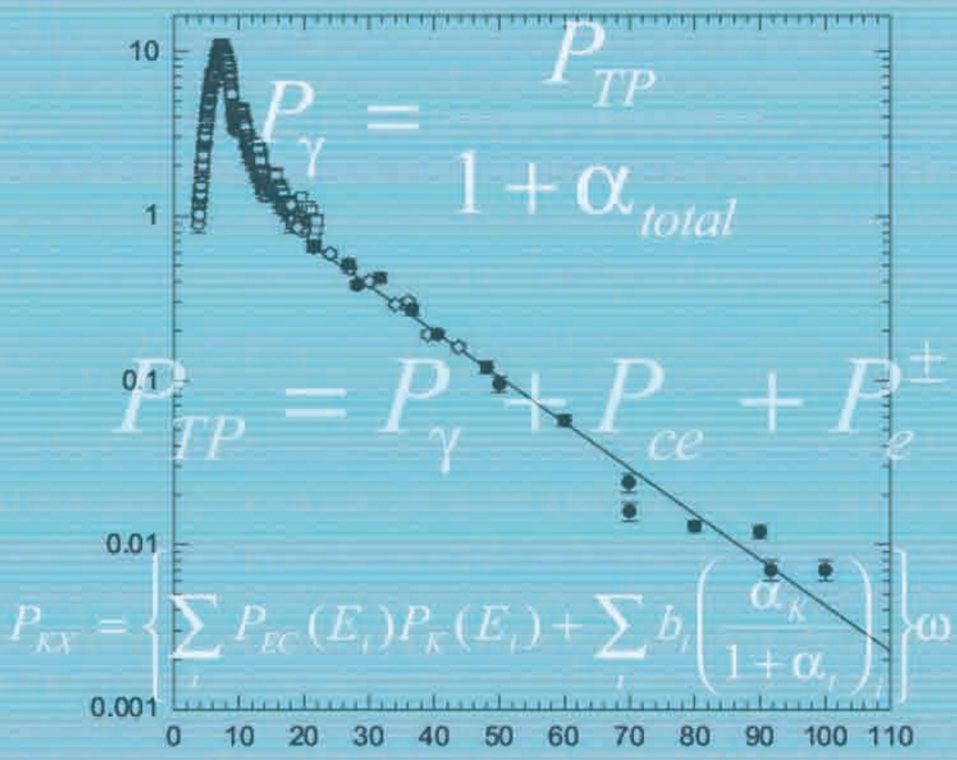
Update of X Ray and Gamma Ray Decay Data Standards for Detector Calibration and Other Applications

Volume 2:

Data Selection, Assessment and Evaluation Procedures



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UPDATE OF X RAY AND GAMMA RAY DECAY DATA STANDARDS FOR DETECTOR CALIBRATION AND OTHER APPLICATIONS

VOLUME 2

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UPDATE OF X RAY AND GAMMA RAY DECAY DATA STANDARDS FOR DETECTOR CALIBRATION AND OTHER APPLICATIONS

In two volumes

VOLUME 2

DATA SELECTION, ASSESSMENT AND EVALUATION PROCEDURES

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2007

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Sales and Promotion, Publishing Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
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FOREWORD

Various groups around the world are engaged in the compilation and evaluation of decay data for either all known or specific radionuclides. Many evaluators operate independently and recommend slightly different values for the same parameter. Even small deviations in the recommended data can have a significant impact on the definition of the decay characteristics of radionuclides used as standards in detector efficiency calibrations and subsequent applications (e.g. in nuclear medicine and environmental monitoring). Under such circumstances, these differences can be propagated into the measurements of decay data for other radioactive nuclides and may also bring into question the efficacy of adopting specific radionuclides in diagnostic and therapeutic treatments. High quality decay data are essential for the efficiency calibration of X and γ ray detectors that are used to quantify the radionuclidic content of a sample by determining the intensities of any resulting X and γ rays.

A major objective of the IAEA nuclear data programme is to promote improvements in the quality of nuclear data used in science and technology. Hence the IAEA established a Coordinated Research Project (CRP) in 1986 on Measurements and Evaluation of X and Gamma Ray Standards for Detector Efficiency Calibration, with the aim of reducing the discrepancies and uncertainties in those decay data parameters judged to be important in such work. This CRP was completed in 1990, and the results of the work were assembled as a database and presented in IAEA-TECDOC-619, X-ray and Gamma-ray Standards for Detector Calibration. Recommended values for the half-lives and photon emission probabilities were given for a selected set of radionuclides that were judged to be suitable for detector efficiency calibration (X rays from 5 to 90 keV, and γ rays from 30 to about 3000 keV). Detector efficiency calibrations for higher gamma ray energies were also considered (i.e. prompt emissions up to 14 MeV from specific nuclear reactions). This timely initiative contributed to the development of measurement techniques and an agreed evaluation methodology. The evaluation procedures used to obtain the recommended values and their estimated uncertainties were documented, along with a summary of the remaining discrepancies. Many important experimental studies were catalysed by the demands of this earlier CRP, and a significant fraction of these new data were not published until the 1990s nor included in the original evaluation process. New efforts under the auspices of a further CRP were judged to be necessary in order to incorporate these new data and update the existing database, along with extending these files to encompass the related needs of a number of important applications such as environmental monitoring and nuclear medicine.

A Consultants meeting was held in Vienna on 24 and 25 November 1997 to assess the current needs and identify the most suitable radionuclides. The experts at this meeting advised the establishment of a new CRP on Update of X ray and Gamma Ray Decay Data Standards for Detector Calibration and other Applications. The IAEA established this CRP in 1998 and the participants completed an agreed work programme in 2005. All of the results are presented in Volume 1 of this report, while Volume 2 details the data selection, assessment and evaluation processes adopted in order to ensure traceability. Recommended half-lives, and X and γ ray emission probabilities are given for a carefully selected set of radionuclides and nuclear reactions that are suitable for detector efficiency calibration and other applications. The evaluation procedures used to obtain the recommended values and their uncertainties are detailed, and comments have been made on the remaining discrepancies. Consideration is also given to the coincidence method of determining absolute γ ray detection efficiencies and the statistical correlation of decay data. An appropriate set of suitable X and γ ray decay data standards have been derived, with the expectation that the recommended values will be recognized as international reference standards.

The IAEA is grateful to members of the Decay Data Evaluation Project and laboratories affiliated with the International Committee for Radionuclide Metrology for their assistance in the work and for support of the CRP meetings. Both O.A.M. Helene and V.R. Vanin wish to thank their State and Federal funding agencies (FAPESP and CNPq) for financial support during the course of their evaluation studies. The IAEA officers responsible for this publication were M. Herman and A.L. Nichols (ex AEA Technology) of the Division of Physical and Chemical Sciences. The participants in this evaluation study dedicate their work and results to the memory of their co-workers: R.G. Helmer (USA), G.L. Molnár (Hungary) and S.A. Woods (UK).

CONTRIBUTING AUTHORS

M.-M. Bé	Laboratoire National Henri Becquerel, France
V.P. Chechev	V.G. Khlopin Radium Institute, Russian Federation
R. Dersch	Physikalisch-Technische Bundesanstalt, Germany
O.A.M. Helene	Universidade de São Paulo, Brazil
R.G. Helmer†	Idaho National Laboratory, United States of America
M. Herman	International Atomic Energy Agency
S. Hlaváč	Slovak Academy of Sciences, Slovakia
A. Marcinkowski	The Andrzej Soltan Institute for Nuclear Sciences, Poland
G.L. Molnár†	Institute of Isotope and Surface Chemistry, Hungary
A.L. Nichols	AEA Technology, United Kingdom
E. Schönfeld	Physikalisch-Technische Bundesanstalt, Germany
V.R. Vanin	Universidade de São Paulo, Brazil
M.J. Woods	National Physical Laboratory, United Kingdom

† Deceased

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The desire to improve the decay data used to undertake accurate efficiency calibrations of γ ray detectors arose with an increased awareness of the publication of important new measurements instigated during a previous IAEA Coordinated Research Project (CRP) on X Ray and Gamma Ray Standards for Detector Calibration [1]. Some measurements were not completed and published within the time frame of the original CRP (1986–90). Therefore it was recommended that the desired decay data be reassessed and evaluated in order to reformulate and update the internationally accepted IAEA data files. Such a proposal was supported by the International Nuclear Data Committee (INDC), the external review body of IAEA nuclear data activities, which also recommended the establishment of technical links with the International Committee for Radionuclide Metrology (ICRM). Therefore, a Consultants Meeting was held in Vienna on 24 and 25 November 1997 to discuss the quality of the relevant data and define a suitable programme to resolve various issues [2]. As a consequence of these discussions, a CRP (Update of X Ray and Gamma Ray Decay Data Standards for Detector Calibration and Other Applications) was established by the IAEA. The participants in the programme were specialists in γ ray spectroscopy and in the related areas of standards and data evaluation. Their objective was to produce a recommended set of decay parameters for selected radionuclides and nuclear reactions judged to be important for the efficiency calibration of equipment used to detect and quantify X and γ ray emissions over a range of applications.

1.2. SCOPE

Various factors such as source preparation and source–detector geometry may affect the quality of measurements made with intrinsic germanium and other γ ray spectrometers. However, the accuracy of such measurements invariably depends on the accuracy of the efficiency versus energy calibration curve and hence on the accuracy of the decay data for the radionuclides from which calibration standard sources are prepared. Both half-lives and X and γ ray emission probabilities need to be known to good accuracy.

Members of the CRP reviewed and modified the list of radionuclides most suited for detector calibration and were able to include some of the specific needs of such nuclear applications as safeguards, material analysis, environmental monitoring, nuclear medicine, waste management, dosimetry and basic spectroscopy. CRP meetings were held in Vienna (1998 [3]), Braunschweig, Germany (2000 [4]) and Vienna (2002 [5]) to monitor progress, promote measurements, formulate and implement the evaluation methodology (Annex I), and agree upon the final recommended half-lives and X and γ ray emission probabilities as presented in this report.

The recommendations and report of this work are published in two volumes:

Volume 1 — Recommended Decay Data, High Energy Gamma Ray Standards and Angular Correlation Coefficients;
Volume 2 — Data Selection, Assessment and Evaluation Procedures.

Volume 1 is a self-contained assembly of the recommended decay data covering half-lives and the X ray and γ ray emission probabilities of the selected radionuclides, and listings of various high energy γ ray standards and a set of angular correlation coefficients; these data are presented in a concise manner for rapid and easy access. More detailed technical features of the CRP are described in Volume 2, including the evaluation procedures adopted and extensive traceable explanations of the origins of the nuclear data used to produce the recommended values listed in Volume 1. This detail was judged to be essential in order to record and demonstrate the quality of the resulting data files and allow the reader to trace the origins of the nuclear data used to determine the recommended values.

All evaluations were based on the available experimental data, supplemented with the judicious use of well established theory. Three types of data (half-lives, energies and emission probabilities) were compiled and evaluated (Annex II). Consideration was also given to the adoption of a number of prompt high energy γ rays from specific nuclear reactions (Annex III), as well as to using the γ–γ coincidence technique for efficiency calibrations (Annex IV). Well defined evaluation procedures were strictly applied to determine the recommended half-lives and emission probabilities for all prominent X and γ rays emitted by each selected radionuclide.

1.3. UPDATE OF THE DATABASE

IAEA-TECDOC-619 [1] contains recommended decay data for 36 radionuclides, extending up to a γ ray energy of 3.6 MeV. These data were revisited and revised, where appropriate, as a consequence of the availability of new experimental data measured and published after 1990. New measurements of half-lives have also been published for at least 29 of the original 36 radionuclides. A more comprehensive list of 62 radionuclides and two heavy element decay chains was prepared at the Consultants Meeting and adopted as a suitable starting point by the participants of the CRP. Decay data were compiled, evaluated and recommended for the half-lives and X ray and γ ray emission probabilities. These radionuclides have been re-evaluated in a combined international exercise led by laboratories involved in the Decay Data Evaluation Project (DDEP) [6] and affiliated with the ICRM, with the CRP providing additional impetus and the necessary co-ordination to achieve the desired objectives. Only average X ray energies and their emission probabilities are given in IAEA-TECDOC-619 — the new work eliminates this shortcoming through a systematic analysis of the emissions of the individual $K\alpha_1$, $K\alpha_2$, $K\beta_1'$ and $K\beta_2'$ components.

1.4. EXTENSION OF THE ENERGY RANGE

New nuclear techniques suffer from a lack of high energy calibration standards (for example, radiotherapy). There is an urgent need to provide such data for the calibration of γ ray detectors up to 25 MeV. Appropriate radionuclides and nuclear reactions have been identified, and γ ray emission probabilities were compiled and evaluated (see Annex III). Various options were explored in order to provide energy and intensity calibration γ lines above 10 MeV. An example is the $^{11}B(p, \gamma)^{12}C$ reaction at proton energies of up to 100 MeV.

1.5. OTHER CONSIDERATIONS

Angular correlation coefficients were evaluated for a few appropriate radionuclides of relevance to the γ–γ coincidence method (Annex IV). Attention was also focused on the analysis of uncertainties, including an investigation of the feasibility and usefulness of including uncertainty correlations in the evaluation procedures (Annex V). A limited number of radionuclides were evaluated in this manner. One conclusion arising from this exercise was the need to establish rules for the documentation of experiments that enable the evaluators to estimate input covariances from the published decay data.

A major aim has been to redefine the contents of a set of data files that should be internationally accepted so as to improve the consistency and uniformity of subsequent measurements of photon emission probabilities. The CRP has also assisted in the definition of an agreed evaluation methodology that provides consistent and high quality results. A primary aim is that γ ray spectroscopists will accept the decay data standards presented in this report and use these recommended values in their work.

2. OBJECTIVES OF THE CRP

The primary objective of the CRP was to improve detector efficiency calibration in the most critical non-energy applications, including safeguards, material analysis, environmental monitoring, nuclear medicine, waste management, dosimetry, and basic spectroscopy. Ancillary objectives of the CRP were identified with the following steps:

(a) Selection of appropriate calibrant nuclides;
(b) Assessment of the status of the existing data;
(c) Identification of data discrepancies and limitations;
(d) Stimulation of measurements to meet major data needs;
(e) Evaluation and recommendation of improved efficiency calibration data.

Every effort was made to cover as wide a range of photon energy as possible. X ray and γ ray emitting radionuclides were included to cover the energy range from 1 keV to 5 MeV. Other considerations for the selection of radionuclides included:

(1) Commonly used and readily available nuclides;
(2) Nuclides used and offered as standards by national laboratories, including multi-line nuclides for rapid calibrations;
(3) Definition of a set of single-line nuclides to avoid the need for coincidence summing corrections;
(4) Nuclides with accurately known emission probabilities.

Emission probability data for selected photons were evaluated and expressed as absolute emission probabilities per decay.

A recommended list of 62 nuclides and two heavy element decay chains evolved from the meetings of the CRP (Table 1). A primary standard is a nuclide for which γ ray emission probabilities (or intensities) are calculated from various data that do not include significant γ ray measurements (emission probabilities are usually close to 1.0, expressed per decay); these data may include internal conversion coefficients and intensities of weak β branches. Secondary standards are nuclides for which the recommended γ ray intensities depend on prior measurements of the γ ray intensities. The laboratories contributing to the CRP evaluations are listed in Table 2, along with various comments on the resulting data. When relative intensities had been measured, these parameters were evaluated as well as the normalization factor; this combination of data was then used to generate absolute emission probabilities. Thus, both relative intensities and absolute emission probabilities were included in the evaluation exercise and both can be extracted from the database.

The following nuclear reactions were adopted as γ ray calibration standards:

(i) $^{14}N(n, \gamma)^{15}N^*$
(ii) $^{35}Cl(n, \gamma)^{36}Cl^*$
(iii) $^{48}Ti(n, \gamma)^{49}Ti^*$
(iv) $^{50, 52, 53}Cr(n, \gamma)^{51, 53, 54}Cr^*$
(v) $^{11}B(p, \gamma)^{12}C^*$
(vi) $^{23}Na(p, \gamma)^{24}Mg^*$
(vii) $^{27}Al(p, \gamma)^{28}Si^*$.

Their cross-sections and the energies and transition probabilities of the most prominent high energy γ transitions have been evaluated.

Emphasis has been placed on the X and γ rays most suited as detector efficiency calibrants, and only these emissions have been included in the final CRP dataset (i.e. only a limited number of strong lines are recommended). Detailed comments and complete decay data listings are not necessarily included in this report. However, the user is referred to a number of parallel publications by laboratories involved in the DDEP [7–9] and the web pages located on web page:
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

TABLE 1. SELECTED RADIONUCLIDES AND APPLICATIONS

Nuclide	Type of standard	Dosimetry	Medical applications	Environmental monitoring	Waste management	Safeguards
^{22}Na	P	–	×	–	–	–
^{24}Na	P	–	–	–	–	–
^{40}K	S	–	–	×	–	–
^{46}Sc	P	–	–	–	–	–
^{51}Cr	S	–	×	–	–	–
^{54}Mn	P	–	–	×	×	–
^{56}Mn	P	–	×	–	–	–
^{55}Fe	S	–	×	–	×	–
^{59}Fe	S	–	×	–	–	–
^{56}Co	S	–	–	–	–	–
^{57}Co	P (122 keV)	–	×	–	–	×
^{58}Co	P	–	–	×	–	–
^{60}Co	P	–	×	×	×	×
^{64}Cu	–	–	×	–	–	–
^{65}Zn	S	–	–	×	×	–
^{66}Ga	S	–	×	–	–	–
^{67}Ga	S	–	×	–	–	–
^{68}Ga	–	–	×	–	–	–
^{75}Se	S	–	×	–	–	–
^{85}Kr	–	–	–	×	–	–
^{85}Sr	P	–	×	×	–	–
^{88}Y	P (1836 keV) S (898 keV)	–	–	–	–	–
^{93m}Nb	–	×	–	–	–	–
^{94}Nb	P	–	–	–	–	–
^{95}Nb	P	–	–	×	–	×
^{99}Mo–^{99m}Tc	P (140.5 keV)	–	×	–	–	–
^{99m}Tc	P (140.5 keV)	–	×	–	–	–
^{103}Ru	–	–	×	×	–	×
^{106}Ru–^{106}Rh	S	–	×	×	–	×
^{110m}Ag(^{110}Ag)	S	–	–	×	×	–
^{109}Cd	S	–	–	×	–	–
^{111}In	P	–	×	–	–	–
^{113}Sn	P	–	–	–	–	–
^{125}Sb	–	–	–	×	–	×
^{123m}Te	–	–	×	–	×	–
^{123}I	P	–	×	–	–	–
^{125}I	S	×	×	–	–	–

TABLE 1. SELECTED RADIONUCLIDES AND APPLICATIONS (cont.)

Nuclide	Type of standard	Dosimetry	Medical applications	Environmental monitoring	Waste management	Safeguards
^{129}I	S	–	–	×	×	–
^{131}I	S	×	×	×	–	×
^{134}Cs	S	–	–	×	–	×
^{137}Cs	P	×	–	×	×	×
^{133}Ba	S	–	×	–	–	–
^{139}Ce	P	–	–	×	–	–
^{141}Ce	S	–	–	×	–	×
^{144}Ce–^{144}Pr	S	–	×	×	–	×
^{153}Sm	–	–	×	–	–	×
^{152}Eu	S	–	–	×	×	×
^{154}Eu	S	–	–	×	×	×
^{155}Eu	S	–	–	×	×	×
^{166m}Ho–^{166}Ho	S	–	×	–	–	×
^{170}Tm	S	–	–	–	–	–
^{169}Yb	S	–	×	–	–	–
^{192}Ir	S	×	×	–	–	–
^{198}Au	P	–	–	–	–	–
^{203}Hg	P	–	–	–	–	–
^{201}Tl	–	–	×	–	–	–
^{207}Bi	P (569.7 keV)	–	×	–	–	–
^{226}Ra decay chain	S	×	–	×	×	×
^{228}Th decay chain	P	–	–	×	–	×
^{234m}Pa	–	–	–	×	×	–
^{241}Am	P	–	–	×	×	×
^{243}Am	–	–	–	–	×	×

P: Primary efficiency calibration standard.
S: Secondary efficiency calibration standard.

