncertainty in any of the experimental values used in the calculation.

* From Table 4

From 1996Sa23

& From 1968Va09

[^] Estimated by 2003Br12 from α_M(43.1γ, exp.) = 31, I_M(ce, 43.1γ) / I_γ(117) = 3.56 (1969En02), and I_γ(117) = 0.57.

[@] Uncertainties are at least 10%.

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²⁴⁴Cm – COMMENTS ON EVALUATION OF DECAY DATA**by V.P.Chechev**

This evaluation was completed in December 2004 and corrected in February 2005. The literature available by January 2005 was included.

1. DECAY SCHEME

The decay scheme is based on the evaluation of 2004Ch64. It can be considered as basically completed though some weak gamma transitions were not observed in ²⁴⁴Cm alpha decay. These transitions have been included in the decay scheme from data on the ²⁴⁰Np β⁻-decay and the ²⁴⁰Am electron capture.

2. NUCLEAR DATA

Q(α) value is from 2003Au03.

The evaluated half-life of ²⁴⁴Cm is based on the experimental values given in Table 1.

Table 1. Experimental values of the ²⁴⁴Cm half-life (in years)

Reference	Author(s)	Value	Measurement method
1954Fr19	Friedman et al.	17.9(5)	a-activity relative to ²⁴² Cm
1954St33	Stevens et al.	19.2(6)	a-activity relative to ²⁴² Cm
1961Ca01	Carnall et al.	17.59(6)	Specific activity
1968Be26	Bentley	18.099(32) ^a	2π a-counting
1972Ke29	Kerrigan and Dorsett	18.13(4)	Calorimetry
1982Po14	Polyukhov et al.	18.24(25)	Specific activity

^a Revised value, recalculated in 2000Ho27

The EV1NEW program has led to successive rejections of values from 1961Ca01 and 1954St33 due to their too large contribution to χ^2 -value (more than 80%). The LRSW method has increased 1.03 times the uncertainty of the value from 1968Be26. The weighted mean of the data set including only the four remaining values is 18.115, with the internal uncertainty 0.028 and $\chi^2/\nu = 0.25$. The smallest experimental uncertainty is 0.032, thus the recommended value of ²⁴⁴Cm half-life is **18.11(3) a**.

The evaluated spontaneous fission partial half-life of ²⁴⁴Cm is based on the experimental values given in Table 2.

Table 2. Experimental values of the ²⁴⁴Cm spontaneous fission half-life (in 10⁷ years)

Reference	Author(s)	Value	Measurement method
1952Gh27	Ghiorso et al.	1.4(2) ^a	Ionization chamber
1963Ma56	Malkin et al.	1.46(6)	Gas scintillator
1965Me02	Metta et al.	1.345(8) ^a	a/SF counting, α with low geometry counter, SF with 2π parallel plate chamber
1967Ar09	Armani and Gold	1.33(3)	Fission neutron counting, LiI detector
1970Ba11	Barton and Koontz	1.250(7)	Low geometry fission fragment counting
1972Ha80	Hastings and Strohm	1.343(6) ^a	a/SF counting, Si(Au) detector
1993Pa29	Pandey et al.	1.263(5)	a/SF counting by sequential etching of alpha and fission tracks

^a Revised value, recalculated in 2000Ho27

The data set in Table 2 is discrepant. The LWEIGHT computer program has recommended the unweighted mean of 1.342 and expanded the uncertainty to 0.079 so its range includes the most precise value of 1993Pa29.

The recommended value of ²⁴⁴Cm spontaneous fission half-life is 1.34(8) 10⁷ years.

2.1 Alpha Transitions

The energies of the alpha transitions have been calculated from the Q value and the ²⁴⁰Pu level energies given in Table 3 from 2004Ch64.