TABLE 2. DECAY DATA EVALUATIONS AND COMMENTS

Radionuclide	Evaluation	Comments*
^{22}Na	INL/PTB	—
^{24}Na	INL/PTB	—
^{40}K	INL	—
^{46}Sc	INL	—
^{51}Cr	INL/PTB	—
^{54}Mn	INL/PTB	—
^{56}Mn	AEA	—
^{55}Fe	LNHB	—
^{59}Fe	LNHB	—
^{56}Co	NPL/LBNL	A total of 87 statistical outliers were identified from approximately 770 data points (representing a large fraction). Only data from eight selected references were considered in the evaluation for Eγ > 3000 keV. This situation implies the need for further measurements for high energy γ ray standards.
^{57}Co	KRI	Assumed no electron capture feeding to the ground and first excited states of ^{57}Fe.
^{58}Co	LNHB	—
^{60}Co	INL	—
^{64}Cu	INL	—
^{65}Zn	INL	—
^{66}Ga	LBNL	—
^{67}Ga	KRI	Decay scheme evaluation is based on absolute $P_{ec1,0}$(93.3 keV) = 0.325(4). However, this emission has been obtained from two discrepant measurements of 0.3206(23) and 0.329(4). Further studies of this important parameter are required.
^{68}Ga	PTB	—
^{75}Se	LBNL/PTB	Recommended relative γ ray emission probabilities were deduced from 11 published measurements and 13 additional measurements of an ICRM intercomparison coordinated by the CRP. Absolute emission probabilities were obtained from a weighted average value of 0.589(3) for the 264 keV γ ray. Calculated KX ray probabilities agree well with measured values and confirm the consistency of the decay scheme.
^{85}Kr	LNHB	—
^{85}Sr	PTB	—
^{88}Y	PTB	—
^{93m}Nb	KRI	—
^{94}Nb	NPL	—
^{95}Nb	INL	—
^{99}Mo-^{99m}Tc	LNHB/KRI	—
^{99m}Tc	LNHB/KRI	—
^{103}Ru	NPL	—
^{106}Ru-^{106}Rh	NPL	—
^{110m}Ag(^{110}Ag)	INL	—
^{109}Cd	PTB	—
^{111}In	KRI	More accurate measurements of γ ray energies are recommended.
^{113}Sn	INL	—
^{125}Sb	INL/LBNL	Assumed no direct β decay to the ground and 35.5 keV excited levels of ^{125}Te, and set the total γ ray feeding to these two states to be 100%.

TABLE 2. DECAY DATA EVALUATIONS AND COMMENTS (cont.)

Radionuclide	Evaluation	Comments*
^{123m}Te	LNHB	—
^{123}I	LNHB	—
^{125}I	PTB	—
^{129}I	KRI	Second unique forbidden β^- transition to the $1/2^+$ ground state of ^{129}Xe has not been observed. Although an upper limit for the intensity of this β^- branch was obtained experimentally in 1954, further refinement is required because the recommended Pγ(39.58 keV) depends on this parameter.
^{131}I	LNHB	—
^{134}Cs	USP/LBNL	—
^{137}Cs	INL/PTB	—
^{133}Ba	KRI	—
^{139}Ce	INL/PTB	—
^{141}Ce	PTB	—
^{144}Ce-^{144}Pr	PTB	—
^{153}Sm	INL/PTB	Significant uncertainties exist in the detail and accuracy of the proposed decay scheme. Therefore, γ ray measurements are recommended to help resolve these issues, particularly with respect to the lower energy transitions (<100 keV).
^{152}Eu	USP/LBNL	—
^{154}Eu	KRI	—
^{155}Eu	KRI	Weak overlap between the two most accurate measurements of an important decay parameter for ^{155}Eu [P_γ(86.548 keV) = 0.305 (3) and 0.311 (4)] prevents accurate determinations of the absolute X and γ ray emission probabilities. Further studies are warranted in order to achieve a more precise recommendation for P_γ(86.548 keV).
^{166}Ho	PTB	—
^{166m}Ho	PTB	Only one known published measurement of the half-life in 1965.
^{170}Tm	KRI	Half-life measurements before 1970 are discrepant, and further studies are warranted.
^{169}Yb	PTB/LNHB	—
^{192}Ir	LBNL	Recommended relative γ ray emission probabilities were deduced from 11 measurements. Absolute emission probabilities were derived from the decay scheme using relative emission probabilities and theoretical conversion coefficients. Calculated KX ray probabilities agree well with measured values and confirm the consistency of the decay scheme.
^{198}Au	PTB	—
^{203}Hg	AEA	—
^{201}Tl	PTB	—
^{207}Bi	LNHB	—
^{226}Ra decay chain	INL	—
^{228}Th decay chain	AEA	^{224}Ra decay: P_γ(240.986 keV) of 0.0412(4) was derived from the relatively large number of direct γ ray measurements. However, α particle measurements and their adoption in decay scheme calculations gave P_γ(240.986 keV) of 0.0390(3). While the γ ray measurements were assumed to be more reliable in the evaluation, further α particle and γ ray studies are required to resolve this significant discrepancy between the two spectroscopic techniques.

TABLE 2. DECAY DATA EVALUATIONS AND COMMENTS (cont.)

Radionuclide	Evaluation	Comments*
^{234m}Pa	AEA	The recommended P_γ(1001 keV) of 0.00832(10) was based on a series of extensive measurements in the 1980/1990s. However, three of these studies gave significantly higher values (by ~10%, at approximately 0.0091) than the other six measurements. Further studies are warranted to aid in the resolution of this discrepancy.
^{241}Am	KRI	Although observed, some γ ray transitions have scarcely been studied (27.03, 54.1 and 95.0 keV), which leads to poor intensity balances for some nuclear levels. Measurements of γ ray and conversion electron emission probabilities are required for these γ transitions.
^{243}Am	LBNL/INL	—

* Further details of specific evaluations can be found in Annex II.

AEA: AEA Technology, UK.
INL: Idaho National Laboratory, USA.
KRI: V.G. Khlopin Radium Institute, Russian Federation.
LBNL: Lawrence Berkeley National Laboratory, USA.
LNHB: Laboratoire National Henri Becquerel, France.
NPL: National Physical Laboratory, UK.
PTB: Physikalisch-Technische Bundesanstalt, Germany.
USP Universidade de São Paulo, Brazil.

3. DATA EVALUATIONS

Data were evaluated from the public literature and laboratory reports published over a considerable period of time. Possible omissions of individual values had to be justified on the basis of their quality or other specific grounds. Following an initial assessment of the existing half-life and γ ray emission probability data, members of the CRP noted that:

(a) Certain half-lives and emission probabilities would benefit from further measurements (specific cases are noted in Table 2);
(b) Considerable efforts were expended to ensure consistency between the data recommended by the various evaluators.

Evaluation procedures were developed as outlined briefly below and detailed in Annex I and Ref. [7].

The recommended value consisted of the weighted average of the published values in which the weights were taken to be the inverse of the squares of the overall uncertainties. A set of data was self-consistent if the probability of χ^2 exceeding the calculated value was 1% or less. When the data in a set were inconsistent and there were three or more values, the method of limitation of the relative weight proposed by Zijp [10] was recommended. The sum of the individual weights was computed; if any one weight contributed over 50% of the total the corresponding uncertainty was increased so that the contribution of the value to the sum of the weights would be less than 50%. The weighted average was then recalculated and used if the probability of χ^2 exceeding the recalculated value was greater than 1%; otherwise the weighted or unweighted mean was chosen according to whether or not the 1 σ uncertainty on each mean value included the other term. The basis for the latter choice is that it may be unreasonable to use the weighted average if the data do not comprise a consistent set.

It was not considered necessary to carry out evaluations of the X and γ ray energies because the photon energies are only required to the nearest 1 or 0.1 keV for detector efficiency calibrations and the other specified applications. However, for completeness it was decided to include the best available energy values, many of which have been precisely measured and evaluated. A significant number of the energy values quoted in this report were taken from Ref. [11]; original references were cited when data were not available from this source.

A γ transition occurs when a nucleus in an excited state de-excites to a lower energy level, leading to the emission of a γ ray and conversion electron (and electron–positron pair when energy conditions permit). The total γ transition probability is defined as:

$$P_{TP} = P_\gamma + P_{ce} + P_e^{\pm}$$

where P_γ, P_{ce} and $P_e^{\pm}$ are the γ ray, conversion electron and electron-positron pair emission probabilities per decay, respectively (see Annex I). Internal conversion coefficients are often used in the evaluation of γ ray emission probabilities, either directly in the determination of a particular emission probability or in testing the consistency of the decay scheme. The total conversion coefficient is given by:

$$\alpha_{total} = \alpha_K + \alpha_L + \alpha_M + ... = P_{ce} / P_\gamma$$

where α_K, α_L and α_M are the K, L and M internal conversion coefficients, respectively, and:

$$P_\gamma = \frac{P_{TP}}{1+\alpha_{total}}$$

Theoretical internal conversion coefficients were normally taken from Refs [12, 13]; when necessary these data were obtained by interpolation using a computer program written at LNHB [14].

3.1. HALF-LIVES

All recommended half-lives are based on the evaluation of these quantities, incorporating both old and newly measured values and the methodology outlined above. The exclusion of measured values and modifications to the uncertainties are noted for each radionuclide. When a laboratory has published more than one measured value, only the most recent value has been used. Furthermore, if sufficient data are available no measurements published prior to 1968 have been included in the evaluation. Such an approach maintains consistency with the procedure adopted in the earlier CRP and corresponds to the approximate date after which high resolution γ ray spectrometers became generally available. This latter development allowed experimentalists to determine impurities to levels that were significantly more accurate than previously achieved.

3.2. X RAY EMISSIONS

X ray emissions originate from the creation of inner shell vacancies and the subsequent reorganization of the unstable atomic shells. Orbital electron capture by the nucleus and internal conversion of γ rays can produce these inner shell vacancies during radioactive decay.

X ray energies were not evaluated but taken from Refs [15, 16]. The intensity per decay of the KX ray emission is given by:

$$P_{KX} = \left\{ \sum_i P_{EC}(E_i) P_K(E_i) + \sum_i b_i \left(\frac{\alpha_K}{1+\alpha_t} \right)_i \right\} \omega_K$$

for any particular decay scheme, where $P_{EC}(E_i)$ and $P_K(E_i)$ are the capture probabilities to the energy level E_i by total electron capture and K electron capture, respectively; α_K and α_t are the K shell and total internal conversion coefficients, respectively; b_i is the branching fraction for the i^{th} γ ray transition, and ω_K is the K shell fluorescence yield. The relevant data were evaluated so that $K\alpha_1$, $K\alpha_2$, Kβ and the total KX ray emission probabilities could be calculated for all Z; in addition, further subdivisions were made for a few nuclides.

A similar equation can be used to calculate LX ray emission probabilities. However, these values depend on the mode of vacancy production in the three L subshells, which is different for internal conversion and electron capture by the nucleus. Furthermore, interpretation of LX ray data may be complicated by the transfer of the primary vacancies between the L subshells due to Coster–Kronig transitions.

Note that the X ray peaks differ in shape from γ ray peaks when measured with semiconductor detectors, due to the larger natural line widths of X rays. This can result in calibration errors of several per cent when using the same procedure to analyse both X ray and γ ray data for high atomic number radionuclides.

3.3. GAMMA RAY EMISSION PROBABILITIES

Various methods can be used to obtain evaluated γ ray emission probabilities. For example, the emission probabilities of ^{60}Co are calculated from the decay scheme using various parameters (notably the internal conversion coefficients), rather than direct γ ray measurements.

The γ ray emission probabilities of other radionuclides are derived primarily from γ ray measurements, as for example in the case of ^{152}Eu, where a large number of sets of spectral data were included in the evaluation. This extensive study of ^{152}Eu emission rates originated as a result of an earlier intercomparison programme carried out under the auspices of the ICRM. Similar intercomparisons have been organized for other radionuclides under the auspices of the ICRM and are included in the relevant evaluations.

New experimental data have been generated for the high energy γ ray emitters ^{56}Co [17], ^{66}Ga [18] and ^{226}Ra decay chain [17]. Furthermore, above an energy of 5 MeV, measured and evaluated data were adopted from a select number of radiative neutron and proton reactions [17, 19, 20], as discussed in Section 3.4.

3.4. HIGH ENERGY GAMMA RAYS

Nuclear reactions have been used to extend the recommended γ ray data for detector efficiency calibrations beyond 5 MeV. Although other reactions were assessed in this study, only γ ray emissions from thermal neutron capture, resonance proton capture and continuum proton capture reactions were known to the desired accuracy for the applications under consideration. The reactions adopted as γ ray calibration standards are as follows:

$^{14}N(n, \gamma)^{15}N^*$
$^{35}Cl(n, \gamma)^{36}Cl^*$
$^{48}Ti(n, \gamma)^{49}Ti^*$
$^{50, 52, 53}Cr(n, \gamma)^{51, 53, 54}Cr^*$
and $^{11}B(p, \gamma)^{12}C^*$
$^{23}Na(p, \gamma)^{24}Mg^*$
$^{27}Al(p, \gamma)^{28}Si^*$

Gamma ray energies were adopted from the most accurate values quoted in the literature. The emission probabilities of the most prominent high energy γ rays were determined by means of the weighted mean method in the case of consistent data sets, as described above. All of the resulting data are listed in Annex III.

3.5. COINCIDENCE METHOD

The coincidence method offers the possibility of determining absolute γ ray detection efficiency without having to use an absolutely calibrated γ ray source. A second γ ray detector is operated in coincidence with a calibrated detector to study radionuclides that emit two cascading γ rays. Suitable sources with two strong cascading γ rays were identified from Table 1: ^{24}Na, ^{46}Sc, ^{60}Co, ^{66}Ga, ^{75}Se, ^{88}Y, ^{94}Nb, ^{111}In, ^{134}Cs, ^{152}Eu and ^{207}Bi. Angular correlation coefficients for these nuclei were evaluated, covering the energy range from 136 keV to 2.75 MeV. These data are brought together in Annex IV.

3.6. COVARIANCES AND STATISTICAL CORRELATIONS

As with many other physical quantities, decay data may be statistically correlated. However, currently available data do not generally allow for proper evaluations of the correlation coefficients. Although these coefficients have been shown to be negligible in the few cases in which they have been calculated, this observation arises from the nature of the decay schemes analysed and should not be taken as a normal characteristic of decay data. Rather, strong statistical correlations are expected to occur in many cases.

An evaluation of the covariances requires data reduction to be performed by the least squares method (the main formulae are given in Annex V along with an example of such an analysis). Absolute γ ray emission probabilities and relative intensities are handled differently, although both sets of resulting correlations arise from the statistical dependence on the common efficiency curve and normalization factor (NF). A_i is the observed peak area for gamma ray γ_i corrected for summing, absorption, pile-up, etc., and $V_{\mathbf{A}}$ is their covariance matrix (usually diagonal, and containing the variances in the peak areas). The detector peak efficiency for γ_i is ε_i, and V_ε represents their covariance matrix calculated from the covariance matrix of the fitted parameters. The intensity of γ_i can be determined from the formula:

$$I_i = \frac{A_i}{NF(A,\varepsilon,\tau)\varepsilon_i}$$

where the normalization factor (NF) usually depends on many peak areas and efficiencies, as well as on some other quantities represented by τ that are assumed to be independent of A and ε. For example, if relative intensities are being considered, the NF is expressed as:

$$NF_r(A,\varepsilon) = \frac{A_r}{I_r\varepsilon_r}$$

where I_r is the intensity chosen for the reference line (identified by subscript r). The variance matrix of the intensities is given by:

$$\mathbf{V}_I = \mathbf{F}\mathbf{V}_A\mathbf{F}^t + \mathbf{G}\mathbf{V}_\varepsilon\mathbf{G}^t$$

where F and G are matrices defined as:

$$F_{iv} = \frac{\partial I_i}{\partial A_v} \text{ and } G_{iv} = \frac{\partial I_i}{\partial \varepsilon_v},$$

in which the derivatives are calculated with the experimental values of the peak areas and efficiencies. When relative intensities are being analysed, the expression for I_r must be replaced by the formula for NF_r. The set of intensities and associated covariance matrix is the only information required for absolute emission probabilities, while the normalization factor should be rescaled from NF_r to I_r for presentation of the relative intensities and full covariance matrix (see Section V–7 of Annex V).

Therefore, when reporting experimental gamma ray intensities, their covariance matrix $\mathbf{V}_I$ must be given. While covariances between the emission probabilities in calibration standards can be neglected in many cases, the covariances arising from the uncertainties in the activities of multi-gamma ray calibrated sources must be taken into account.

4. CONCLUSIONS

A set of recommended half-life and emission probability data has been prepared by the IAEA CRP to update X ray and γ ray decay data standards for detector calibration and other applications. The results of this work represent a further significant improvement in the quality of specific decay parameters required for the efficiency calibration of X and γ ray detectors.

The accomplishments of the CRP include:

(a) Re-evaluations of all existing relevant data from the 1986–1990 programme;
(b) Extension of the recommended database to satisfy the needs of a number of important applications;
(c) Specific measurements, particularly with respect to high energy γ ray emissions;
(d) Preparation of this report in two volumes which summarize and document the recommended decay data for X and γ ray detector efficiency calibration and other applications.

One important expectation is that the resulting data will be internationally accepted as a significant contribution to improving the quality of X and γ ray spectroscopy over a range of applications.

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Annex I

EVALUATION PROCEDURES

M.-M. Bé

Commissariat à l'Énergie Atomique, France

I–1. DATA SOURCES

Two main sources of data are used to obtain the recommended half-lives and emission probabilities:

(1) Specific data evaluated from all available original publications (e.g. half-life);
(2) Data already evaluated by specialists and compiled (e.g. Q values); if a new experimental study exists, the resulting measurements may be taken into account and the corresponding reference is included in the list of references for the relevant radionuclide.

I–2. EVALUATION RULES

Not all intermediate stages in the compilation and evaluation of a decay parameter are presented in detail, in order to avoid unnecessary complexity. These stages comprise the following:

(a) 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;
(b) Data obtained through private communications are only used when all of the necessary information has been provided directly by the scientist carrying out the measurements;
(c) Adjustments may be made to the reported uncertainties;
(d) Recommended values are derived from an analysis of all available measurements (or theoretical considerations), along with the combined standard uncertainty for a coverage factor of 1 corresponding to the 1σ confidence level.

I–2.1. Evaluation of uncertainties

Definitions from Ref. [I–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:

$$u_c = \sqrt{\sigma_A^2 + \sigma_B^2} \qquad \text{(I–1)}$$

where

u_c is the combined standard uncertainty,
σ_A is the type A standard deviation,
σ_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).

I–2.2. Determination of the best value and associated uncertainty

I–2.2.1. 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…n), the best value is the arithmetical mean:

$$\bar{a} = \sum_{i=1}^{n} \frac{a_i}{n} \qquad \text{(I–2)}$$

with type A standard deviation:

$$\sigma_A(\bar{a}) = \left[\frac{\sum_i (a_i - \bar{a})^2}{n(n-1)} \right]^{1/2} \qquad \text{(I–3)}$$

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

$$\sigma_B(\bar{a}) = \left[\sum_{j=1}^{m} \sigma_{Bj}^2 \right]^{1/2} \qquad \text{(I–4)}$$

Combined standard uncertainty:

$$u_c(\bar{a}) = \sqrt{\sigma_A^2(\bar{a}) + \sigma_B^2(\bar{a})} \qquad \text{(I–5)}$$

Recommended value:

$$a = \bar{a} \pm u_c(\bar{a}) \qquad \text{(I–6)}$$

I–2.2.2. Results obtained by several authors employing the same method

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

$$\bar{\bar{a}} = \frac{\sum_i \left(\bar{a}_i / \sigma_{Ai}^2 \right)}{\sum_i \left(1/\sigma_{Ai}^2 \right)} \qquad \text{(I–7)}$$

The associated values σ_A and σ_B are:

$$\sigma_A\left(\bar{\bar{a}}\right) = \left[\sum_i \left(1/\sigma_{Ai}^2 \right) \right]^{-1/2} \qquad \text{(I–8)}$$

$$\sigma_B\left(\bar{\bar{a}}\right) = \sum_i \left(\sigma_{Bi}\right)_{\min} \text{ or}$$

$$\sigma_B\left(\bar{\bar{a}}\right) = \sqrt{\sum_i \left(\sigma_{Bi}\right)_{\min}^2} \text{ or } \sigma_B\left(\bar{\bar{a}}\right) = \left(\sigma_B\right)_{\min}$$

depending on the individual case, although $\sigma_B\left(\bar{\bar{a}}\right)$ cannot be less than the smallest σ_{Bi}.

σ_A and σ_B are combined quadratically to determine u_c:

$$u_c\left(\bar{\bar{a}}\right) = \sqrt{\sigma_A^2\left(\bar{\bar{a}}\right) + \sigma_B^2\left(\bar{\bar{a}}\right)} \qquad \text{(I–9)}$$

and the recommended value is given by the expression:

$$a = \bar{\bar{a}} \pm u_c\left(\bar{\bar{a}}\right) \qquad \text{(I–10)}$$

I–2.2.3. 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:

$$a_w = \frac{\sum_{i=1}^{n} p_i a_i}{\sum_{i=1}^{n} p_i} \qquad \text{(I–11)}$$

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

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

$$\sigma_{int}\left(a_w\right) = \left[\sum_i \left(1/u_{c_i}^2 \right) \right]^{-1/2} \qquad \text{(I–12)}$$

The internal variance $\sigma_{int}^2\left(a_w\right)$ is the expected uncertainty of the mean based on the individual a priori variances $u_{c_i}^2$ (by uncertainty propagation).

The external uncertainty is given by the equation:

$$\sigma_{ext}(a_w) = \left[\frac{\sum_i (a_i - a_w)^2 / u_{c_i}^2}{(n-1)\sum 1/u_{c_i}^2}\right]^{½} \qquad \text{(I–13)}$$

The external variance $\sigma_{ext}^2(a_w)$ 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 [I–2, I–3]:

$$\sigma_{ext}/\sigma_{int} = \sqrt{\chi^2/(n-1)} \qquad \text{(I–14)}$$

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 $\chi^2/(n-1)$ at the 1% confidence level is used as a practical test for discrepant data. Table I–1 lists critical values of $\chi^2/(n-1)$ for an increasing degree of freedom $v = N - 1$ [I–4].

TABLE I–1. CRITICAL VALUES OF $\chi^2/(n-1)$ FOR AN INCREASING DEGREE OF FREEDOM $v = N - 1$ [I–4]

v	Critical $\chi^2/(n-1)$	v	Critical $\chi^2/(n-1)$
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	$1 + 2.33\sqrt{2/v}$

If $\chi^2/(n-1) \leq$ critical $\chi^2/(n-1)$, the recommended value is given by:

$$a = a_w \pm \sigma_{int}(a_w) \qquad \text{(I–15)}$$

If $\chi^2/(n-1) >$ critical $\chi^2/(n-1)$, the method of limitation of the relative statistical weight [I–3, I–5] is recommended when there are three or more values; the uncertainty of a value contributing more than 50% to the total weight is increased to give a contribution less than 50% (weighting factor <0.50). The weighted and unweighted average and critical $\chi^2/(n-1)$ are then recalculated:

if $\chi^2/(n-1) \leq$ critical $\chi^2/(n-1)$, the recommended value is given by:

$$a = a_w \pm (\text{the larger of } \sigma_{int}(a_w) \text{ and } \sigma_{ext}(a_w)) \qquad \text{(I–16)}$$

If $\chi^2/(n-1) >$ critical $\chi^2/(n-1)$, the weighted or unweighted mean is chosen, depending on whether or not the uncertainties of the average values result in overlap. 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.

I–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 obvious relationships, such as the following:

(a) The sum of the transition probabilities for all the decay transitions (α, β, γ, ε) in the horizontal plane of a decay scheme is equal to 1 (or 100%); this ruling is valid for the highest energies of the decay scheme where only β (or α, ε) transitions are relevant, and for the lowest levels of the decay scheme where sometimes only γ transitions are involved.

(b) Excited nuclear level — the sum of the transition probabilities for transitions feeding the level (α, β…) is equal to the sum of transition probabilities (including conversion electrons) of those transitions depopulating this level.

(c) When the relative emission probabilities $P(rel)_{\gamma_i}$ of the γ emission are known with respect to one emission (γ_1), and no feeding to the ground state from α, β and ε transitions is assumed, all the absolute emitted photon numbers for the γ emissions $P(abs)_{\gamma i}$ can be calculated from the equation:

$$P(abs)_{\gamma i} = P(rel)_{\gamma i} \times \frac{1}{k} \qquad \text{(I–17)}$$

where k is the normalization factor and is determined from the equation:

$$k \sum_i P(rel)_{\gamma i} \left(1 + \alpha_{t_i}\right) = 1 \qquad \text{(I–18)}$$

where the sum represented by Eq. (I–18) covers the γ transitions feeding the ground state.

I–3. COMPILATIONS

I–3.1. Beta and electron capture transitions

Depending on the individual radionuclide, β transition energies are either evaluated on the basis of experimental data (maximum β energies) or derived from the atomic mass differences obtained from the tabulations of Wapstra et al. [I–6] and the γ transition energies. The average β energies are generally computed [I–7] and the values of log *ft* are calculated from the tables of Gove and Martin [I–8], as well as ε/β^+ if possible.

Electron capture transition energies are derived from the atomic mass differences and the γ transition energies. Capture probabilities P_K, P_L… can be calculated from equations where the ratios of the radial wave function components of the electron [I–9 to I–11] and the corrective terms for exchange $X^{L/K}$ [I–12 to I–16] are evaluated from tables.

I–3.2. Gamma transitions

Internal conversion coefficients (ICCs) of pure transitions are evaluated and compared with theoretical values, which are sometimes preferred if the experimental data are extremely uncertain. The theoretical values can be deduced from the tables of either Rösel et al. interpolated with a cubic spline method for 30 ≤ Z ≤ 104 [I–17], or Band et al. for Z < 30 [I–18] in particular. The uncertainties of these theoretical values are estimated to be 3%.

ICCs for some particular M1 and E2 transitions are calculated according to Ref. [I–19] in order to account for the penetration effects.

Experimental mixing ratios are sometimes used in conjunction with the available tables of theoretical ICC data to derive the ICCs of multipole transitions (e.g. M1 + E2):

$$\alpha_{i(M1+E2)} = \left(1 - \delta^2\right)\alpha_{i(M1)} + \delta^2 \alpha_{i(E2)} \qquad \text{(I–19)}$$

where i = K, L … t.

α_π coefficients are interpolated from theoretical values [I–20] and the uncertainties are assumed to be between 5 and 10%.

I–3.3. Level spins and parities

Level spins and parities are normally extracted from Nuclear Data Sheets [I–21].

I–3.4. Atomic shell constants

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

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

Mean M shell fluorescence yields $\bar{\omega}_L$ are obtained from the fitting of experimental data by Hubbell [I–28, I–30].

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

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

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

Energies of the K and L-Auger electrons are taken from Larkins [I–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.

I–3.5. m_0c^2 energy

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

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Annex II

EVALUATIONS AND ORIGINS OF THE RECOMMENDED DECAY DATA

This annex contains the recommended decay data derived by means of the agreed evaluation procedures and methodology. All relevant data have been evaluated to produce values recommended for detector efficiency calibration and other applications. Half-lives, X ray emission probabilities and γ ray emission probabilities are listed for each radionuclide considered by the CRP. Source references are also given for these evaluations.

The data uncertainties are defined as standard deviations corresponding to the 1σ confidence level. These uncertainties are expressed in terms of the last digits of the recommended value, for example:

78.3(9) means 78.3 ± 0.9, and 56.2(12) means 56.2 ± 1.2

^{22}Na

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA) and E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), January 1999.

Recommended data

Half-life

$T_{1/2}$ = 950.57(23) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
511	1.798(2)[a]
1274.537(3)[b]	0.99940(14)[c]

[a] Annihilation radiation emission probability is taken to be twice (× 2.0) the positron emission probability; however, the emission probability for 511 keV photons will be somewhat lower due to annihilation in flight of some of the positrons.

[b] From Ref. [1].

[c] Emission probability for the 1274 keV gamma ray is equal to the feeding of this level because the internal conversion is negligible; feeding of this level is determined from the measured ratio of 1600(400) from Ref. [2] of the positron feeding to the 1274 keV level and to the ground state, and the theoretical electron capture to positron ratios of ε/β+(1274 keV) = 0.1125 (12) and ε/β+(0) = 0.01786(18), as computed by the LOGFT code.

Input data

HALF-LIFE

Half-life (d)	Reference
950.97(15)	[H1]
950.30(27)	[H2]
950.34(13)	[H3]
950.57(23)	

REFERENCES — HALF-LIFE

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{24}Na

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA) and E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), November 2001.

Recommended data

Half-life

$T_{1/2}$ = 0.62329(6) d

SELECTED GAMMA RAYS

E_γ (keV)[a]	P_γ per decay
1368.626(5)	0.999935(5)[b]
2754.007(11)	0.99872(8)[c]

a From Ref. [1].

b From:

P_γ(1368 keV) = [1.00 – P_γ(4237 keV) – P_γ(4122 keV) – P_γ(5236 keV)]/[1.0 + α(1368 keV) + α_π(1368 keV)] where the latter two γ rays have not been observed; the measured limits for these two γ rays are P_γ(4122 keV) < 0.00001 [2], < 0.000009 [3, 4] and P_γ(5236 keV) < 0.0000023 [2] and 0.0000002 [3, 4]; P_γ(4237 keV) = 0.0000084(10) from [3]. Both the internal and pair conversion coefficients for the γ rays above 4000 keV are negligible, while α = 0.0000104(3) [5] and α_π = 0.000045(4) for the 1368 keV γ ray [6]. Adopting these values, P_γ(1368 keV) is determined to be 0.999990(3)/1.000055(1).

c emission probability of the 2754 keV γ ray is calculated from the balance condition:

P_γ(2754 keV) =
{P_γ(1368 keV) × [1.0 + α(1368 keV) + α_π(1368 keV)] – [P_γ(2869 keV) + P_γ(3867 keV) + $P_{\beta-}$(1368 keV)]}/
[1.0 + α(2754 keV) + α_π(2754 keV)].

Gamma ray emission probabilities are P_γ(3867 keV) = 0.00056(7) from an average of the values from [3, 7–10], and P_γ(2869 keV) = 0.0000024(3) from P_γ(2869 keV)/P_γ(4237 keV) = 0.284(7) from average of values determined from ^{23}Na(p, γ) and ^{24}Mg(n, n'γ) reactions [2, 3, 11–14]. $P_{\beta-}$(1368 keV) = 0.00003(2), where the value is from Ref. [15] and the uncertainty has been assigned by the evaluator. Internal conversion gives a negligible contribution from the 2869 and 3867 keV γ rays, while for the 2754 keV γ ray, α = 0.0000028(1) [5] and α_π = 0.00068(4) [6], yielding P_γ(2754 keV) = 0.99940(7)/1.00068(4).

Input data

HALF-LIFE

Half-life (d)	Reference
0.623483(167)	[H1]
0.61924(486)	[H2]
0.6208(9)[a]	[H3]
0.62613(9)[a]	[H4]
0.62323(12)	[H5]
0.62317(11)	[H6]
0.62354(42)	[H7]
0.623292(50)[b]	[H8]
0.62350(63)	[H9]
0.62542(117)	[H10]
0.6288(25)	[H11]
0.6237(5)[c]	[H12]
0.62625(13)[a]	[H13]
0.62329(6)	

a Rejected as an outlier.

b Uncertainty increased to (71) to ensure a weighting factor not greater than 0.50.

c Weighted mean of six published values.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{40}K

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA), July 1998.

Recommended data

Half-life

$T_{½} = 4.563(13) \times 10^{11}$ d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
1460.822(6)[a]	0.1066(13)[b]

[a] From Ref. [1].
[b] ^{40}K decays by both ε+β+ and β– modes, and 1460.8 keV γ ray follows ε decay. From Ref. [2], $I_\gamma(1460\ keV)/I_{\beta-} = 0.1195(14)$ and $I_{\beta+}/I_{\beta-} = 1.12(14)$. β+ decay occurs directly to the ground state of ^{40}Ar, so the total ground state feeding can be computed from the ε/β+ ratio for this third forbidden transition. However, the available codes calculate this value for only allowed, first forbidden and second forbidden transitions. Evaluator's estimate of the ε/β+ ratio for the third forbidden transition is 200(100). Hence, the γ ray emission probability is $I_\varepsilon(1460\ keV)/[1.0 + \alpha(1460\ keV) + \alpha_\pi(1460\ keV)] = 0.1066(13)/1.000102(5)$, where the internal conversion coefficient of 0.0000295(9) is interpolated from the tables of Ref. [3] and the pair-production coefficient of 0.000073(5) is interpolated from the tables of Ref. [4].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Ar	K	2.96–3.19	0.00997(22)

Input data

HALF-LIFE

Half-life (d)	Reference
$4.558(11) \times 10^{11}$	[H1]
$4.558(8) \times 10^{11}$ [a]	[H2]
$4.624(26) \times 10^{11}$	[H3]
$4.563(13) \times 10^{11}$	

[a] Uncertainty increased to (11) to ensure a weighting factor not greater than 0.50.

REFERENCES — HALF-LIFE

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{46}Sc

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA), February 2001.

Recommended data

Half-life

$T_{1/2}$ = 83.79(4) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
889.271(2)[a]	0.999833(5)[b]
1120.537(3)[a]	0.99986(+4–36)[c]

[a] From Ref. [1].
[b] Emission probability is [1.00 – P_γ(2009 keV)]/[1.00 + α(889 keV)] = 0.99999987(10)/1.000167(5), where the emission probability of the 2009 keV γ ray is 0.00000013(10) from Ref. [2] and the internal conversion coefficient of 0.000167(5) is interpolated from Ref. [2]; β branch to the ground state is assumed to be negligible (fourth forbidden transition).
[c] emission probability is: [$I_{\beta-}$(2009 keV) – P_γ(2009 keV)]/[1.0 + α(1120 keV) + α_π(1120 keV)] = 0.99996 (+4–36)/1.000095(3); β branch to the 889 keV level is taken to be 0.00004 (+36–4) from consideration of several measurements [3–6]; internal conversion coefficient is 0.000095(3); internal pair coefficient of 0.0000022(4) is from Ref. [7].

SELECTED X RAY

Origin		E_X (keV)	P_X per decay
Ti	K	4.51	0.000047(2)

Input data

HALF-LIFE

Half-life (d)	Reference
83.831(66)	[H1]
83.73(12)	[H2]
83.752(15)	[H3]
83.819(6)[a]	[H4]
83.79(6)	[H5]
84.34(13)[b]	[H6]
83.691(84)	[H7]
83.79(4)	

[a] Uncertainty increased to (14) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

REFERENCES — HALF-LIFE

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{51}Cr

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany) and R.G. Helmer (Idaho National Laboratory, USA), February 2000.

Recommended data

Half-life

$T_{1/2}$ = 27.7009 (20) d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
320.0835(4)[a]	0.0987(5)[b]

[a] From Ref. [1].
[b] From direct emission probability measurements.

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
V	Kα	4.94–4.95	0.202(3)
V	Kβ	5.43–5.46	0.0269(7)

Input data

HALF-LIFE

Half-life (d)	Reference
27.7010(12)[a]	[H1]
27.71(3)	[H2]
27.704(3)	[H3]
27.690(5)	[H4]
27.72(3)	[H5]
27.703(8)	[H6]
27.75(1)[b]	[H7]
28.1(17)[b]	[H8]
27.76(15)[b]	[H9]
27.80(51)[b]	[H10]
27.7009(20)	

[a] Uncertainty increased to (25) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

REFERENCES — HALF-LIFE

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GAMMA RAY: MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITY

Eγ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]
320.0835	0.098(6)	0.09(1)	0.0972(15)	0.102(6)	0.0975(20)	0.102(10)
Eγ (keV) [1]	[8]	[9]	[10]	Evaluated		
320.0835	0.0985(9)	0.1030(19)	0.0986(8)	0.0987(5)		

Evaluated emission probabilities are the weighted averages calculated according to the limitation of the relative statistical weights method; no value has a relative weighting factor greater than 0.50.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{54}Mn

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA) and E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), March 2001.

Recommended data

Half-life

$T_{1/2}$ = 312.29(26) d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
834.838(5)[a]	0.999746(11)[b]

[a] From Ref. [1].

[b] Emission probability of the 834 keV gamma ray is: I_ε(834 keV)/[1.00 + α(834 keV)] = 0.999997(3)/1.000251(11); electron-capture branch to the ground state is estimated to be 0.000003(3) from measurements of the limit of the positron intensity to the ground state [2–4]. The internal conversion coefficient is derived from an analysis of experimental data [5], and is based on the measurement reported in Ref. [6].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Cr	Kα	5.405–5.415	0.227(3)
Cr	Kβ	5.947	0.0305(7)

Input data

HALF-LIFE

Half-life (d)	Reference
312.6(5)	[H1]
312.11(5)	[H2]
312.028(34)[a]	[H3]
312.6(8)	[H4]
315.40(3)[b]	[H5]
312.2(9)	[H6]
312(5)	[H7]
312.2(3)	[H8]
312.99(5)	[H9]
312.29(26)	

[a] Uncertainty increased to (35) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{56}Mn

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by A.L. Nichols (IAEA and AEA Technology, UK), January 2004.

Recommended data

Half-life

$T_{1/2}$ = 0.107449 (19) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
846.7638(19)[a]	0.9885(3)
1810.726(4)[a]	0.269(4)
2113.092(6)[a]	0.142(3)
2523.06(5)[b]	0.0102(2)

[a] From Ref. [1] for equivalent decay of ^{56}Co.
[b] Derived from Ref. [2].

Input data

HALF-LIFE

Half-life (d)	Reference
0.107454(4)[a]	[H1]
0.107350(33)	[H2]
0.107438(8)	[H3]
0.10779(25)	[H4]
0.10742(33)	[H5]
0.10771(4)	[H6]
0.107449(19)	

[a] Uncertainty increased to (8) to ensure a weighting factor not greater than 0.50.

REFERENCES — HALF-LIFE

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[3]	[4]	[5]	[6]	[7]	[8]	Evaluated
846.76	100(3)[a]	100(3)[a]	100(3)[a]	100(3)[a]	100(3)[a]	100.000(103)	100(3)
1810.73	30(3)	29.4(16)	28.6(15)	26.9(13)	27.5(8)	26.610(72)	27.2(4)[b]
2113.09	17.4(17)	16.0(9)	16.0(8)	14.3(7)	14.5(4)	13.956(53)	14.4(3)[c]
2523.06	1.10(15)	1.6(5)	1.14(5)	1.01(5)	1.00(3)	1.025(9)	1.03(2)[b]

[a] Arbitrarily assigned an uncertainty of 3%.
[b] Recommended values are the weighted averages calculated according to the limitation of the relative statistical weights method; no value has a relative weighting factor greater than 0.50.
[c] Recommended value adopted from a combination of the normalized residuals and Rajeval methods [9].

Comments:

(a) The complete decay scheme was defined in terms of seven β^- transitions and ten γ ray emissions (only four with $P\gamma > 0.01$, see above); a comprehensive study of the full decay scheme can be found on: http://www.nucleide.org/DDEP_WG/DDEPdata.htm

(b) An additional γ ray with an energy of 3119.3(5) keV was detected by Ref. [4], but was discarded due to lack of evidence in all other studies.

(c) NF for the γ ray relative emission probabilities was calculated by two methods:

— Beta population of all ^{56}Fe nuclear levels derived from γ ray population/depopulation, and summed assuming β^- decay to the ^{56}Fe ground state is zero (from consideration of spin and parity $(3^+ \rightarrow 0^+)$):
$\Sigma P_\beta = 101.163(1479)$ NF = 1.0
NF = 0.009885(145)

– Population of ^{56}Fe ground state by γ transitions, assuming β^- decay to ^{56}Fe ground state is zero:
$\Sigma P_{\gamma i} (1 + \alpha_i)$ NF = $[P_\gamma(3369.84 \text{ keV}) + P_\gamma(2959.92 \text{ keV}) + P_\gamma(2657.62 \text{ keV}) + P_\gamma(846.7638 \text{ keV}) (1 + \alpha_i)]$ NF = 1.0
101.163(23) NF = 1.0
NF = 0.009885(3)

Normalization factor of 0.009885(3) was adopted as the more accurate determination.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{55}Fe

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by M.-M. Bé (Commissariat à l'Énergie Atomique, France), April 1998.