Table 3. ²⁴⁰Pu levels populated in the ²⁴⁴Cm α-decay

Level number	Energy, keV	Spin and parity	Half-life	Probability of α-transition (x100)
0	0.0	0 ⁺	6561(7) yr	76.7(4)
1	42.824(8)	2 ⁺	164(5) ps	23.3(4)
2	141.690(15)	4 ⁺		0.0204(15)
3	294.319(24)	6 ⁺		0.00352(18)
4	497.6 ^a	8 ⁺		4×10 ⁻⁵
5	597.34(4)	1 ⁻		5.5(9)×10 ⁻⁵
6	648.85(4)	3 ⁻		4.2(30)×10 ⁻⁶ ^b
7	860.71(7).	0 ⁺		1.49(16)×10 ⁻⁴
8	900.32(4)	2 ⁺		5.0(5)×10 ⁻⁵
9	938.06(6)	(1 ⁻)		4.7(11)×10 ⁻⁶ ^b

^a Energy has been taken from ²³⁸U(α, 2n γ)-reaction measurements of 1972Sp06.

^b Calculated from P(γ+ce) decay-scheme probability balances.

The probabilities of the transitions α_{0,i} (i = 0, 1, 2, 3, 7) have been obtained by averaging experimental data (Table 4). The experimental results from 1998Ga19 agree well with the evaluated

probabilities of the most intense alpha-transitions. The probabilities of the remaining α -transitions have been deduced using the experimental values and the values obtained from $P(\gamma+ce)$ decay-scheme balances (see footnotes).

Table 4. Experimental and evaluated α -transition probabilities ($\times 100$) in the ^{244}Cm decay

	a-particle energy keV	1956 Hu96	1960 As11, 1984 Asaro	1963 Dz07	1966 Ba07	1984 BuZJ	1996 Bu50	1996 Sa24	1997 Ka59	1998 Ga19	1998 Ya17	2002 Da21*	Evaluated
a _{0,0}	5805	76.7 (6)	-	76.2 (20)	76.4 (20) ^a	76.98 (5)	76.8 (7)	76.9 (5)	-	76.63 (18)	76.31 (5)	77.16 (11)	76.7(4) ^b
a _{0,1}	5763	23.3 (6)	-	23.8 (9)	23.6 (9) ^a	23.00 (5)	23.2 (5)	23.1 (5)	-	23.34 (18)	23.69 (6)	22.80 (5)	23.3(4) ^c
a _{0,2}	5664	0.017 (3)	0,023 (2)	0.021 (2)	0.02	0.0163 (7)	-	0.0135 (2)	-	0.0205 (15)	-	0.020 (1)	0.0204(15) ^d
a _{0,3}	5515	-	0.0036 (3)	0.003 (1)	0.0034	-	-	-	0.00342 (9)	0.0038 (5)	-	0.012 (1)	0.00352(18) ^e
a _{0,4}	5315	-	~1.5 $\times 10^{-4}$	-	~4 $\times 10^{-5}$	-	-	-	-	-	-	-	4×10^{-5} ^f
a _{0,5}	5215	-	1.5 $\times 10^{-4}$	-	1 $\times 10^{-4}$	-	-	-	4.2(9) $\times 10^{-5}$	-	-	-	$5.5(9) \times 10^{-5}$ ^g
a _{0,7}	4960	-	1.55(16) $\times 10^{-4}$	-	3 $\times 10^{-4}$	-	-	-	1.42(16) $\times 10^{-4}$	-	-	-	$1.49(16) \times 10^{-4}$ ^h
a _{0,8}	4920	-	5.0(5) $\times 10^{-5}$	-	1.3 $\times 10^{-4}$	-	-	-	4.9(8) $\times 10^{-5}$	-	-	-	$5.0(5) \times 10^{-5}$ ⁱ

^aNo uncertainties are quoted by the authors. The uncertainties have been adopted by the evaluator based on the analogy of the spectra obtained with magnetic spectrometers in 1963Dz07 and 1966Ba07.

^bThis set of experimental values is discrepant. The LWEIGHT computer program has recommended a weighted average and expanded the uncertainty so the range includes the most precise value from 1998Ya17.