Recommended data

Half-life

$T_{1/2}$ = 1002.7 (23) d

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Mn	L	0.556–0.721	0.0066(10)
Mn	$K\alpha_2$	5.8877	0.0845(14)
Mn	$K\alpha_1$	5.8988	0.1656(27)
Mn	$K\beta_1'$	6.49–6.54	0.0340(7)

Emission probabilities have been computed using the adopted values of ω_K = 0.321(7), ω_L = 0.0053(4) from Ref. [1] and P_K = 0.8853(16), P_L = 0.0983(13) from Ref. [2]; more details can be found in Refs [3, 4].

Input data

HALF-LIFE

Half-life (d)	Reference
1003.5(21)	[H1]
995(3)	[H2]
996.8(60)	[H3]
1009.0(17)	[H4]
1000.4(13)	[H5]
1002.7(23)	

REFERENCES — HALF-LIFE

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{59}Fe

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by M.-M. Bé (Commissariat à l'Énergie Atomique, France), January 2002.

Recommended data

Half-life

$T_{1/2}$ = 44.494(13) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
142.651(2)	0.00972(15)
192.349(5)	0.0292(3)
1099.245(3)	0.5659(21)
1291.590(6)	0.4321(25)

SELECTED X RAY

Origin		E_X (keV)	P_X per decay
Co	$K\alpha$	6.92	0.000177(3)

Emission probability of K X ray was calculated from the data set described on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

Input data

HALF-LIFE

Half-life (d)	Reference
44.472(8)	[H1]
44.5074(72)	[H2]
44.53(3)	[H3]
44.496(7)	[H4]
44.75(4)[a]	[H5]
44.5(2)	[H6]
44.494(13)	

[a] Rejected as an outlier.

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GAMMA RAYS: MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITIES

Eγ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	Evaluated
142.651(2)	0.0110(16)	0.0098(2)	0.0079(8)	0.008(2)	0.00955(30)	0.0085(15)	0.0102(4)	0.00972(15)
192.349(5)	0.033(3)	0.0295(4)	0.0250(25)	0.028(3)	0.02851(48)	0.024(4)	0.0308(10)	0.0292(3)
1099.245(3)	0.575(3)	0.555(8)	0.562(56)	0.565(15)	0.5668(22)	0.56(3)	0.565(15)	0.5659(21)
1291.590(6)	0.424(23)	0.441(6)	0.435(43)	0.432(15)	0.4299(30)	0.44(3)	0.432(11)	0.4321(25)

Notes: Measured data were given by the authors as absolute values.
Recommended values are the weighted averages calculated according to the limitation of the relative statistical weights method; no value has a relative weighting factor greater than 0.50.
Beta transition probability to ground state is assumed to be 0.0025(15).

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{56}Co

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by S.A. Woods, T.D. MacMahon (National Physical Laboratory, UK) and C.M. Baglin (Lawrence Berkeley National Laboratory, USA), August 2004.

Recommended data

Half-life

$T_{1/2}$ = 77.236 (26) d

SELECTED GAMMA RAYS

E_γ (keV)[a]	P_γ per decay
846.7638(19)	0.999399(23)
977.363(4)	0.01422(7)
1037.8333(24)	0.1403(5)
1175.0878(22)	0.02249(9)
1238.2736(22)	0.6641(16)
1360.196(4)	0.04280(13)
1771.327(3)	0.1545(4)
2015.176(5)	0.03017(14)
2034.752(5)	0.07741(13)
2598.438(4)	0.1696(4)
3009.559(4)	0.01038(19)
3201.930(11)	0.03203(13)
3253.402(5)	0.0787(3)
3272.978(6)	0.01855(9)
3451.119(4)	0.00942(6)

[a] From Ref. [1].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Fe	$K\alpha_2$	6.39091(5)	0.0753(10)
Fe	$K\alpha_1$	6.40391(3)	0.1475(17)
Fe	$K\beta_1'$	7.058–7.108	0.0305(5)

Input data

HALF-LIFE

Half-life (d)	Reference
77.290(40)[a]	[H1]
77.210(28)[a]	[H1]
77.30(9)	[H2]
77.08(8)	[H3]
77.28(4)	[H4]
77.12(10)	[H5]
78.4(5)[b]	[H6]
78.76(12)[b]	[H7]
77.236(26)	

[a] Values determined independently, but reported in the same publication.
[b] Rejected as an outlier.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

Eγ (keV)	[2]	[3]	[4]	[5]	[6]	[7]
846.8	100	100	100	100	100	100
977.4	1.73(35)	—	—	—	1.36(36)	1.62(10)
1037.8	14.1(15)	12.4(5)	14.0(20)	14.5(15)	12.8(9)	13.7(8)
1175.1	2.1(6)	—	1.4(2)	2.8(5)	2.4(2)	2.03(14)
1238.3	66.8(40)	71.2(26)	66.3(60)	70.5(70)	69.5(35)	72.1(50)
1360.2	4.0(8)	3.8(3)	3.8(4)	4.5(7)	4.5(3)	4.8(3)
1771.3	16.2(14)	15.6(13)	13.5(14)	12.5(13)	16.1(8)	16.9(10)
2015.2	4.1(12)	3.8(7)	3.5(4)	3.7(6)	2.7(2)	2.93(30)
2034.8	9.2(17)	7.8(10)	6.5(8)	8.3(15)	7.4(6)	7.37(50)
2598.4	17.4(15)	16.0(27)	17.4(17)	20.0(20)	17.3(9)	15.0(13)

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

Eγ (keV)	[8]	[9]	[10]	[11]	[12]	[13]
846.8	100(15)	100	100	100	100	100
977.4	1.5(3)	1.01(30)	1.1(1)	—	1.35(5)	1.448(14)
1037.8	14.0(30)	12.1(8)	9.6(6)	13.08(35)	14.0(7)	14.24(14)
1175.1	1.6(3)	2.2(1)	1.9(2)	1.73(13)	2.25(5)	2.300(25)
1238.3	64(14)	70.2(25)	69.6(35)	68.3(14)	68.5(12)	67.64(68)
1360.2	4.0(8)	4.2(4)	4.6(3)	4.15(12)	4.37(13)	4.340(45)
1771.3	14.0(30)	16.7(10)	16.2(10)	14.95(40)	16.0(5)	15.78(16)
2015.2	2.6(6)	2.9(4)	3.9(3)	2.78(14)	3.13(10)	3.095(31)
2034.8	6.6(14)	7.7(5)	8.2(5)	7.56(21)	8.1(2)	7.95(8)
2598.4	14.0(30)	17.0(6)	18.7(11)	16.55(44)	17.2(4)	16.85(17)

Eγ (keV)	[14]	[15]	[16]	[17]	[17]	[17]
846.8	100	100	100	100(6)	100.0(56)	100.0(57)
977.4	—	1.42(14)	1.21(6)	—	—	—
1037.8	12.9(5)	14.4(9)	12.44(31)	13.45(206)	13.03(187)	12.72(169)
1175.1	2.26(23)	2.29(22)	2.11(5)	1.99(30)	2.18(36)	1.93(27)
1238.3	67.8(15)	69.6(35)	—	70.9(88)	68.2(81)	66.9(84)
1360.2	4.16(21)	3.96(40)	4.42(8)	4.08(57)	4.4(6)	5.3(8)
1771.3	16.5(8)	14.9(9)	—	15.36(197)	15.98(201)	14.55(186)
2015.2	2.99(20)	2.83(30)	2.60(12)	2.88(45)	2.28(30)	2.59(47)
2034.8	8.2(6)	7.7(6)	7.0(3)	6.25(96)	6.8(9)	6.85(89)
2598.4	18.0(9)	16.5(10)	—	15.65(224)	17.3(24)	14.44(193)
3009.6	—	—	1.55(12)	—	—	—
3201.9	—	—	—	—	—	—
3253.4	—	—	—	—	—	—
3273.0	—	—	1.71(9)	—	—	—
3451.1	—	—	0.94(2)	—	—	—

Eγ (keV)	[18]	[19]	[20]	[21]	[22]	[23]
846.8	100	100	100	100(1)	100	100
977.4	1.37(4)	—	1.386(15)	1.426(21)	1.38(4)	1.41(2)
1037.8	—	13.7(6)	13.922(116)	14.04(20)	13.5(2)	14.11(19)
1175.1	2.25(11)	2.3(1)	2.180(24)	2.28(3)	2.11(10)	2.30(32)
1238.3	—	66.2(10)	66.366(742)	66.4(10)	65.1(4)	68.47(87)
1360.2	4.35(12)	4.4(1)	4.189(52)	4.24(6)	4.24(15)	4.32(6)
1771.3	—	15.9(3)	15.369(241)	15.65(22)	15.26(15)	15.5(4)
2015.2	—	3.1(1)	3.025(72)	3.09(6)	2.97(3)	3.182(66)
2034.8	—	7.8(1)	7.694(146)	7.95(14)	7.64(6)	8.14(17)
2598.4	—	17.3(4)	16.64(22)	17.34(31)	17.19(15)	17.40(38)
3009.6	—	1.0(2)	—	1.06(3)	1.05(3)	0.84(4)
3201.9	—	3.2(1)	—	3.18(10)	3.24(3)	3.03(7)
3253.4	—	8.2(4)	—	7.79(25)	7.97(11)	7.60(15)

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

Eγ (keV)	[18]	[19]	[20]	[21]	[22]	[23]
3273.0	—	1.9(1)	—	1.85(6)	1.84(3)	1.815(36)
3451.1	—	1.00(4)	—	0.93(3)	0.95(2)	0.90(2)

Eγ (keV)	[24]	[25]	[26]	[27]	[28]	[29]
846.8	100	100.0(3)	100	100	100	100
977.4	1.38(3)	1.435(16)	—	1.440(15)	1.450(15)	—
1037.8	14.06(28)	14.16(7)	13.85(35)	14.0(1)	14.18(13)	14.11(22)
1175.1	2.22(5)	2.241(14)	—	2.28(2)	2.289(21)	2.25(4)
1238.3	67.59(131)	66.06(29)	65.8(16)	67.6(4)	66.96(60)	66.6(10)
1360.2	4.29(8)	4.265(21)	4.27(15)	4.33(4)	4.29(4)	4.23(7)
1771.3	15.61(30)	15.49(7)	15.11(38)	15.70(15)	15.48(15)	15.42(25)
2015.2	2.95(6)	3.026(17)	2.97(11)	3.08(3)	3.04(5)	3.03(5)
2034.8	7.74(2)	7.766(36)	7.60(19)	7.89(7)	7.90(13)	7.84(12)
2598.4	16.41(33)	16.96(8)	—	17.29(15)	17.26(28)	17.1(3)
3009.6	—	—	—	1.05(1)	—	—
3201.9	—	—	—	3.24(3)	—	3.16(6)
3253.4	—	—	—	7.937(65)	—	7.81(16)
3273.0	—	—	—	1.89(2)	—	1.84(4)
3451.1	—	—	—	0.954(10)	—	0.93(3)

Eγ (keV)	[30]	Reduced χ^2	Evaluated	Absolute P_γ
846.8	100.0(2)	—	100	0.999399(23)
977.4	1.424(7)	2.7	1.423(7)	0.01422(7)
1037.8	14.07(5)	4.5	14.04(5)	0.1403(5)
1175.1	2.252(10)	2.8	2.250(9)	0.02249(9)
1238.3	66.20(17)	1.8	66.45(16)	0.6641(16)
1360.2	4.22(15)	0.9	4.283(13)	0.04280(13)
1771.3	15.24(9)	1.3	15.46(4)	0.1545(4)
2015.2	2.976(15)	2.5	3.019(14)	0.03017(14)
2034.8	7.69(3)	1.7	7.746(13)	0.07741(13)
2598.4	16.82(8)	1.3	16.97(4)	0.1696(4)
3009.6	1.033(11)	7.5	1.039(19)	0.01038(19)
3201.9	3.196(18)	1.6	3.205(13)	0.03203(13)
3253.4	7.85(4)	1.1	7.87(3)	0.0787(3)
3273.0	1.854(13)	1.1	1.856(9)	0.01855(9)
3451.1	0.940(10)	1.2	0.943(6)	0.00942(6)

Comments:

When authors indicated an uncertainty in the relative intensity of the 846.7 keV reference line, that uncertainty was combined in quadrature with the statistical uncertainty for each of the other transitions. That combined uncertainty is quoted in the above table.

Analysis of these data is complicated by two factors:

(1) Discrepant data sets — of approximately 770 data points, successive runs of LWEIGHT identified a total of 87 statistical outliers based on the Chauvenet criterion, which represents an unusually large fraction; most outliers, though by no means all, arise from the earlier measurements.
(2) Some authors use Ge detector efficiency calibration curves that are inadequate at the highest energies — identified by McCallum and Coote [31], and discussed further by Baglin et al. [32].

One prescription for dealing with discrepant data is the limitation of the relative statistical weight method (LRSW) proposed by Zijp [33] and incorporated in LWEIGHT. This program identifies a set of data as 'discrepant' whenever the reduced chi-squared value exceeds the critical reduced chi-squared value for the relevant number of data points. For those cases, the uncertainty is increased for any datum whose statistical weight exceeds 50% until this no longer occurs when the weighted mean is recalculated. If the weighted mean overlaps the unweighted mean, the weighted mean will be adopted. The adopted uncertainty 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, which does not appear to be a particularly useful number since this parameter could easily be skewed by the least reliable data. The LRSW method has been applied to the above data in cases where the reduced χ^2 value is less than 2, to produce the recommended data in the 'evaluated' column.

The normalized residuals [34] and Rajeval [35] techniques have been designed specifically to deal with discrepant data. Both are iterative procedures that increase the uncertainties of any discrepant data, but they use different prescriptions for identifying and adjusting the discrepant data. Where the reduced χ^2 value is greater than 2 these techniques have been applied to obtain the recommended values in the 'evaluated' column.

The second problem has been approached by considering data from only the eight experiments Refs [16, 19, 21–23, 27, 29, 30] in which the detector efficiency has been measured (not extrapolated) up to at least the highest ^{56}Co transition energy (3611 keV). Details of the efficiency calibrations for many of the other measurements are sketchy at best, and some rely partially or totally on Monte Carlo calculations. As a consequence of this restriction on the evaluated dataset, this measure should only be resorted to at energies where significant problems are anticipated. Thus only data from the eight selected references have been considered for $E_\gamma > 3000$ keV. Other measured data in this high energy region have been omitted from the above table. With the exception of the 3009.6 keV γ ray, the adopted values in this energy range derived from the LRSW method are straightforward weighted means. While the 3009.6 keV data are discrepant, the LRSW value has been adopted and is consistent with the results of the normalized residuals and Rajeval methods.

Absolute gamma ray emission probabilities

The decay scheme has been normalized assuming zero $\varepsilon + \beta^+$ feeding from the 4^+ ^{56}Co parent to the 0^+ ^{56}Fe ground state and therefore $\Sigma[P(\gamma+ce)]$ per decay to ground state = 1.0. Only the 846.8, 2657 and 3370 keV gamma transitions feed the ground state, and the NF is given by:

$$NF = 1.0 / [I_\gamma(846.8\text{ keV})(1 + \alpha(846.8\text{ keV})) + I_\gamma(2657\text{ keV}) + I_\gamma(3370\text{ keV})]$$

I_γ(2657 keV) and I_γ(3370 keV) have been evaluated to be 0.0195(20) and 0.0103(8), respectively, but are not included in the recommended table of γ rays due to their low intensities.

Assuming that the 846.8 keV transition is E2, and $\alpha = 3.03(9) \times 10^{-4}$ [36], $\alpha = \alpha_K + 1.33\alpha_L$ and 3% uncertainty, then

$$NF = 1.0 / [100.0303(9) + 0.0195(20) + 0.0103(8)] = 1.0 / [100.0601(23)] = 0.00999399(23)$$

This NF has been used to determine the absolute γ ray emission probabilities listed above. With this normalization the total (γ + e) emission probability of the 846.8 keV transition is 0.999702(23) per decay.

X rays: Energies and emission probabilities

X ray energies are taken from Ref. [37]. Emission probabilities are the evaluators' values calculated using the EMISSION program, Version 3.04 [38], with atomic data from Ref. [39], and the recommended γ ray emission probabilities shown above.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{57}Co

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by V.P. Chechev and N.K. Kuzmenko (V.G. Khlopin Radium Institute, Russian Federation), October 2001.

Recommended data

Half-life

$T_{1/2}$ = 271.80 (5) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
14.41295(31)	0.0915(17)
122.06065(12)	0.8551(6)
136.47356(29)	0.1071(15)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Fe	L	0.61–0.79	0.0155(13)
Fe	$K\alpha_2$	6.39084	0.168(3)
Fe	$K\alpha_1$	6.40384	0.332(5)
Fe	$K\beta_1'$	7.058–7.108	0.071(2)

Input data

HALF-LIFE

Half-life (d)	Reference
271.68(9)	[H1]
272.11(26)	[H2]
271.84(4)	[H3]
271.90(9)	[H4]
271.77(5)	[H5]
269.8(4)[a]	[H6]
271.23(21)	[H7]
271.80(5)	

[a] Rejected as an outlier.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]	Evaluated
14.413	—	—	11.4(5)	—	—	—	10.7(2)[a]
122.061	100	100	100	100	100	100	100
136.474	12.5(8)	12.0(1)	13.0(4)	12.9(7)	12.36(9)	12.45(30)	12.53(18)

[a] Calculated from the correlation $P_\gamma = P_{\gamma+ce}/(1 + \alpha_T)$ where α_T = 8.58(18) and $P_{\gamma+ce}$ = 87.57(16) come from the intensity balance of the 14.4 keV nuclear level.

Comments:

The evaluators have assumed no electron capture feeding to the ^{57}Fe ground and first excited states, and used the total γ ray transition probabilities (γ + ce) to these two states (except that of the 14.4 keV transition) to normalize the intensities in the decay scheme (using the evaluated relative emission probabilities from the above table and theoretical internal conversion coefficients) — this procedure produced an NF of 0.008551(6).

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{58}Co

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by M.-M. Bé (Commissariat à l'Énergie Atomique, France), October 1998.

Recommended data

Half-life

$T_{1/2}$ = 70.86(6) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
511	0.300(4)
810.759(2)	0.9945(1)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Fe	Kα	6.40	0.235(3)
Fe	Kβ	7.06	0.0320(10)

Note: Emission intensities of K X rays were calculated from the data set described in Ref. [7].

Input data

HALF-LIFE

Half-life (d)	Reference
70.77(11)	[H1]
70.916(15)[a]	[H2]
70.810(33)	[H3]
70.78(5)	[H4]
71.83(612)[b]	[H5]
70.62(67)	[H6]
71.1(2)	[H7]
71.64(75)[b]	[H8]
70.86(6)	

[a] Uncertainty increased to (27) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

REFERENCES — HALF-LIFE

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Gamma rays: Measured and evaluated relative emission probabilities

Comments:

(a) No new measurement since Ref. [1];
(b) Energy of the 810 keV γ ray is from Ref. [2];
(c) Absolute emission probabilities were calculated from $\Sigma P_{\gamma+ce}$ = 1.0 to ground state level to give an NF of 0.009945(1):

— Experimental total internal conversion coefficients are 3.4(1) × 10^{-4} and 2.6(4) × 10^{-4} from Bambynek and Legrand [3] for the 810 and 863 keV transitions, respectively; and 0.83 × 10^{-4} from the theoretical tables of Hager and Seltzer [4] for the 1674 keV transition;

— Theoretical calculations from the tables of Band et al. (see Gorozhankin et al. [5]) give total internal conversion coefficients of 3.3 × 10^{-4} and 2.7 × 10^{-4} for 810(pure E2) and 863(85% E2) keV transitions, respectively (very close to experimental data);

(d) Detailed tables and comments can be found in Refs [6, 7] and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{60}Co

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA), January 1999.

Recommended data

Half-life

$T_{1/2}$ = 1925.23(27) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
1173.228(3)[a]	0.9985(3)[b]
1332.492(4)[a]	0.999826(6)[c]

[a] From Ref. [1].

[b] Emission probability is calculated from:
$\{P_\beta(2505\text{ keV}) - P_\gamma(347\text{ keV}) \times [1.0 + \alpha(347\text{ keV})] - P_\gamma(2505\text{ keV}) \times [1.0 + \alpha(2505\text{ keV})]\}/ [1.00 + \alpha(1173\text{ keV}) + \alpha_\pi(1173\text{ keV})]$
= [0.9988(3) – 0.000075(4)]/[1.000174(4)].
P_β(2505 keV) is determined from P_β(1173 keV) = 0.0012 (3) from measurements of Refs [2–5]; P_γ(347 keV) and P_γ(2505 keV) are from relative emission probability measurements of Refs [6–8] and [9, 10], respectively; and the internal conversion and internal pair coefficients are from Refs [11] and [12], respectively.

[c] Emission probability is calculated from:
$\{1.00 - P_\gamma(2158\text{ keV}) \times [1.0 + \alpha(2158\text{ keV})] - P_\gamma(2505\text{ keV}) \times [1.0 + \alpha(2505\text{ keV})]\}/ [1.00 + \alpha(1332\text{ keV}) + \alpha_\pi(1332\text{ keV})]$
= [1.00 – 0.000012(2)]/[1.000162 (6)].
P_γ(2158 keV) is from measurements of Refs [7, 13, 14].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Ni	Kα	7.46–7.48	0.000098(3)
Ni	Kβ	8.26–8.33	0.0000136(5)

Input data

HALF-LIFE

Half-life (d)	Reference
1925.12(46)	[H1]
1925.5(4)	[H2]
1925.02(47)	[H3]
1925.2(4)	[H4]
1929.6(10)[a]	[H5]
1914(77)[a]	[H6]
1924.9(24)	[H7]
1925.23(27)	

[a] Rejected as an outlier.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{64}Cu

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA), January 2002.

Recommended data

Half-life

$T_{1/2}$ = 0.52929(18) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
511	0.3572(28) [a]
1345.77(16)[b]	0.00475(10) [c]

[a] Annihilation radiation emission probability is taken to be twice (× 2.0) the positron emission probability of 0.1786(14) [1, 2]; however, the emission probability for 511 keV photons will be somewhat lower due to annihilation of some of the positrons in flight.
[b] From Ref. [3].
[c] From Refs [1, 2].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Ni	Kα	7.46–7.48	0.1415(17)
Ni	Kβ	8.26–8.33	0.0195(4)

Input data

HALF-LIFE

Half-life (d)	Reference
0.52921(13)[a]	[H1]
0.52933(25)	[H2]
0.52913(34)	[H3]
0.525(40)	[H4]
0.5342(17)	[H5]
0.5298(29)	[H6]
0.5271(71)	[H7]
0.5333(17)	[H8]
0.5292(5)	[H9]
0.52929(18)	

[a] Uncertainty increased to (19) to ensure a weighting factor not greater than 0.50.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{65}Zn

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA), January 1999.

Recommended data

Half-life

$T_{1/2}$ = 243.86(20) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
511	0.0284(4)[a]
1115.539(2)[b]	0.5060(22)[c]

[a] Annihilation radiation emission probability is taken to be twice (× 2.0) the positron emission probability of 0.0142(2) — this value was calculated from the emission probability of the 1115 keV γ ray, total internal conversion coefficient of 0.000185(7) [1], and the theoretical electron capture to positron ratio of 34.03 for the ground state transition (from the LOGFT code). The emission probability for 511 keV photons will be somewhat lower due to annihilation of some of the positrons in flight.

[b] From Ref. [2].

[c] From measurements given below.

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Cu	Kα	8.03–8.05	0.347(3)
Cu	Kβ	8.90–8.98	0.0482(7)

Input data

HALF-LIFE

Half-life (d)	Reference
243.66(9)	[H1]
243.8(2)	[H2]
244.164(99)	[H3]
243.75(12)	[H4]
244.3(4)	[H5]
244.520(22)[a]	[H6]
243(4)[a]	[H7]
243.86(20)	

[a] Rejected as an outlier.

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GAMMA RAY: MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITY

E_γ (keV)	[3]	[4]	[5]	[6]	[7]	[8]	Evaluated
1115	0.507(5)	0.513(15)	0.524(10)	0.5075(10)[a]	0.493(8)	0.502(4)	0.5060(22)

[a] Uncertainty was increased to (27) to reduce relative weighting factor from 0.88 to 0.50.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{66}Ga

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Browne (Lawrence Berkeley National Laboratory, USA), July 2003.

Recommended data

Half-life

$T_{1/2}$ = 0.3889(34) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay[a]
833.5324(21)[b]	0.059(5)
1039.220(3)[b]	0.37(3)
1333.112(5)[b]	0.0117(9)
1418.754(5)[b]	0.0061(5)
1508.158(7)[b]	0.0055(4)
1898.823(8)[b]	0.0039(3)
1918.329(5)[b]	0.0199(16)
2189.616(6)[b]	0.053(4)
2422.525(7)[b]	0.0188(15)
2751.835(5)[b]	0.227(18)
3228.800(6)[b]	0.0151(12)
3380.850(6)[b]	0.0146(12)
3422.040(8)[b]	0.0086(7)
3791.004(8)[b]	0.0109(9)
4085.853(9)[b]	0.0127(10)
4295.187(10)[c]	0.038(3)
4461.202(9)[b]	0.0084(7)
4806.007(9)[b]	0.0186(15)

[a] Values recommended in Ref. [1], although the derived uncertainties may differ.
[b] From Ref. [2].
[c] From Ref. [3], but adjusted by a least squares procedure to align with data of Ref. [2].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Zn	$K\alpha_2$	8.61587(5)	0.058(3)
Zn	$K\alpha_1$	8.63896(5)	0.113(6)
Zn	$K\beta_1'$	9.57–9.65	0.0242(12)

Input data

HALF-LIFE

Half-life (d)	Reference
0.3888(33)[a]	[H1]
0.3917(83)	[H2]
0.3833(83)	[H3]
0.3917(83)	[H4]
0.3889(34)	

[a] Uncertainty increased to (48) to ensure a weighting factor not greater than 0.50.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[4][a]	[5][a]	[6]	[1]	[1]	Evaluated
833.53	16.2(7)	15.92(17)	16.02(24)	15.94(14)	15.92(6)	15.93(6)[b]
1039.22	≡100	≡100	100.0(16)	100.0(9)	100.0(3)	100.0(3)[b]
1333.11	3.21(5)	3.18(4)	3.17(5)	3.20(3)	3.171(13)	3.175(13)[b]
1418.75	1.61(3)	1.659(27)	—	1.640(23)	1.659(8)	1.657(8)[c]
1508.16	1.44(9)	1.478(24)	—	1.503(23)	1.496(7)	1.497(7)[c]
1898.82	1.11(3)	1.05(4)	—	1.062(23)	1.050(8)	1.051(8)[c]
1918.33	5.45(2)	5.427(80)	5.33(8)	5.44(6)	5.360(23)	5.368(23)[b]
2189.62	14.5(3)	14.56(18)	14.54(21)	14.50(13)	14.39(6)	14.42(6)[b]
2422.53	4.93(10)	5.023(5)	5.12(8)	5.15(6)	5.072(24)	5.085(24)[b]
2751.84	60.3(8)	60.6(6)	61.2(8)	61.5(6)	61.34(26)	61.35(26)[b]
3228.80	3.96(6)	4.08(4)	4.06(8)	4.07(4)	4.087(22)	4.082(22)[b]
3380.85	3.85(4)	3.95(4)	3.96(8)	3.99(4)	3.950(23)	3.960(23)[b]
3422.04	2.21(9)	2.29(4)	—	2.29(3)	2.321(16)	2.314(16)[c]
3791.00	2.89(11)	2.940(35)	2.96(5)	2.96(4)	2.929(24)	2.941(24)[b]
4085.85	3.33(7)	3.52(5)	3.38(8)	3.42(4)	3.455(20)	3.445(20)[b]
4295.19	10.88(24)	10.84(13)	10.24(26)	10.54(15)	10.25(7)	10.30(8)[b, d]
4461.20	2.23(5)	2.277(27)	—	2.20(4)	2.275(23)	2.26(3)[c]
4806.01	5.10(6)	4.92(4)	4.93(11)	5.00(7)	5.04(3)	5.03(3)[b]

[a] Data corrected for a systematic inaccuracy in the detector efficiency curve above 1050 keV.
[b] Weighted average (LWM) of values from Refs [1, 6].
[c] Weighted average (LWM) of values from Ref. [1].
[d] Corrected for single escape contribution from 4806 keV emission.

Comments:

- The decay scheme proposed in Ref. [7] was adopted for this evaluation; full details are available on: http://www.nucleide.org/DDEP_WG/DDEPdata.htm
- Relative gamma ray emission probabilities are weighted averages of the results from Refs [1, 6]. Some of the resulting uncertainties differ from those quoted in Ref. [1] because they were originally lower than the smallest uncertainty of the individual experimental values and were adjusted upwards accordingly.
- Relative gamma ray emission probability data are also listed from other sources [4, 5]; although not used in the LWM calculations of the main gamma ray emissions, these data have been corrected for a systematic error in the detector efficiency curve above 1050 keV. The correction factor (CF) given in Ref. [1] has been used:

$$CF = 1.116 - 0.155\, E_\gamma(\text{MeV}) + 0.0397\, E_\gamma^2(\text{MeV})$$

- NF was determined as follows:

P_{ce}(1039.2 keV)/$P_{\beta+}$(gs) = 2.08 (10) × 10^{-4}, Ref. [8]
$P_{\beta+}$(gs)/$\Sigma P_{\beta i+}$ = 0.8697, Ref. [8]
P_{ce}(1039.2 keV, E2)/P_γ(1039 keV)
= 2.69(8) × 10^{-4}, Ref. [9],

hence,

P_γ(1039.2 keV)/$\Sigma P_{\beta i+}$
= 2.08(10) × 10^{-4} × 0.8697/2.69(8) × 10^{-4}
= 0.67(4).
Also $\Sigma P_{\beta i+}/\Sigma P_{\varepsilon i}$ = 1.265 from the full decay scheme and theoretical $P_{\beta i+}/\varepsilon_i$.
Since $\Sigma P_{\beta i+} + \Sigma P_{\varepsilon i} = 1.00$,
$\Sigma P_{\beta i+}$ = 0.558(24)
and P_γ(1039.2 keV) = 0.67(4) × 0.558(24)
= 0.37(3) per decay.

Therefore, NF = 0.0037(3) was adopted to convert relative γ ray emission probabilities to absolute emission probabilities.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{67}Ga

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by V.P. Chechev and N.K. Kuzmenko (V.G. Khlopin Radium Institute, Russian Federation), April 2000.

Recommended data

Half-life

$T_{1/2}$ = 3.2616(4) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
91.265(5)	0.0307(11)
93.310(5)	0.378(9)
184.576(10)	0.209(7)
208.950(10)	0.0237(8)
300.217(10)	0.168(6)
393.527(10)	0.0466(16)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Zn	L	0.884–1.107	0.0182(12)
Zn	$K\alpha_2$	8.61587(5)	0.170(6)
Zn	$K\alpha_1$	8.63896(5)	0.330(11)
Zn	$K\beta_1'$	9.57–9.65	0.0709(20)

Input data

HALF-LIFE

Half-life (d)	Reference
3.2623(15)	[H1]
3.2634(16)	[H2]
3.26154(54)	[H3]
3.2607(8)	[H4]
3.2638(14)	[H5]
3.261(1)	[H6]
3.2608(15)	[H7]
3.2616(4)	

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1, 2]	[3]	[4]	[5]	[6]	[1]
91.26	7.4(26)[a]	—	21.0(19)[a]	15.1(6)	14.49(10)
93.31	314(22)[a]	—	161(11)	—	181.2(11)
184.58	100	100	100	100	100
208.95	10.8(13)	10.9(5)	11.5(9)	—	11.38(8)
300.22	70(5)	75.6(50)	81(6)	—	81.2(5)
393.53	—	20.4(12)	22.6(19)	—	22.72(15)

E_γ (keV) [1, 2]	[7]	[8]	[9]	Evaluated
91.26	15.0(5)	13.8(11)	14.9(7)	14.7(2)
93.31	185(6)	169(10)	184(5)	181(3)
184.58	100	100	100	100
208.95	11.35(15)	11.1(7)	11.3(4)	11.34(9)
300.22	79.9(11)	76.5(37)	79.2(11)	80.2(6)
393.53	22.0(3)	20.7(10)	22.1(3)	22.3(2)

[a] Rejected value.

Comments:

Absolute γ ray emission probabilities have been computed from the evaluated relative emission probabilities and the absolute emission probability of the 93.31 keV γ ray. The latter has been obtained from the absolute emission probability of the conversion electrons for the 93.31 keV transition [0.325(4)] determined on the basis of precise measurements [10, 11] and the total internal conversion coefficient $\alpha_T = 0.859(17)$ from Ref. [12].

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{68}Ga

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), October 1996.

Recommended data

Half-life

$T_{1/2}$ = 0.04703(7) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
511	1.7828(22)[b]
1077.34(5)[a]	0.0322(3)[c]

[a] From Ref. [1].
[b] Annihilation radiation emission probability is taken from Schönfeld et al. [2] and is assumed to be twice (× 2.0) the positron emission probability.
[c] Decay scheme proposed by Vo et al. [3] has been adopted in conjunction with the studies of Lange et al. [4], while an absolute emission probability of 0.0322(3) for the 1077 keV gamma ray was taken from Ref. [2].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Zn	$K\alpha_2$	8.61587(5)	0.01389(7)
Zn	$K\alpha_1$	8.63896(5)	0.02701(24)

Input data

HALF-LIFE

Half-life (d)	Reference
0.0469646(167)[a]	[H1]
0.04757(35)	[H2]
0.047083(46)	[H3]
0.04703(7)	

[a] Uncertainty increased to (460) to ensure a weighting factor not greater than 0.50.

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[4] LANGE, J.,et al., Phys. Rev. **C7** (1973) 177.

Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{75}Se

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Browne (Lawrence Berkeley National Laboratory, USA) and E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), August 1997.

Recommended data

Half-life

$T_{1/2}$ = 119.778(29) d

SELECTED GAMMA RAYS

E_γ (keV) [1]	P_γ per decay
66.0518(8)	0.01112(12)
96.7340(9)	0.0342(3)
121.1155(11)	0.172(3)
136.0001(6)	0.582(7)
198.6060(12)	0.0148(4)
264.6576(9)	0.589(3)
279.5422(10)	0.2499(13)
303.9236(10)	0.01316(8)
400.6572(8)	0.1147(9)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
As	L	1.28	0.0206(7)
As	$K\alpha_2$	10.5080	0.1659(23)
As	$K\alpha_1$	10.5437	0.322(4)
As	$K\beta$	11.72–11.86	0.0764(12)

Emission probabilities per decay of K X rays were calculated from the data set described in Ref. [14].

Input data

HALF-LIFE

Half-life (d)	Reference
119.809(66)	[H1]
119.76(5)	[H2]
119.779(4)[a]	[H3]
118.45(84)[b]	[H4]
119.778(29)	

[a] Uncertainty increased to (40) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2(1)]	[2(2)]	[2(3)]	[2(4)]	[2(5)]
66.1	0.0185(3)	0.0182(6)	0.0176(8)	0.0195(6)	—
96.7	0.0593(8)	0.0568(15)	0.0613(18)	0.0647(18)	—
121.1	0.2923(15)	0.291(6)	0.279(6)	0.292(4)	0.293(5)
136.0	0.999(3)	0.963(20)	0.946(21)	0.999(9)	0.999(18)
198.6	0.02518(13)	0.0252(7)	0.0225(8)	0.02568(21)	0.0248(5)
264.7	1.000(4)	1.000(21)	1.000(22)	1.000(11)	1.000(15)
279.5	0.4253(16)	0.439(9)	0.422(9)	0.421(3)	0.426(6)
303.9	0.02248(9)	0.0225(5)	0.0221(6)	0.02091(14)	0.0224(4)
400.7	0.1927(11)	0.197(4)	0.191(4)	0.1941(12)	0.195(3)

E_γ (keV) [1]	[2(6)]	[2(7)]	[2(8)]	[2(9)]	[2(10)]
66.1	0.0178(6)	0.0200(17)	0.0186(2)	0.0196(4)	0.0191(2)
96.7	0.0541(13)	0.0513(30)	0.0579(3)	0.0563(5)	0.0591(5)
121.1	0.285(5)	0.300(10)	0.2865(11)	0.2896(14)	0.2916(23)

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

E_γ (keV) [1]	[2(6)]	[2(7)]	[2(8)]	[2(9)]	[2(10)]
136.0	0.959(21)	0.995(31)	0.982(4)	0.999(5)	0.997(8)
198.6	0.0238(4)	0.0253(7)	0.02509(16)	0.02581(12)	0.02534(23)
264.7	1.000(17)	1.000(26)	1.000(5)	1.000(4)	1.000(8)
279.5	0.424(5)	0.426(11)	0.4248(23)	0.4236(14)	0.425(3)
303.9	0.0223(4)	0.0224(6)	0.02234(15)	0.02224(8)	0.02242(18)
400.7	0.1917(21)	0.195(5)	0.1960(10)	0.1979(6)	0.1949(16)

E_γ (keV) [1]	[2(11)]	[2(12)]	[2(13)]	[3]	[4]
66.1	0.0194(3)	0.0188(2)	0.0195(2)	0.0172(4)	0.0097(6)[a]
96.7	0.058(6)	0.0583(4)	0.0591(5)	0.0512(10)	0.047(2)[a]
121.1	0.2943(22)	0.2931(20)	0.2924(20)	0.2770(50)	0.254(12)[a]
136.0	1.004(7)	1.012(4)	0.994(10)	0.950(18)	0.903(28)[a]
198.6	0.02514(20)	0.02586(20)	0.0250(3)	0.0238(7)	0.025(1)[a]
264.7	1.000(8)	1.000(3)	1.000(7)	1.00	1.00
279.5	0.424(4)	0.4225(8)	0.4269(21)	0.420(8)	0.425(15)
303.9	0.02220(22)	0.02219(16)	0.02239(16)	0.0219(7)	0.0220(8)
400.7	0.1908(17)	0.1936(5)	0.1951(10)	0.204(5)	0.190(6)

E_γ (keV) [1]	[5]	[6]	[7]	[8-1] [b]	[8-2][b]
66.1	0.0146(20)	0.0186(9)	0.0193(4)	—	—
96.7	0.0522(20)	0.059(3)	0.0589(13)	0.0578(17)	—
121.1	0.271(40)	0.298(9)	0.293(3)	0.2924(29)	0.2912(31)
136.0	0.9546(600)	1.02(3)	0.998(8)	0.992(9)	0.991(13)
198.6	0.0248(40)	0.0253(8)	0.0249(5)	0.0251(4)	0.0257(4)
264.7	1.00	1.00(3)	1.000(8)	1.000(5)	1.000(6)
279.5	0.426(8)	0.424(13)	0.426(4)	0.4243(20)	0.4245(24)
303.9	0.0226(40)	0.0221(3)	0.0227(2)	0.02234(17)	0.02226(19)
400.7	0.188(6)	0.191(3)	0.1956(16)	0.1942(13)	0.1938(12)

E_γ (keV) [1]	[9]	[10]	[11]	[12]	Evaluated
66.1	0.0196(3)	0.0187(1)	0.0191(2)	—	0.01888(18)
96.7	0.0591(6)	0.0572(21)	0.0591(5)	0.0578(3)	0.05807(33)
121.1	0.2910(31)	0.298(2)	0.2916(23)	0.2976(11)	0.2920(56)
136.0	0.995(10)	1.000(3)	0.997(8)	1.002(3)	0.989(11)
198.6	0.0250(3)	0.0254(2)	0.02534(20)	0.0256(2)	0.0251(7)
264.7	1.00(1)	1.000(5)	1.000(8)	1.000(3)	1.000(3)
279.5	0.424(5)	0.422(4)	0.4247(34)	0.4278(12)	0.4243(8)
303.9	0.0225(3)	0.0223(2)	0.02242(18)	0.02238(14)	0.02235(8)
400.7	0.202(2)	0.195(3)	0.1949(16)	0.1931(7)	0.1947(11)

[a] Discrepant data omitted from evaluation.
[b] Independent measurements reported in Ref. [8].