^cCalculated from the relation $P(a_{0,1}) = 100 - P(a_{0,0})$ per 100 disintegrations. An unweighted average of the discrepant set of the experimental values is 23.31, a weighted average is 23.11.

^dWeighted average of the values from 1956Hu96, 1960As11, 1963Dz07, 1998Ga19 and 2002Da21. The lower values from 1984BuZJ and 1996Sa24 have been omitted as outliers. These values conflict greatly with the ratio $P(\gamma_{2,1})/P(\gamma_{1,0}) = 0.067(7)$ measured in 1972Sc01. The uncertainty of the evaluated $a_{0,2}$ probability has been adopted from the experimental result of 1998Ga19.

^eAverage of values from 1960As11, 1963Dz07, 1997Ka59 and 1998Ga19. The EVINEW computer program using a limitation of relative statistical weights of 0.5 has expanded the uncertainty from 1997Ka59 to 0.00025 and recommended a weighted average and an internal uncertainty.

^fAdopted from 1966Ba07.

^gCalculated from the $P(\gamma+ce)$ -probability balance at the 597-keV level ("5").

^hWeighted average of values from 1960As11, 1997Ka59.

ⁱWeighted average of values from 1960As11, 1997Ka59 and a value of $5.2(7) \times 10^{-5}$, calculated from $P(\gamma+ce)$ -probability balance at the 900-keV level ("8"). The uncertainty is the smallest experimental one.

* In 2002Da21 a new treatment of the experimental spectra obtained by Garcia-Torano (1998Ga19) was done with another de-convolution code. Omitting 2002Da21 or 1998Ga19 leads to the same evaluated values.

2.2. Gamma-Ray Transitions and Internal Conversion Coefficients

The evaluated energies of gamma-ray transitions are virtually the same as the photon energies because nuclear recoil is negligible.

The probabilities, $P(\gamma+ce)$, for gamma-ray transitions of 42.8-($\gamma_{1,0}$), 98.9-($\gamma_{2,1}$), 152.6-($\gamma_{3,2}$), and 202-keV ($\gamma_{4,3}$) have been deduced from intensity balances, using the probabilities of α -particle transitions evaluated directly from experimental data.

For the 861-($\gamma_{7,0}$) E0 transition its $P(ce)$ value has been obtained from the (α -ce)-coincidence measurement of 1963Bj03: $P(ce \gamma_{7,0}) + P(ce \gamma_{7,1}) = 9.5(20) \times 10^{-6}$ per 100 disintegrations.

The remaining $P(\gamma+ce)$ values have been calculated from the gamma-ray emission probabilities and the total internal conversion coefficients (ICC's). The ICC's have been interpolated from tables of 1978Band and 1993Ba60 using the computer program "ICC99v3.a". The fractional uncertainties of α_K , α_L , α_M , α_T for pure multipolarities have been taken as 2%.

Multipolarities are from 2004Ch64. These are based on conversion electron measurements of 1956Sm18, 1963Bj03, 1968Du06, and 1990Pe03.

3. ATOMIC DATA

3.1. Fluorescence yields

The fluorescence yields are from 1996Sc06 (Schönfeld and Janßen).

3.2. X Radiations

The Pu KX-ray energies and relative emission probabilities are from 1999Schönfeld, where the calculated energy values are based on X-ray wavelengths from 1967Be65 (Bearden). In Table 5 the adopted values of U KX-ray energies are compared with experimental values.