Comments:

An arbitrary numbering system was assigned to the participants of the ICRM intercomparison, Ref. [2], as [2(x)], etc.

Absolute emission probabilities were determined using absolute measurement data — corrected values for the absolute emission probability of the 264 keV γ ray are 0.5944(83) [7], 0.5796(85) [8-1], 0.5816(85) [8-2], 0.5955(90) [13], 0.5903(32) [12], giving a weighted average (LWM) of 0.589(3) [recommended value].

For more details see Refs [14, 15].

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Detailed tables and comments can be found in Refs [14, 15], and on: http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{85}Kr

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by M.-M. Bé and V. Chisté (Commissariat à l'Énergie Atomique, France), November 2003.

Recommended data

Half-life

$T_{1/2}$ = 3927(8) d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
513.997(5)	0.00435(10)

SELECTED X RAY

Origin		E_X (keV)	P_X per decay
Te	Kα	13.356	0.0000158(28)

Emission probability per decay of K X ray was calculated from the data set described on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

Input data

HALF-LIFE

Half-life (d)	Reference
3916.8(25)	[H1]
3934.4(14)[a]	[H2]
3930(4)	[H3]
3927(8)	

[a] Uncertainty increased to (22) to ensure a weighting factor not greater than 0.50.

REFERENCES — HALF-LIFE

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GAMMA RAY: MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITY

E_γ (keV) [1]	[2]	[3]	[4]	Evaluated
513.997(5)	0.0046(4)	0.00431(17)	0.00435(13)	0.00435(10)

Comments:

Internal conversion coefficients are α_K = 0.00635(19), α_L = 0.00072(2) and α_{total} = 0.00721(21) as deduced from the tables of Rösel et al. [5] for an adopted M2 multipolarity.

The recommended γ ray emission probability is the weighted average; more details can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{85}Sr

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), June 1999.

Recommended data

Half-life

$T_{1/2}$ = 64.851(5) d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
514.0048(22)	0.985(4)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Rb	L	1.58–2.20	0.0255(7)
Rb	$K\alpha_2$	13.3359(2)	0.1716(17)
Rb	$K\alpha_1$	13.3955(1)	0.3304(29)
Rb	$K\beta_1'$	14.95–15.09	0.0804(10)
Rb	$K\beta_2'$	15.19–15.21	0.0093(4)

Emission probabilities per decay of K X rays were calculated from the data set described in Ref. [8].

Input data

HALF-LIFE

Half-life (d)	Reference
64.8530(81)	[H1]
64.85(14)	[H2]
64.845(9)	[H3]
64.856(7)	[H4]
64.84(3)	[H5]
65.0(50)	[H6]
65.0(49)	[H7]
64.93(22)	[H8]
64.68(8)	[H9]
66.6(6)[a]	[H10]
64.851(5)	

[a] Rejected as an outlier.

REFERENCES — HALF-LIFE

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2][a]	[3]	[4]	[5]	[6]	[7]	Evaluated [8]
514.0	100	100	100	100	100	100	100
868.98(5)	0.017	0.010	0.014	0.01154	0.0125	0.0125	0.0123(3)

[a] Rejected value.

Comments:

Evaluated emission probabilities are the weighted averages calculated according to the limitation of relative statistical weights method; no value has a relative weighting factor greater than 0.50.

The transition probability of 0.008(4) for the EC transition directly feeding the ground state of ^{85}Rb yields for $P_{\gamma+ce}$(514 keV) = 0.992(4). Furthermore, when this value is combined with the total conversion coefficient of the 514 keV transition, P_γ(514 keV) = 0.985(4).

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Detailed tables and comments can be found in Refs [8, 9].

^{88}Y

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), November 1998.

Recommended data

Half-life

$T_{1/2}$ = 106.625 (24) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
898.036(4)	0.9390(23)
1836.052(13)	0.9938(3)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Sr	L	1.6–2.2	0.0277(8)
Sr	$K\alpha_2$	14.0980(1)	0.1730(22)
Sr	$K\alpha_1$	14.1652(2)	0.332(4)
Sr	$K\beta_1'$	15.8359(4)	0.0821(12)
Sr	$K\beta_2'$	16.0847(6)	0.0107(4)

Input data

HALF-LIFE

Half-life (d)	Reference
106.65(13)	[H1]
106.626(44)	[H2]
106.66(6)	[H3]
106.612(14)[a]	[H4]
107.15(65)[b]	[H5]
107.1(14)[b]	[H6]
106.6(14)	[H7]
108.4(9)[b]	[H8]
106.625(24)	

[a] Uncertainty increased to (34) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

REFERENCES — HALF-LIFE

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2]	[3][a]	[4][b]	[5][a]	[6]	[7]	[8]	[9]	Evaluated [10]
898.0	94.0(7)	91	92.0(7)	92.1	93.8(11)	94.4(3)	94.9(4)	94.8(9)	94.44(22)
1836.1	100	100	100	100	100	100	100	100	100

[a] Rejected because uncertainties are not quantified.
[b] Classified as outlier.

Comments:

Evaluated emission probabilities are the weighted averages calculated according to the limitation of relative statistical weights method; no value has a relative weighting factor greater than 0.50.

Absolute emission probabilities were calculated from $\Sigma P_{\gamma+ce}$(1836 + 2734 + 3219 keV) = 1.0 to give an NF of 0.009938(3).

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[9] SCHÖTZIG, U., Nucl. Instrum. Methods Phys. Res. **A286** (1990) 523.
[10] BÉ, M.-M., et al., Table de Radionucléides, Comments on Evaluations, CEA Saclay, Gif-sur-Yvette (1999).
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Detailed tables and comments can be found in Refs [10, 11] and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{93m}Nb

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by V.P. Chechev and N.K. Kuzmenko (V.G. Khlopin Radium Institute, Russian Federation), June 1999.

Recommended data

Half-life

$T_{1/2} = 5.73(22) \times 10^3$ d

GAMMA RAY

E_γ (keV)	P_γ per decay
30.77(2)	$5.59(16) \times 10^{-6}$

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Nb	L	1.90–2.66	0.0289(13)
Nb	$K\alpha_2$	16.5213	0.0316(7)
Nb	$K\alpha_1$	16.6152	0.0604(12)
Nb	$K\beta_1'$	18.618	0.0156(5)
Nb	$K\beta_2'$	18.953	0.0023(1)

Input data

HALF-LIFE

Half-life (d)	Reference
5891(55)[a]	[H1]
5884(70)	[H2]
4164(330)	[H3]
4967(110)	[H4]
$5.73(22) \times 10^3$	

[a] Uncertainty increased to (59) to ensure a weighting factor not greater than 0.50.

REFERENCES — HALF-LIFE

[H1] VANINBROUKX, R., Int. J. Appl. Radiat. Isot. **34** (1983) 1211.
[H2] LLORET, R., Radiochem. Radioanal. Lett. **50** (1981) 113.
[H3] HEGEDUES, F., Rep. EUR 5667E (1976) 757.
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Gamma ray: Energy and absolute emission probability

The energy of γ ray has been taken from Ref. [1].

The absolute γ ray emission probability has been computed from the decay scheme using the total internal conversion coefficient $\alpha_T = 2.62(5) \times 10^4$ from Ref. [2] for M4 multipolarity (determined confidently from measured sub-shell conversion electron ratios).

XK rays: Total absolute emission probability

The total absolute XK ray emission probability computed from the internal conversion coefficients $\alpha_T = 1.79(5) \times 10^5$, $\alpha_K = 2.62(8) \times 10^4$ [2] and K-fluorescence yield $\omega_K = 0.751(4)$ [3] is 0.1099(40). This value coincides with the average [0.1099(22)] of three measurements of 0.107(3) [4], 0.1104(28) [5] and 0.1112(22) [6]. Other measurements give slightly higher values: 0.116(4) [7] and 0.115(3) [8].

Adopted total absolute XK ray emission probability is 0.1099(22) [9, 10].

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[5] GEHRKE, R.J., ROGERS, J.W., BAKER, J.D., Reactor Dosimetry (Proc. 5th ASTM–EURATOM Symp. Geesthacht, 1984), Dordrecht (1985) 319.
[6] COURSEY, B.M., et al., Nucl. Instrum. Methods Phys. Res. **A290** (1990) 537.
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[10] CHECHEV, V.P., KUZMENKO, N.K., Izmeritelnaya Tekhnika **2** (2000) 49 (in Russian).

Detailed tables and comments can be found in Refs [9, 10] and on
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{94}Nb

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by S.A. Woods and T.D. MacMahon (National Physical Laboratory, UK), March 2004.

Recommended data

Half-life

$T_{1/2} = 7.3\ (9) \times 10^6$ d

SELECTED GAMMA RAYS

E_γ (keV)[a]	P_γ per decay
702.639(4)	0.99815(6)
871.114(3)	0.99892(3)

[a] From Ref. [1].

Input data

HALF-LIFE

Half-life (d)	Reference
$7.41(59) \times 10^{6}$[a]	[H1]
$6.6(15) \times 10^6$	[H2]
$8.0(19) \times 10^6$	[H3]
$7.3(9) \times 10^6$	

[a] Uncertainty increased to (118) to ensure a weighting factor not greater than 0.50.

REFERENCES — HALF-LIFE

[H1] SCHUMANN, R.P., GORIS, P., J. Inorg. Nucl. Chem. **12** (1959) 1.
[H2] ROLLIER, M.A., SAELAND, E., MORPURGO, A., CAGLIERIS, A., Acta Chem. Scand. **9** (1955) 57.
[H3] DOUGLAS, D.L., McWHERTER, A.C., SCHUMANN, R.P., Phys. Rev. **92** (1953) 369.

Gamma rays: Emission probabilities

Absolute γ ray emission probabilities were determined from the assumption of 100% β branch to the 1573.7 keV 4^+ level in ^{94}Mo, followed by an E2 transition of 702.6 keV with $P_{\gamma+ce} = 1.0$ to the 871.1 keV 2^+ level, and a second E2 transition of 871.1 keV with $P_{\gamma+ce} = 1.0$ to the ^{94}Mo 0^+ ground state. These E2 assignments arise from the studies of Kuebbing and Casper [2]. Total internal conversion coefficients have been derived from the tables of Hager and Seltzer [3] as follows:

702.6 keV transition: $\alpha_{tot} = 1.85(6) \times 10^{-3}$
and therefore $P_\gamma = 0.99815(6)$,

871.1 keV transition: $\alpha_{tot} = 1.08(3) \times 10^{-3}$
and therefore $P_\gamma = 0.99892(3)$,

assuming 3% uncertainty on the internal conversion coefficients. A measurement of the relative intensities [4]

$I_\gamma(703\ \text{keV})/I_\gamma(871\ \text{keV}) = 0.98(2)$

is consistent with the above recommendations.

REFERENCES — RADIATIONS

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[2] KUEBBING, R.A., CASPER, K.J., Nucl. Phys. **A98** (1967) 75.
[3] HAGER, R.S., SELTZER, E.C., Nucl. Data **A4** (1968) 1.
[4] EAST, L.V., Nucl. Instrum. Methods **93** (1971) 193.

^{95}Nb

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA), January 1999.

Recommended data

Half-life

$T_{1/2}$ = 34.985 (12) d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
765.803(6)[a]	0.99808(7)[b]

[a] From Ref. [1] for equivalent decay of ^{95m}Tc.
[b] Emission probability is
$\{1.00 - I_\beta(0) - I_\beta(204\text{ keV}) - P_\gamma(561\text{ keV})[(1.0 + \alpha(561\text{ keV})]\}/[1.00 + \alpha(765\text{ keV})]$
$= [0.9988(3) - 0.000075(4)]/[1.000174(4)]$

$P_\beta(0)$ is 0.00030(5) from the measurement of Ref. [2], I_β(204 keV) is less than or equal to 0.00002 from log*ft* systematics [3], and the internal conversion coefficient is interpolated from the tables of Ref. [4].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Mo	L	2.01–2.83	0.000055(9)
Mo	$K\alpha_2$	17.374	0.000286(9)
Mo	$K\alpha_1$	17.479	0.000546(17)
Mo	$K\beta_1'$	19.59–19.77	0.000143(5)
Mo	$K\beta_2'$	19.96–20.00	0.0000220(11)

Input data

HALF-LIFE

Half-life (d)	Reference
34.997(6)[a]	[H1]
34.98(2)	[H2]
34.979(9)	[H3]
34.97(1)	[H4]
35.10(7)[b]	[H5]
35.15(3)[b]	[H6]
34.985(12)	

[a] Uncertainty increased to (7) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

REFERENCES — HALF-LIFE

[H1] MARTIN, R.H., BURNS, K.I.W., TAYLOR, J.G.V., Nucl. Instrum. Methods Phys. Res. **A390** (1997) 267.
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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{99}Mo–^{99m}Tc

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by M.-M. Bé, C. Morillon (Commissariat à l'Énergie Atomique, France) and V.P. Chechev, A.G. Egorov (V.G. Khlopin Radium Institute, Russian Federation), January 2001.

Recommended data

Half-life (^{99}Mo)

$T_{1/2}$ = 2.7478(7) d

SELECTED GAMMA RAYS

Parent	E_γ (keV)	P_γ per decay
^{99}Mo	40.58323(17)[a]	0.01022(27)
^{99m}Tc	140.511(1)[b]	0.896(17)
^{99}Mo	181.094(2)	0.0601(11)
^{99}Mo	366.421(15)[c]	0.01194(23)
^{99}Mo	739.500(17)[c]	0.1212(15)
^{99}Mo	777.921(20)[c]	0.0428(8)

[a] From Ref. [1].
[b] From Ref. [2].
[c] From Ref. [3].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Tc	L	2.424–2.537	0.00697(17)
Tc	$K\alpha_2$	18.2510	0.0319(9)
Tc	$K\alpha_1$	18.3672	0.0606(16)
Tc	$K\beta_1'$	20.60–20.79	0.0161(5)
Tc	$K\beta_2'$	21.00–21.04	0.00254(11)

Input data

HALF-LIFE

Half-life (d)	Reference
2.7489(6)	[H1]
2.746829(242)	[H2]
2.74771(13)*	[H3]
2.75083(42)	[H4]
2.7478(7)	

* Uncertainty increased to (20) to ensure a weighting factor not greater than 0.50.

REFERENCES — HALF-LIFE

[H1] SCHRADER, H., Appl. Radiat. Isot. **60** (2004) 317.

[H2] UNTERWEGER, M.P., HOPPES, D.D., SCHIMA, F.J., Nucl. Instrum. Methods Phys. Res. **A312** (1992) 349.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[4]	[5]	[6]	[7]	[8]	[9]
40.58	—	6.9(8)	4.6(18)*	5.9(15)	8.68(27)	—
140.51	649(25)	704(45)	730(49)	743(19)	747(12)	759(20)
181.09	48.7(23)	49.9(34)	49.6(42)	49.1(16)	50.1(7)	—
366.42	10.6(8)	10.7(6)	10.0(9)	9.8(3)	9.52(32)	—
739.50	100	100	100	100	100	100
777.92	35.1(24)	34.9(20)	35.8(30)	35.5(10)	35.8(9)	—

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

E_γ (keV)	[10]	[11]	[3]	[12]	Evaluated
40.58	7.7(6)	—	8.6(5)	8.49(25)	8.43(20)
140.51	689(49)	752(20)	755(26)	739(11)	739(11)
181.09	49.8(33)	48.7(13)	50.3(17)	49.4(8)	49.6(7)
366.42	9.8(8)	—	9.92(25)	9.82(15)	9.85(15)
739.50	100	100	100	100	100
777.92	34.8(19)	—	35.3(12)	35.1(5)	35.3(5)

* Rejected as an outlier.

Comments:

Energy of 181.094(2) keV has been computed from the adopted energies of other γ transitions using γ cascades of the decay scheme.

^{99}Mo and ^{99m}Tc are considered to be in equilibrium, and all absolute emission probabilities are given per decay of ^{99}Mo.

Absolute emission probability of the 739.50 keV γ ray has been obtained by averaging data of 0.1200(33) [3], 0.1214(22) [8], 0.119(3) [11] and 0.123(3) [13].

REFERENCES — RADIATIONS

[1] GARDULSKI, P.L., WIEDENBECK, M.L., Nucl. Instrum. Methods **105** (1972) 169.

[2] HELMER, R.G., VAN DER LEUN, C., Nucl. Instrum. Methods Phys. Res. **A450** (2000) 35.

[3] MEYER, R.A., Fizika, Zagreb **22** (1990) 153.

[4] VAN EIJK, C.W.E., et al., Nucl. Phys. **A121** (1968) 440.

[5] COOK, W.B., SCHELLENBERG, L., JOHNS, M.W., Nucl. Phys. **A139** (1969) 277.

[6] GEHRKE, R.J., McISAAC, L.D., HEATH, R.L., Rep. ANCR-1129 (1973) 23.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{99m}Tc

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by M.-M. Bé, C. Morillon (Commissariat à l'Énergie Atomique, France) and V.P. Chechev, A.G. Egorov (V.G. Khlopin Radium Institute, Russian Federation), January 2001.

Recommended data

Half-life

$T_{1/2}$ = 0.250281(22) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
140.511(1)	0.885(2)
142.683(1)	0.00023(2)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Tc	L	2.424–2.537	0.00482(12)
Tc	$K\alpha_2$	18.2510	0.0222(7)
Tc	$K\alpha_1$	18.3672	0.0421(12)
Tc	$K\beta_1'$	20.60–20.79	0.0112(4)
Tc	$K\beta_2'$	21.00–21.04	0.00177(8)

Input data

HALF-LIFE

Half-life (d)	Reference
0.25024(5)	[H1]
0.2502975(863)	[H2]
0.2502992(363)	[H3]
0.25029(4)	[H4]
0.25025(9)	[H5]
0.2508(4)[a]	[H6]
0.25025(12)	[H7]
0.25129(17)[a]	[H8]
0.25058(17)[a]	[H9]
0.250281(22)	

[a] Rejected as an outlier.

REFERENCES — HALF-LIFE

[H1] SCHRADER, H., Appl. Radiat. Isot. **60** (2004) 317.

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[H9] VUORINEN, A., Ann. Acad. Sci. Fenn. Ser. **311** (1969) 1.

Gamma rays: Energies and measured emission probabilities

The energy of 140.511(1) keV has been taken from Ref. [1], while an energy of 142.683(1) keV was calculated in terms of a gamma cascade that represents the sum of the adopted energies of the 2.17 keV [2]and 140.51 keV gamma transitions.

Absolute emission probability of the 140.51 keV γ ray was obtained by averaging the experimental data of 0.880(24) [3], 0.872(5) [4], 0.8875(14) [5], 0.8730(21) [6] and 0.8820(26) [7].

The absolute emission probability of the 142.68 keV γ ray was derived from the ratio of the emission probabilities:

$P_{\gamma+ce}$ (142.68 keV)/$P_{\gamma+ce}$(140.51 keV) = 0.0097(7) to be found in ^{99}Mo + ^{99m}Tc evaluation, which corresponds to
P_{γ}(142.68 keV)/P_{γ}(140.51 keV) = 0.00026(2), and an absolute γ ray emission probability of 0.00023(2).

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{103}Ru

Half-life evaluated by M.J. Woods, S.M. Collins and S.A. Woods (National Physical Laboratory, UK), January 2004.

Gamma ray and X ray emission probabilities evaluated by T.D. MacMahon (National Physical Laboratory, UK) and M.-M. Bé (Commissariat à l'Énergie Atomique, France), December 2005.

Recommended data

Half-life

$T_{1/2}$ = 39.247(13) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
39.760(10)[a]	0.00071(3)
53.275(10)[b]	0.00384(6)
294.98(2)[c]	0.00289(6)
443.80(2)[c]	0.00344(3)
497.08(2)[c]	0.9131(7)
557.04(2)[c]	0.00855(5)
610.33(2)[c]	0.0578(3)

[a] Weighted mean from Refs [3, 4].
[b] From Ref. [3].
[c] From Ref. [6].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Rh	L	2.38–3.36	0.0412(19)
Rh	$K\alpha_2$	20.074	0.0248(15)
Rh	$K\alpha_1$	20.216	0.047(3)
Rh	$K\beta_1'$	22.699–22.911	0.0128(8)
Rh	$K\beta_2'$	23.172–23.217	0.00212(15)

Input data

HALF-LIFE

Half-life (d)	Reference
39.272(16)	[H1]
39.214(13)	[H2]
39.260(20)	[H3]
39.254(8)[a]	[H4]
39.247(13)	

[a] Uncertainty increased to (10) to ensure a weighting factor not greater than 0.50.