Table 5. Experimental and adopted (calculated) values of Pu KX-ray energies (keV)

	1980Di13	1982Ba56	Adopted
$K\alpha_2$	99.55(3)	99.530(2)	99.525
$K\alpha_1$	103.76(3)	103.741(2)	103.734
$K\beta_3$	116.27	116.242(2)	116.244
$K\beta_1$	117.26	117.233(2)	117.228
$K\beta_{2,4}$	120.60(15)	-	120.553
$KO_{2,3}$	121.55(6)	-	121.543

In 1980Di13 the Pu KX-ray energies were measured in the alpha decay of ²⁴⁵Cm. The relative emission probabilities of KX-rays were obtained as :

$$K\alpha_2:K\alpha_1:K\beta_3:K\beta_1:K\beta_{2,4} = 64.7(23):100.0(33):12.9(7):23.1(10):8.9(5).$$

3.3. Auger Electrons

The energies of Auger electrons have been calculated from atomic electron binding energies.

The $P(KLX)/P(KLL)$, $P(KXY)/P(KLL)$ ratios have been taken from 1996Sc06.

4. ALPHA EMISSIONS

The energy of alpha particles to the ground state of ²⁴⁰Pu, $E(\alpha_{0,0})$, are from the absolute measurement of 1971Gr17 but including the correction of -0.19 keV recommended by A.Rytz in 1991Ry01.

The energies of all other α -particles have been calculated from Q_α and ²⁴⁰Pu level energies, taking into account the relevant recoil energies.

In Table 6 the calculated (evaluated) values of α -particle energies are compared with experimental results obtained with magnetic alpha spectrometers.

Table 6. Experimental ^a and evaluated α -particle energies in the decay of ²⁴⁴Cm, keV

	1960 As11	1963 Dz07	1966 Ba07	1971 Gr17	1992 Fr04	1998 Ga19	Evaluated
$\alpha_{0,0}$	5805	5805(3)	5805(1)	5804.77(5)	5803.6(22)	-	5804.77(5)
$\alpha_{0,1}$	5763	5762	5763(1)	5762.16(3)	-	-	5762.65(5)
$\alpha_{0,2}$	5666	5665	5664(3)	-	-	5664(2)	5665.41(5)
$\alpha_{0,3}$	5514	5514	5513(3)	-	-	5515(3)	5515.29(6)
$\alpha_{0,4}$	5316	-	5313	-	-	-	5315.3
$\alpha_{0,5}$	5215	-	5215(3)	-	-	-	5217.24(7)
$\alpha_{0,7}$	4956	-	4960(3)	-	-	-	4958.20(9)
$\alpha_{0,8}$	4916	-	4920(3)	-	-	-	4919.24(7)

^a Authors' values have been adjusted for changes in calibration energies (see 1991Ry01)

5. ELECTRON EMISSIONS

The energies of conversion electrons have been deduced from gamma transition energies and relevant electron binding energies. The emission probabilities of conversion electrons have been deduced from the evaluated $P(\gamma)$ and ICC values.

The total absolute emission probability of K Auger electrons has been deduced using the evaluated emission probability of K-conversion electrons $P(\text{ceK}) = 0.000205(10)\%$ and the adopted K-fluorescence yield (ω_K) given in section 3. The total absolute emission probability of L Auger electrons has been deduced using the evaluated total (L1 + L2 + L3) absolute emission probability of L-conversion electrons $P(\text{ceL}) = 17.0(6)\%$ and the adopted ω_L given in section 3.

6. PHOTON EMISSIONS

6.1. X-Ray Emissions

The absolute emission probabilities of Pu KX-rays have been deduced using the adopted value of $\omega_K(\text{Pu})$, the evaluated absolute emission probability of K conversion electrons (see above) and relative intensities of KX-ray components from 1999Schönfeld.

The absolute emission probabilities of LX-rays in the ²⁴⁴Cm α -decay are from the accurate measurements of 1995Jo23. The absolute LX-ray emission probabilities (per 100 disintegrations) calculated with the program EMISSION [0.219(8)-Ll; 3.41(11)-La; 0.092(4)-L η ; 4.19(14)-L β ; 0.97(4)-L γ], as well as the total $P(\text{XL}) = 8.9(4)\%$, agree with the adopted experimental values from 1995Jo23.

In 1990Po14 the relative LX-ray emission probabilities in ²⁴⁴Cm α -decay were measured: [5.3(8)-Ll; 72(7)-La; 100-L $\eta\beta$; 22.4(23)-L γ]. These values agree with the recommended ones with the exception of the (La/L $\eta\beta$)-ratio.

6.2. Gamma-Ray Emissions

6.2.1. Gamma-Ray Energies

The energies of the 43-keV ($\gamma_{1,0}$), 99-keV ($\gamma_{2,1}$), and 153-keV ($\gamma_{3,2}$) gamma rays are from ²⁴⁴Cm α -decay (1972Sc01). Other, less accurate measurements of ²⁴⁴Cm α -decay (1956Sm18), ²⁴⁰Np β^- -decay (1981Hs02) and ²⁴⁰Am ϵ -decay (1972Ah07) agree with data from 1972Sc01.

The energies of remaining gamma rays have been calculated from the adopted level energies. In Table 7 the evaluated (recommended and calculated) gamma ray energies are compared with the available experimental data.

Table 7. Experimental and recommended gamma-ray energies (keV)

	1967Lederer (1978LeZA)	1972Ah07	1972Sc01	1981Hs02	Recommended
$\gamma_{1,0}$		42.9(1)	42.824(8)	-	42.824(8)
$\gamma_{2,1}$	-	98.9(1)	98.860(13)	-	98.860(13)
$\gamma_{3,2}$	-	-	152.630(20)	-	152.630(20)
$\gamma_{8,6}$	251.20(20)	-	-	251.5(1)	251.47(6)
$\gamma_{7,5}$	263.34(15)	-	-	263.4(1)	263.37(8)
$\gamma_{8,5}$	302.99(15)	-	-	303.0(1)	302.98(6)
$\gamma_{6,2}$	506.9(3)	-	-	507.2(1)	507.16(5)
$\gamma_{5,1}$	554.5(2)	-	-	554.6(1)	554.52(4)
$\gamma_{5,0}$	597.2(2)	-	-	597.4(1)	597.34(4)
$\gamma_{6,1}$	605.8(2)	-	-	606.1(1)	606.03(4)
$\gamma_{8,2}$	758.6(2)	-	-	758.6(1)	758.63(5)
$\gamma_{7,1}$	817.8(2)	-	-	817.9(1)	817.89(7)
$\gamma_{8,1}$	857.5(2)	-	-	857.5(1)	857.50(4)
$\gamma_{9,1}$	894.7(5)	-	-	895.3(1)	895.24(6)
$\gamma_{8,0}$	900.1(5)	-	-	900.3(1)	900.32(4)
$\gamma_{9,0}$	937.6(10)	-	-	938.0(1)	938.06(6)

6.2.2. Gamma-Ray Emission Probabilities

The absolute emission probabilities for gamma rays of 43-($\gamma_{1,0}$), 99-($\gamma_{2,1}$), 153-($\gamma_{3,2}$), and 202-keV ($\gamma_{4,3}$) have been deduced from intensity balances, using the experimental α -particle probabilities. The relative emission probabilities for the first three gamma rays were measured in 1972Sc01 as [100- $\gamma_{1,0}$, 6.7(7)- $\gamma_{2,1}$, and 4.1(1)- $\gamma_{3,2}$]. The measured $P(\gamma_{2,1})/P(\gamma_{1,0})\times 100$ ratio disagrees with the evaluated 5.3(4), and the measured $P(\gamma_{3,2})/P(\gamma_{1,0})\times 100$ ratio agrees with the evaluated 3.95(23).

The recommended relative emission probabilities of gamma rays with energies greater than 150-keV, obtained by averaging the experimental data from 1967Lederer (1978LeZA) and 1969Sc18 (1970Sc39), are given in Table 8.