REFERENCES — HALF-LIFE

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[1]	[2]	[3]	[4]	[5]	[6]
39.759	0.063(5)	0.073(6)	0.037(9)	—	—	0.079(2)
53.282	0.38(3)	0.39(3)	0.34(6)	—	0.6(2)	0.42(2)
294.98	0.24(2)	0.30(3)	0.30(3)	0.30(5)	0.4(2)	0.280(9)
443.80	0.40(3)	0.49(5)	0.34(3)	0.42(5)	0.8(3)	0.36(1)
497.08	100	100	100	100	100	100(3)
557.04	0.90(6)	0.88(9)	0.88(7)	0.94(4)	1.4(2)	0.93(3)
610.33	6.1(4)	6.2(6)	6.24(31)	6.43(13)	6.7(10)	6.3(2)

E_γ (keV)	[7]	[8]	[9][a]	Evaluated Relative P_γ	Absolute P_γ
39.759	0.098(9)	—	0.0776(29)	0.078(3)	0.00071(3)
53.282	0.487(11)	—	0.422(7)	0.420(6)	0.00384(6)
294.98	0.333(5)	—	0.322(9)	0.316(6)	0.00289(6)
443.80	0.379(4)	—	0.374(6)	0.376(3)	0.00344(3)
497.08	100.0(11)	100.0(3)	100	100	0.9131(7)
557.04	0.954(11)	0.933(7)	0.926(13)	0.936(5)	0.00855(5)
610.33	6.33(5)	6.35(4)	6.19(8)	6.32(3)	0.0578(3)

[a] Absolute γ ray emission probabilities from Ref. [9] converted to relative emission probabilities.

Comments:

53.282 keV gamma ray: data are discrepant with a reduced χ^2 of 5.9. Normalized residuals (NORM) and Rajeval evaluation techniques are designed to deal with such cases [10] — both techniques adjust the uncertainty of Ref. [7] datum, and agree on the result listed above.

294.98 keV gamma ray: the reduced χ^2 is 6.2, with discrepant data identified with Refs [1, 6, 7]. The NORM result is 0.313(6) and that of Rajeval is 0.320(6) — a mean of these two results has been adopted.

443.80, 557.04 and 610.33 keV γ rays: data are consistent in each case (reduced χ^2 of 1.9, 1.3 and 0.6, respectively), and the weighted means have been adopted.

The absolute emission probability of the 497.1 keV γ ray can be determined in two ways:

(i) From the population/depopulation balance of the 536.8 keV level of the ^{103}Rh daughter nucleus. P_β(536.8 keV level) has been measured by Ohshima et al. [11] to be 0.922(4), to give an NF of 0.00914(4).

(ii) From the requirement that the sum of all transitions to the ground state and 39.8 keV first excited state (excluding the 39.8 keV isomeric transition) should equal unity. Using the decay scheme of Ref. [9] and the beta branching ratio to the ground state of 0.0087(5), as measured by Ohshima et al. [11], leads to an NF of 0.009131(7).

Conversion coefficients for the transitions in the above calculations have been taken from the output of the EMISSION program [12]. The two NFs are in good agreement, and the more precise value of 0.009131(7) has been adopted to derive the absolute γ ray emission probabilities shown in the table above.

X rays: Energies and emission probabilities

X ray emission probabilities were calculated using the EMISSION program [12], atomic data from Schönfeld and Janβen [13], and the recommended γ ray emission probabilities. The KX ray energies are taken from Bearden [14] and the ICCs are calculated from Band et al. [15].

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^{106}Ru–^{106}Rh

Half-life evaluated by M.J. Woods, S.M. Collins and S.A. Woods (National Physical Laboratory, UK), January 2004.

Decay scheme evaluated by T.D. MacMahon (National Physical Laboratory, UK), February 2005.

Recommended data

Half-life

$T_{1/2}$ (^{106}Ru) = 371.8(18) d

$T_{1/2}$ (^{106}Rh) = 0.000348(4) d

SELECTED GAMMA RAYS OF ^{106}Rh

E_γ (keV)	P_γ per decay
511.8534(23)[a]	0.2050(21)
616.22(9)[b]	0.00724(13)
621.93(6)[b]	0.0986(11)
873.49(5)[b]	0.00435(8)
1050.41(6)[b]	0.01488(22)
1128.07(5)[b]	0.00399(6)

[a] From Ref. [1].
[b] From Ref. [2].

Input data

HALF-LIFE (^{106}Ru)

Half-life (d)	Reference
370.5(6)	[H1]
373.59(15)[a]	[H2]
368.0(18)	[H3]
371(1)	[H4]
365.8(17)	[H5]
371.8(18)	

[a] Uncertainty increased to (48) to ensure a weighting factor not greater than 0.50.

HALF-LIFE (^{106}Rh)

Half-life (d)	Reference
0.0003449(9)[a]	[H6]
0.0003514(17)	[H7]
0.000348(4)	

[a] Uncertainty increased to (17) to ensure a weighting factor not greater than 0.50.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[3]	[4]	[5]	[6]	[7]	[8]
511.9	100	100	100	100	100	100
616.2	4.9(13)	3.5(3)	3.4(4)	5(1)	3.5(7)	3.2(2)
621.9	47(4)	48.5(10)	48.5(10)	47.3(6)	48.0(10)	47.7(5)
873.5	1.8(2)	2.1(1)	2.0(1)	1.80(25)	1.90(12)	2.3(1)
1050.4	6.8(5)	7.5(4)	8.0(5)	6.3(10)	7.2(4)	7.35(30)
1128.1	2.3(3)	2.0(1)	-	1.60(25)	1.9(2)	2.15(10)

E_γ (keV)	[9]	[10]	[11]	[12]	[13]	[14]
511.9	100	100	100	100	100	100
616.2	3.37(27)	3.44(8)	3.8(2)	3.59(7)	—	4.3(6)
621.9	47.6(15)	47.5(5)	47.6(23)	48.7(6)	50(3)	51.5(35)
873.5	2.02(8)	—	2.50(12)	2.09(4)	—	2.37(15)
1050.4	7.06(28)	—	7.35(40)	7.11(9)	—	8.4(5)
1128.1	1.87(8)	—	1.93(9)	1.86(4)	—	2.20(15)

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

E_γ (keV)	[15]	[2]	Reduced χ^2	Evaluated relative P_γ	Absolute P_γ
511.9	100	100	—	100	0.2050(21)
616.2	3.59(72)	3.72(33)	1.0	3.53(5)	0.00724(13)
621.9	47.4(24)	48.68(60)	0.5	48.10(24)	0.0986(11)
873.5	2.09(13)	2.15(3)	2.6	2.12(3)	0.00435(8)
1050.4	7.27(44)	7.64(15)	1.8	7.26(8)	0.01488(22)
1128.1	1.92(4)	1.98(3)	1.8	1.946(20)	0.00399(6)

Comments:

Evaluated relative emission probabilities were obtained from the following assessments:

(a) The weighted mean adopted for the 616 and 622 keV γ rays, where the reduced χ^2 is less than or equal to unity;

(b) The weighted mean for the 873 keV γ ray is 2.12(2) with a reduced χ^2 of 2.6, but LRSW [17] and normalized residuals [18] techniques both support an increase in the uncertainty to 3 to take into account the slight discrepancy in the data;

(c) Reduced χ^2 is 1.8 for each of the 1050 and 1128 keV γ rays — weighted mean, LRSW, normalized residuals and Rajeval [19] techniques are all consistent and lead to the recommendations listed above.

GAMMA RAYS: MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITIES

E_γ (keV)	[7]	[9]	[13]	[14]	Evaluated
511.9	0.21(2)	0.206(6)	0.2047(23)	0.220(11)	0.2050(21)
616.2	0.0069(7)[a]	0.00729(23)[a]	0.00735(12)	—	0.00733(11)
621.9	0.093(9)[a]	0.099(3)[a]	0.0995(8)	0.110(10)	0.0995(8)
873.5	—	—	0.00421(6)	—	0.00421(6)
1050.4	—	—	0.01452(13)	—	0.01452(13)
1128.1	—	—	0.00376(6)	—	0.00376(6)

[a] Refs [7] and [9] gave emission probabilities for only the sum of the 616 and 622 keV γ transitions [0.100(10) and 0.106(3), respectively]. As listed above, these values have been apportioned using the ratio P_γ(622 keV)/P_γ(614 keV) = 13.55(20), as measured by Debertin et al. [13].

Comments:

The absolute emission probability for the 511.9 keV γ ray is taken from the above evaluation to be 0.2050(21). This value has been applied to the evaluated relative emission probabilities to obtain the recommended absolute γ ray emission probabilities, as listed above.

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^{110m}Ag with ^{110}Ag

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA), December 2002.

Recommended data

Half-life (^{110m}Ag)

$T_{1/2}$ = 249.85(10) d

SELECTED GAMMA RAYS

E_γ (keV)[a]	P_γ per decay[b]
446.812(3)	0.0365(5)
620.3553(17)	0.0272(8)
657.7600(11)	0.9438(8)
677.6217(12)	0.1056(6)
687.0091(18)	0.0645(3)
706.6760(15)	0.1648(8)
744.2755(18)	0.0471(3)
763.9424(17)	0.2231(9)
818.0244(18)	0.0733(4)
884.6781(13)	0.740(12)
937.483(3)	0.3451(27)
1384.2931(20)	0.247(5)
1475.7792(23)	0.0403(5)
1505.0280(20)	0.1316(16)
1562.294(18)	0.0121(3)

[a] From Ref. [1].

[b] Emission probabilities are derived from the averages of the relative emission probabilities [2–9] in the table below by means of the following normalization procedure:

Sum of the probabilities of the decay to the ground state of ^{110}Ag and those following the β^- decay of ^{110m}Ag to the ^{110}Cd ground state is defined as 1.00. However, the 657 keV γ ray, as listed in the table below, includes both a component from the direct β^- decay of the isomer and a component for the decay through the ^{110}Ag ground state. Since 4.6(4)% of the ^{110}Ag ground state decays lead to the 657 keV γ ray, the intensity of the isomeric decay is reduced by this fraction. Based on the units of the table below, the sum to be normalized to 1.00 is:

I_γ(116 keV) × [1.0 + α(116 keV)][0.954] + I_γ(657 keV)[1.0 + α(657 keV)] + I_γ(1475 keV) + I_γ(1783 keV) = [0.085 × 169 × 0.954] + 1000[1.003] + 42.7 + 0.107 = 1059.5(9),

so NF is 0.0009438(8).

I_γ(116 keV) = 0.085(3) [8], I_γ(1783 keV) = 0.107(5) [4, 6–9], α(116 keV) = 168(8) [10], and α(657 keV) = 0.00318(9) [10]. An uncertainty of 5% in α(116 keV) has been assigned by the evaluator.

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Ag	$K\alpha_2$	21.9906	0.00198(12)
Ag	$K\alpha_1$	22.1632	0.00372(22)
Ag	$K\beta_1'$	24.912–25.146	0.00103(7)
Ag	$K\beta_2'$	25.457–25.512	0.000179(12)
Cd	$K\alpha_2$	22.9843	0.00153(9)
Cd	$K\alpha_1$	23.1738	0.00288(16)
Cd	$K\beta_1'$	26.061–26.304	0.00080(5)
Cd	$K\beta_2'$	26.64–26.70	0.000146(9)

Input data

HALF-LIFE

Half-life (d)	Reference
249.950(24)[a]	[H1]
249.79(20)	[H2]
249.74(5)	[H3]
252.2(3)[b]	[H4]
250.38(30)	[H5]
249.85(10)	

[a] Uncertainty increased to (48) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[2]	[3]	[4]	[5]	[6]	[7]
446.8	-	38.6(4)	41.8(6)[a]	39.0(12)	39.55(28)	39(2)
620.3	-	29.3(3)	29.5(4)	31.4(13)	29.65(19)	28.0(5)
657.7	≡1000	1000	1000	1000	1000	1000
677.6	-	113.1(11)	111(2)	112.6(29)	110.9(8)	112(6)
687.0	-	68.5(7)	75.8(14)[a]	69.0(27)	68.0(6)	67(3)
706.6	175(10)	176.7(18)	176.4(20)	176.2(22)	176.6(10)	174(7)
744.2	-	49.2(5)	52.3(8)	49.5(16)	50.00(27)	48.0(25)
763.9	237(2)	236.0(24)	243.7(30)	237.4(31)	235.5(9)	243(12)
818.0	-	77.3(8)	80.5(22)	77.4(17)	77.6(4)	79(4)
884.6	775(5)	769(8)	811(10)	780(10)	767.6(26)	800(40)
937.4	366(3)	362.2(36)	380(4)	369(4)	363.1(12)[b]	374(18)
1384.2	261(2)	257.0(26)	277.9(30)	271(5)	256.6(8)[b]	278(14)
1475.7	-	42.1(4)	44.8(6)	44.9(12)	42.22(17)[b]	45(2)
1505.0	139(1)	138.4(14)	145.2(16)	147.0(29)	137.8(5)[b]	151(7)
1562.2	-	12.50(13)[b]	13.2(2)	14.0(8)	10.87(7)	13.0(7)

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

E_γ (keV)	[8]	[9]	Evaluated
446.8	38.9(6)	38.22(12)[b]	38.7(5)
620.3	29.4(5)	28.00(15)[b]	28.8(8)
657.7	1000	1000	1000
677.6	112(2)	112.6(11)	111.9(5)
687.0	68.5(5)[b]	69.2(21)	68.3(3)
706.6	172.8(5)[b]	176.9(26)	174.6(7)
744.2	49.3(8)	50.2(14)	49.9(3)
763.9	236(3)	239.1(53)	236.4(7)
818.0	77.1(5)	78.8(18)	77.7(4)
884.6	771(10)	706.6(12)[b]	784(12)
937.4	363(6)	376(8)	365.7(26)
1384.2	261(5)	276.6(26)	262(5)
1475.7	42.4(8)	45.7(13)	42.7(5)
1505.0	140.1(19)	149.2(28)	139.4(16)
1562.2	12.6(6)	13.5(4)	12.8(3)

[a] Rejected as an outlier.
[b] Published uncertainty is listed; this value was increased in the analysis in order to reduce the relative weighting factor to 0.50.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{109}Cd

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), November 1996.

Recommended data

Half-life

$T_{1/2}$ = 461.4 (12) d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
88.0336(11)	0.03626(20)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Ag	L	2.63–3.75	0.1034(26)
Ag	$K\alpha_2$	21.9906(2)	0.2899(25)
Ag	$K\alpha_1$	22.1632(1)	0.547(4)
Ag	$K\beta_1'$	24.912–25.146	0.1514(18)
Ag	$K\beta_2'$	25.457–25.512	0.0263(10)

Input data

HALF-LIFE

Half-life (d)	Reference
459.6(17)	[H1]
460.2(2)	[H2]
463.26(63)	[H3]
463.1(3)	[H4]
461.90(30)	[H5]
459(6)	[H6]
450(5)[a]	[H7]
461.4(12)	

[a] Rejected as an outlier.

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GAMMA RAY: MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITY

E_γ (keV) [1]	[2][a]	[3][a]	[4][a]	[5][a]	[6][a]	[7][a]
88.0	0.0365(4)	0.03594(19)	0.0367(7)	0.0365(3)	0.0370(6)	0.03600(10)
E_γ (keV) [1]	[8][a]	[9]	[10]	[11]	[12]	[13]
88.0	0.0357(10)	0.0365(8)	0.03675(18)	0.0366(5)	0.0368(7)	0.0365(5)
E_γ (keV) [1]	[14][b]	[15][b]	[16][b]	[17][b]	[18][b]	Evaluated [19]
88.0	0.0389(7)	0.0397(21)	0.0329(25)	0.0379(7)	0.0365(5)	0.03626(26)

[a] Determined during BIPM intercomparison, as summarized in Ref. [20].
[b] Deduced from α_t experiments.

Evaluated emission probability is the weighted average calculated according to the limitation of relative statistical weights method; no value has a relative weighting factor greater than 0.50.

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Detailed tables and comments can be found in Refs [19, 20].

^{111}In

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by V.P. Chechev (V.G. Khlopin Radium Institute, Russian Federation), September 1998.

Recommended data

Half-life

$T_{1/2}$ = 2.8049(6) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
171.28(3)	0.9066(25)
245.35(4)	0.9409(6)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Cd	L	2.76–3.95	0.068(2)
Cd	$K\alpha_2$	22.9843	0.236(2)
Cd	$K\alpha_1$	23.1738	0.444(3)
Cd	$K\beta_1'$	26.061–26.304	0.124(4)
Cd	$K\beta_2'$	26.64–26.70	0.023(1)

Input data

HALF-LIFE

Half-life (d)	Reference
2.8063(7)	[H1]
2.80477(53)	[H2]
2.8048(1)[a]	[H3]
2.8071(15)	[H4]
2.802(1)	[H5]
2.83(1)[b]	[H6]
2.84(11)[b]	[H7]
2.96(8)[b]	[H8]
2.8049(6)	

[a] Uncertainty increased to (3.8) to ensure a weighting factor not greater than 0.50.

[b] Rejected as an outlier.

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Gamma rays: Energies and emission probabilities

Energies of γ rays have been taken from Ref. [1].

Absolute γ ray emission probabilities have been computed from the decay scheme using the evaluated total internal conversion coefficients α_T(171 keV) = 0.103(3) and α_T(245 keV) = 0.0628(7) [2–4].

XK, XL rays: Total absolute emission probabilities

The total absolute XK ray emission probability has been calculated using the adopted value of ω_K = 0.842(4) [5] and the evaluated total absolute intensities of K conversion electrons and K electron capture [2–4]. Total absolute XL ray emission probability has been computed using the evaluated ^{111}In decay data [2–4] and the fluorescence yields ω_K = 0.842(4), ω_L = 0.0632(16) and n_{KL} = 0.953(4) from Ref. [5].

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Detailed tables and comments can be found in Refs [3, 4], and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
In	L	2.90–4.23	0.086(3)
In	$K\alpha_2$	24.0020	0.2785(22)
In	$K\alpha_1$	24.2097	0.522(4)
In	$K\beta_1'$	27.238–27.499	0.1460(12)
In	$K\beta_2'$	27.861–27.940	0.0284(2)

^{113}Sn

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA), May 1999.

Recommended data

Half-life

$T_{1/2}$ = 115.09(4) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
255.134(10)[a]	0.0211(8)[b]
391.698(3)[c]	0.6494(17)[d]

[a] Energy from Ref. [1], but scaled by the ratio E_γ(391 keV) from Ref. [2] to E_γ(391 keV) from Ref. [1].

[b] From relative emission probability evaluated below [1, 3–5].

[c] From Ref. [2].

[d] Ground state feeding is P_γ(391 keV) × [1.0 + α(391 keV)] + P_γ(646 keV), but P_γ(646 keV)/P_γ(391 keV) = 0.00149(6) from Ref. [3], i.e. negligible. Therefore, P_γ(391 keV) follows from α(391 keV) = 0.540(4) [6].

Input data

HALF-LIFE

Half-life (d)	Reference
115.079(80)	[H1]
115.12(13)	[H2]
115.09(4)[a]	[H3]
115.2(8)	[H4]
115.07(10)	[H5]
115.09(4)	

[a] Uncertainty increased to (6) to ensure a weighting factor not greater than 0.50.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[1]	[3]	[4]	[5]	Evaluated
255	3.33(13)	2.85(9)	3.37(5)	3.27(8)	3.25 (12)
392	≡ 100	100	100	100	100

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{125}Sb

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA) and E. Browne (Lawrence Berkeley National Laboratory, USA), May 2004.