Table 8. Experimental and recommended relative emission probabilities of >150-keV gamma rays from the decay of ²⁴⁴Cm

	Energy, keV	1967Lederer 1978LeZA	1969Sc18 1970Sc39	Evaluated
$\gamma_{3,2}$	152.6	-	1240(150)	1170(160) ^a
$\gamma_{8,6}$	251.5	14(3)	12.7(20)	13.1(20) ^b
$\gamma_{7,5}$	263.4	73(5)	68(6)	71(5) ^b
$\gamma_{8,5}$	303.0	23(4)	21.0(20)	21.4(20) ^b
$\gamma_{6,2}$	507.2	10(3)	-	10(3) ^c
$\gamma_{5,1}$	554.5	100	100	100
$\gamma_{5,0}$	597.3	61(2)	62(4)	61(2) ^b
$\gamma_{6,1}$	606.0	10(2)	9.1(11)	9.3(20) ^b
$\gamma_{8,2}$	758.6	15.6(8)	18.3(21)	15.9(8) ^b
$\gamma_{7,1}$	817.9	75(4)	91(8)	78(4) ^b
$\gamma_{8,1}$	857.5	6.6(4)	<7.5	6.6(4) ^c
$\gamma_{9,1}$	895.2	2.1(6)	<1.3	2.1(6) ^c
$\gamma_{8,0}$	900.3	1.5(6)	<0.4	1.5(6) ^c
$\gamma_{9,0}$	938.1	0.5(5)	<0.75	0.5(5) ^c

^a Deduced from the evaluated absolute emission probabilities P(γ 153keV) and P(γ 555keV).

^b Weighted average, uncertainty is the smallest experimental value reported.

^c Adopted from 1967Lederer (1978LeZA).

The deduced absolute emission probabilities of gamma-rays with energies greater than 250 keV are based on our recommended relative gamma-ray emission probabilities P(γ)/P(γ 555keV) in Table 8 and a normalization factor obtained from decay scheme.

The absolute gamma-ray emission probability P⁽¹⁾(γ 555keV) = 9.1(11)×10⁻⁵ per 100 disintegrations (used for decay-scheme normalization) has been obtained from the intensity balance at the 861-keV level (“7”) using the alpha-transition probability P($\alpha_{0,7}$) = 1.49(16)×10⁻⁴ per 100 disintegrations, deduced from the experimental data of 1960As11 and 1997Ka59:

P(γ 555keV) = [P($\alpha_{0,7}$) – P(ce 861keV)] / [P’(γ 263keV) × (1 + α_T^{263}) + P’(γ 818keV) × (1 + α_T^{818})], where P’(γ) is a gamma-ray emission probability relative to that of the 555-keV transition (i.e., P(γ)/P(γ 555keV)).

Another way of calculating a normalization factor is by using the relative gamma-ray emission probability P(γ 153keV)/P(γ 555keV) = 12.4(15) measured in 1969Sc18 (1970Sc39) and the absolute probability P(γ 153keV) calculated from the intensity balance for the level 294-keV level (“3”):

P⁽²⁾(γ 555keV) = 8.2(11) × 10⁻⁵ per 100 disintegrations.

The average of the two P(γ 555keV) values, 8.7(11) × 10⁻⁵ per 100 disintegrations, was used as a normalization factor for calculating absolute emission probabilities of gamma-rays with energy greater than 250 keV.

The absolute emission probabilities for the 289-keV ($\gamma_{9,6}$) and 341-keV ($\gamma_{9,5}$) gamma rays have been deduced using the ratios P(γ 895keV)/P(γ 289keV) = 3.6(15) and P(γ 895keV)/P(γ 341keV) = 1.0(3) measured in ²⁴⁰Np β^- -decay (1981Hs02, 2004Ch64).

The absolute emission probability of the 202-keV ($\gamma_{4,3}$) gamma ray has been calculated using the adopted $\alpha_{0,4}$ -transition probability. The 202-keV E2-gamma-ray transition was not observed in the ²⁴⁴Cm alpha decay, however, it is expected from theoretical considerations and by analogy with the ²⁴²Cm decay scheme.

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