Recommended data

Half-life

$T_{1/2}$ = 1007.48(21) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
176.314(2)[a]	0.0682(7)
380.452(8)[b]	0.01520(15)
427.874(4)[a]	0.2955(24)
463.365(4)[a]	0.1048(9)
600.597(2)[a]	0.1776(18)
606.713(3)[a]	0.0502(5)
635.950(3)[a]	0.1132(10)
671.441(6)[a]	0.01783(16)

[a] From Ref. [1].
[b] From Ref. [2].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Te	$K\alpha_2$	27.2020(2)	0.191(7)
Te	$K\alpha_1$	27.4726(2)	0.357(12)
Te	$K\beta_1'$	30.945–31.236	0.102(4)
Te	$K\beta_2'$	31.701–31.774	0.0221(10)

Input data

HALF-LIFE

Half-life (d)	Reference
1007.56(10)[a]	[H1]
1008.1(8)	[H2]
1007.3(3)	[H3]
1007.48(21)	

[a] Uncertainty increased to (29) to ensure a weighting factor not greater than 0.50.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[3][a]	[4][b]	[5]	[6]	[7]	[8][c]
176.3	20.5	—	21.2(11)	24.9(20)	23.9(8)	23.2(13)
380.4	5	5(1)	5.0(4)	5.27(40)	5.22(17)	5.43(32)
427.9	100	100	100	100	100	100
463.4	35.5	33(4)	35.3(20)	35.4(28)	35.3(13)	35.2(23)
600.6	61	—	61.2(34)	61.5(49)	59.6(18)	53.6(32)
606.7	17	—	17.1(12)	16.4(12)	16.9(6)	19.0(11)
635.9	37	42(2)	37.0(22)	37.31(30)	38.2(12)	35.6(23)
671.4	6	6.5(5)	5.6(5)	6.0(5)	6.09(20)	6.24(38)

E_γ (keV)	[9]	[10]	[11]	[12]	[13]	[14]
176.3	23.06(7)[d]	22.9(7)	23.9(7)	22.9(6)	25.45(60)	24.5(8)
380.4	5.16(3)	5.15(20)	5.10(5)	5.18(20)	5.26(10)	6.02(25)[e]
427.9	100.0(3)	100	100.0(10)	100	100	100
463.4	35.50(7)	35.2(10)	35.26(37)	35.1(8)	35.45(84)	35.50(7)
600.6	60.39(10)	60.1(18)	60.6(6)	60.4(11)	59.3(12)	60.50(10)
606.7	17.052(34)	16.8(5)	17.12(17)	16.6(5)	16.25(62)	17.2(3)
635.9	38.45(7)	38.4(11)	38.6(4)	38.7(8)	37.7(10)	39.1(2)
671.4	6.11(14)	6.02(24)	6.18(6)	6.04(16)	6.92(14)[e]	5.9(3)

E_γ (keV)	[15]	[16]	[2]	[17]	[18]
176.3	22.62(21)	22.91(41)	22.96(24)	23.65(34)	23.09(20)
380.4	5.06(4)	5.12(15)	5.14(5)	5.09(3)	5.17(4)
427.9	100.0(7)	100	100.0(8)	100	100
463.4	35.23(14)	35.4(9)	35.07(28)	35.64(10)	35.12(18)
600.6	59.54(22)	60.95(67)	59.09(45)	59.70(10)	59.22(18)
606.7	16.94(7)	16.97(26)	16.70(14)	16.98(21)	16.92(6)
635.9	37.87(14)	37.47(27)	37.52(30)[f]	38.78(32)	38.32(12)
671.4	6.039(24)	5.65(12)	6.05(6)	5.97(11)	6.03(2)

E_γ (keV)	Reduced χ^2	Evaluated	Absolute P_γ
176.3	2.6	23.09(15)	0.0682(7)
380.4	1.2	5.145(13)	0.01520(15)
427.9	—	100	0.2955(24)
463.4	1.0	35.47(4)	0.1048(9)
600.6	6.0	60.1(4)	0.1776(18)
606.7	1.0	16.997(27)	0.0502(5)
635.9	4.7	38.31(14)	0.1132(10)
671.4	1.5	6.036(17)	0.01783(16)

[a] All values from this reference omitted from analysis because they do not have uncertainties assigned.
[b] All values from this reference omitted from analysis because 5 out of 8 were outliers in initial averaging.
[c] All values from this reference omitted from analysis because 9 out of 19 were outliers in initial averaging.
[d] Uncertainty increased from 0.07 to 0.20 by the evaluator.
[e] Rejected as an outlier.
[f] Typographical error in original reference.

Comments:

The 109.3 keV γ ray depopulates the isomeric level at 144.8 keV (^{125m}Te half-life of 57.4 d), so the intensity of this emission depends on any chemical separation and in-growth time. The nuclear level at 35.5 keV is primarily fed from higher levels, but 27% of the 35.5 keV γ ray intensity arises via the isomeric level when at equilibrium. Therefore, for a chemically separated source, approximately 8 months in-growth is required for equilibrium to be established with the other γ rays to within the 1% level.

The NF for the relative γ ray emission probabilities was calculated to be 0.2955(24) by assuming no direct β^- decay to the ground state (1/2+) and 35.5 keV level (3/2+) from ^{125}Sb (7/2+), and setting the total γ ray feeding of these ground and first excited states to 100%. The relative emission probability of the 35.5 keV γ ray is poorly defined, and a summation encompassing these two levels avoids the need to use any such datum. However, the relative emission probability of the 109.3 keV γ ray needs to be adjusted to an equilibrium value based on the relative half-lives of ^{125}Sb and ^{125m}Te (taken to be 1007.48(21) d (see above) and 57.40(15) d [19], respectively).

Gamma ray multipolarities and mixing ratios have been adopted from Ref. [19], and internal conversion coefficients have been derived from Ref. [20]. Although the total theoretical conversion coefficient of the 109.3 keV M4 γ ray is 363.7, this value has been reduced by 2.5% to 354.6 as recommended by Ref. [21].

The sum of all γ ray transition intensities (photons + conversion electrons) per decay to the ground and 35 keV nuclear levels is given by the following equation:

$$[I_\gamma(635.9\text{ keV})(1+\alpha(635.9\text{ keV})) + I_\gamma(671.4\text{ keV})(1+\alpha(671.4\text{ keV}))$$
$$+ I_\gamma(606.7\text{ keV})(1+\alpha(606.7\text{ keV})) + I_\gamma(600.6\text{ keV})(1+\alpha(600.6\text{ keV}))$$
$$+ I_\gamma(427.9\text{ keV})(1+\alpha(427.9\text{ keV})) + I_\gamma(463.4\text{ keV})(1+\alpha(463.4\text{ keV}))$$
$$+ I_\gamma(408.1\text{ keV})(1+\alpha(408.1\text{ keV})) + I_\gamma(443.5\text{ keV})(1+\alpha(443.5\text{ keV}))$$
$$+ \{I_\gamma(109.3\text{ keV})(1+\alpha(109.3\text{ keV})) \times [t_{1/2}(^{125}\text{Sb}) - t_{1/2}(^{125m}\text{Te})]/t_{1/2}(^{125}\text{Sb})]\}] \times \text{NF} = 1.0$$

$$[38.31(1.00526) + 6.036(1.00373) + 16.997(1.00485) + 60.1(1.00498) + 100(1.0138) + 35.47(1.0102)$$
$$+ 0.617(1.0152) + 1.033(1.0118) + \{0.231 \times 355.6 \times 0.943\}] \times \text{NF} = 338.39 \times \text{NF} = 1.0$$

$$\text{NF} = 1/338.39 = 0.002955(24)$$

Recommended relative intensities for the 109.3, 408.1 and 443.5 keV gamma rays were determined during the course of this evaluation, and the full data set can be found on
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

The resulting NF has been used to determine the absolute γ ray emission probabilities listed above. With this NF, the total (γ + e) emission probability of the 427.9 keV transition is determined to be 0.2996(24) per decay.

X rays: Energies and emission probabilities

X ray energies are taken from Schönfeld and Rodloff [22]. Emission probabilities are the evaluators' values calculated using the EMISSION program, Version 3.04 [23], with atomic data from Ref. [24], and the recommended γ ray emission probabilities shown above.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{123m}Te

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by M.-M. Bé and V. Chisté (Commissariat à l'Énergie Atomique, France), October 2002.

GAMMA RAY: MEASURED ABSOLUTE EMISSION PROBABILITY

E_γ (keV) [1]	[2]	[3]	[4]	[5]	[6][a]	[6][a]
158.97(5)	0.8365(50)	0.8348(38)	0.832(5)	0.839(6)	0.8381(32)	0.8407(9)

[a] Two values are given in Ref. [6].

Recommended data

Half-life

$T_{1/2}$ = 119.45(25) d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
158.97(5)	0.8399(8)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Te	L	3.34–4.93	0.0826(21)
Te	$K\alpha_2$	27.2020	0.140(5)
Te	$K\alpha_1$	27.4726	0.260(9)
Te	$K\beta_1'$	30.945–31.241	0.0743(26)
Te	$K\beta_2'$	31.701–31.812	0.0161(7)

Emission intensities of KX rays were calculated from the data set described on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

Input data

HALF-LIFE

Half-life (d)	Reference
119.2(1)	[H1]
119.7(1)	[H2]
119.45(25)	

REFERENCES — HALF-LIFE

[H1] COURSEY, B.M., GOLAS, D.B., GRAY, D.H., HOPPES, D.D., SCHIMA, F.J., Nucl. Instrum. Methods Phys. Res. **A312** (1992) 121.
[H2] EMERY, J.F., REYNOLDS, S.A., WYATT, E.I., GLEASON, G.I., Nucl. Sci. Eng. **48** (1972) 319.

Comments:

Recommended emission probability is the weighted average. More details can be found on: http://www.nucleide.org/DDEP_WG/DDEPdata.htm

Internal conversion coefficients are:

α_K = 0.1648(49); α_L = 0.0216(6); α_T = 0.1918(19) deduced from the tables of Rösel et al. [7] with the adopted multipolarity M1 + 1.22%E2.

REFERENCES — RADIATIONS

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{123}I

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by M.-M. Bé and V. Chisté (Commissariat à l'Énergie Atomique, France), December 2001.

Recommended data

Half-life

$T_{1/2}$ = 0.55098(9) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
158.97(5)	0.8325(21)
528.96(5)	0.0132(8)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Te	L	3.34–4.93	0.0772(16)
Te	$K\alpha_2$	27.2020	0.2469(20)
Te	$K\alpha_1$	27.4726	0.4598(29)
Te	$K\beta_1'$	30.945–31.241	0.1316(17)
Te	$K\beta_2'$	31.701–31.812	0.0386(8)

Emission intensities of K X rays were calculated from the data set described on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

Input data

HALF-LIFE

Half-life (d)	Reference
0.55135(27)	[H1]
0.55095(12)	[H2]
0.550979(79)[a]	[H3]
0.5504(4)	[H4]
0.5625(46)[b]	[H5]
0.558(21)[b]	[H6]
0.55098(9)	

[a] Uncertainty increased to (106) to ensure a weighting factor not greater than 0.50.

[b] Rejected as an outlier.

REFERENCES — HALF-LIFE

[H1] SCHRADER, H., Appl. Radiat. Isot. **60** (2004) 317.

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[H5] KARIM, H.M.A., Radiochim. Acta **19** (1973) 1.
[H6] JONSSEN, G.G., FORKMAN, B., Nucl. Phys. **A107** (1968) 52.

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2]	[3]	[4]	[5]
158.97(5)	≡100	100	100	100
528.96(5)	2.0(3)[a]	1.27(11)[a]	1.26(24)[a]	1.40(5)

E_γ (keV) [1]	[1]	[6]	[7]	Evaluated
158.97(5)	100	100	100	100
528.96(5)	1.670(5)	1.66(5)	1.41(6)[b]	1.58(10)

[a] Value rejected.
[b] Initial uncertainty increased by a factor of 2.

Comments:

Evaluated relative emission probability of the 528 keV γ ray is the weighted mean.

Absolute emission probabilities were calculated from $\Sigma P_{\gamma+ce} = 1.00$ to the ground state to give NF of 0.008325(21).

The internal conversion coefficients of the 158.97 keV γ ray are:

$\alpha_K = 0.1648(49)$; $\alpha_L = 0.0216(6)$; $\alpha_T = 0.1918(19)$ deduced from the tables of Rösel et al. [8] with the adopted multipolarity M1 + 1.22%E2 (see also http://www.nucleide.org/DDEP_WG/DDEPdata.htm)

REFERENCES — RADIATIONS

[1] WALTERS, W.B., MEYER, R.A., Phys. Rev. **C14** (1976) 1925.
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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{125}I

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), April 1997.

Recommended data

Half-life

$T_{1/2} = 59.402(14)$ d

SELECTED GAMMA RAY

E_γ (keV) [1]	P_γ per decay
35.4919(5)	0.0667(17)

Absolute emission probability of the 35.5 keV γ ray: 0.0655(13) [2], 0.0668(13) [3], and a recommended value in Ref. [4]. However, P_γ(35.5 keV) was calculated from the adopted values of α_K and α_t by $P_\gamma = 1 - \alpha_t'$ where $\alpha_t' = \alpha_t/(1 + \alpha_t)$ with $\alpha_t = 14.0(3)$ [5].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Te	L	3.34–4.93	0.149(7)
Te	$K\alpha_2$	27.2020(2)	0.397(6)
Te	$K\alpha_1$	27.4726(2)	0.740(11)
Te	$K\beta_1'$	30.945–31.241	0.212(4)
Te	$K\beta_2'$	31.701–31.812	0.0459(14)

Input data

HALF-LIFE

Half-life (d)	Reference
59.49(13)	[H1]
59.37(6)	[H2]
59.38(3)	[H3]
59.68(28)	[H4]
59.416(10)[a]	[H5]
59.39(2)	[H6]
59.40(5)	[H7]
59.56(17)	[H8]
59.156(20)[b]	[H9]
60.18(17)[b]	[H10]
59.89(6)[b]	[H11]
59.402(14)	

[a] Uncertainty increased to (16) to ensure a weighting factor not greater than 0.50.

[b] Rejected as an outlier.

REFERENCES — HALF-LIFE

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[H10] EMERY, J.F., REYNOLDS, S.A., WYATT, E.I., GLEASON, G.I., Nucl. Sci. Eng. **48** (1972) 319.

[H11] LAGOUTINE, F., GALLIC, Y.L., LEGRAND, J., Int. J. Appl. Radiat. Isot. **19** (1968) 475.

REFERENCES — RADIATIONS

[1] MILLER, J.P., BOEHM, F., HENRIKSON, H.E., Nucl. Instrum. Methods **136** (1976) 403.

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[3] IWAHARA, A., MARECHAL, M.H.H., DA SILVA, C.J., POLEDNA, R., Nucl. Instrum. Meth. Phys. Res. **A286** (1990) 370.

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Detailed tables and comments can be found in Refs [5, 6] and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{129}I

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by V.P. Chechev and V.O. Sergeev (V.G. Khlopin Radium Institute, Russian Federation), September 2001.

Recommended data

Half-life

$T_{1/2} = 5.89(23) \times 10^9$ d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
39.578(4)	0.0742(8)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Xe	L	3.6–5.4	0.079(4)
Xe	$K\alpha_2$	29.459(2)	0.201(3)
Xe	$K\alpha_1$	29.779(1)	0.372(6)
Xe	$K\beta_1'$	33.56–33.88	0.103(4)
Xe	$K\beta_2'$	34.41–34.55	0.0230(13)

Input data

HALF-LIFE

Half-life (d)	Reference
$7.20(51) \times 10^9$	[H1]
$5.73(15) \times 10^9$ [a]	[H2]
$5.70(22) \times 10^9$	[H3]
$6.28(33) \times 10^9$	[H4]
$5.89(23) \times 10^9$	

[a] Uncertainty increased to (18) to ensure a weighting factor not greater than 0.50.

REFERENCES — HALF-LIFE

[H1] KUHRY, J.G., BONTEMS, G., Radiochem. Radioanal. Lett. **15** (1973) 29.

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Gamma ray: Energy and absolute emission probability

The recommended energy for the 39.578 keV γ ray has been adopted from Ref. [1].

The absolute γ ray emission probability has been computed on the basis of the ^{129}I decay scheme using a total absolute (γ + ce) emission probability of 0.995(5) and total internal conversion coefficient $\alpha_T = 12.41(13)$ for a multipolarity of M1 + 0.07(3)% E2 [2]. The evaluator has adopted a value of 0.0005(5) for the absolute emission probability of the second unique forbidden β^- transition to the ground state of ^{129}Xe, taking into account an experimental upper limit of 1% [3].

REFERENCES — RADIATIONS

[1] BARCI-FUNEL, G., KOUASSI, M.C., ARDISSON, G., Nucl. Instrum. Methods Phys. Res. **241** (1985) 252.

[2] VENKATA RAMANIAH, K., SESHI REDDY, T., VENKATA REDDY, K., Current Sci., India **43** (1974) 406.

[3] DER MATEOSIAN, E., WU, C.S., Phys. Rev. **95** (1954) 458.

Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{131}I

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by M.-M. Bé and V. Chisté (Commissariat à l'Énergie Atomique, France), December 2001.

Recommended data

Half-life

$T_{1/2} = 8.0228(24)$ d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
80.1850(19)	0.02607(27)
284.305(5)	0.0606(6)
364.489(5)	0.812(8)
636.989(4)	0.0726(8)
722.911(5)	0.01796(20)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Xe	Kα	29.70	0.044(14)
Xe	Kβ	33.56–34.55	0.01025(11)

Emission intensities of KX rays were calculated from the data set described on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

Input data

HALF-LIFE

Half-life (d)	Reference
8.0252(6)[a]	[H1]
7.9994(9)	[H2]
8.0197(22)	[H3]
8.0213(9)	[H4]
8.020(1)	[H5]
8.031(4)	[H6]
8.040(1)[b]	[H7]
7.969(14)[b]	[H8]
8.0228(24)	

[a] Uncertainty increased to (7) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

REFERENCES — HALF-LIFE

[H1] SCHRADER, H., Appl. Radiat. Isot. **60** (2004) 317.
[H2] DA SILVA, M.A.L., DE ALMEIDA, M.C.M., C.DA SILVA, C.J., DELGADO, J.U., Appl. Radiat. Isot. **60** (2004) 301.
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[H8] ZOLLER, W.H., HOPKE, P.K., FASCHING, J.L., MACIAS, E.S., WALTERS, W.B., Phys. Rev. **C3** (1971) 1699.

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]
80.1850(19)	2.71(19)[a]	2.6(4)[a]	3.5(8)[a]	3.1(2)[a]	3.10(18)[a]	2.72(15)[a]
284.305(5)	6.6(25)[a]	6.0(10)[a]	7.9(8)[a]	6.6(3)[a]	7.4(6)	7.05(40)[a]
364.489(5)	≡100	100	100	100	100	100
636.989(4)	11.6(19)[a]	9.0(10)[a]	8.8(7)[a]	8.3(3)[a]	9.1(11)[a]	8.0(4)[a]
722.911(5)	3.5(31)[a]	3.0(4)[a]	2.05(16)[a]	1.9(1)[a]	2.05(26)	2.10(15)[a]

E_γ (keV) [1]	[8]	[9]	[10]	[11]	[1]	Evaluated
80.1850(19)	3.4(4)[a]	3.210(5)	3.226(37)	3.26(7)	3.23(6)	3.212(9)
284.305(5)	8.2(8)[a]	7.49(5)	7.457(12)	7.56(8)	7.46(15)	7.461(12)
364.489(5)	100	100	100	100	100	100
636.989(4)	8.2(8)[a]	7.79(10)[a]	8.945(25)	8.75(9)	8.95(21)	8.940(23)
722.911(5)	1.8(2)[a]	1.79(9)[a]	2.221(12)	2.19(2)	2.22(7)	2.213(10)

[a] Rejected value

Comments:

— Absolute emission probability of 0.01086(7) [10] has been adopted for the 163.930 keV isomeric transition from ^{131m}Xe ($T_{1/2}$ = 11.930(16) d) to the ground state level of ^{131}Xe. Internal conversion coefficients for this M4 transition have been deduced from the theoretical tables of Band et al. [12, 13] (i.e. α_K = 30.8(9); α_T = 49.6(14)).
— Mixing ratios of 364 and 722 keV γ rays were deduced by Krane [14] from experimental values; ICC values have been calculated from the theoretical tables of Rösel et al. [15].

— The NF was determined to be 0.00812(8) from $\Sigma P_{\gamma+ce}$ = 1.0 to the ground state and P_{γ}(163.9 keV) = 0.0001086(7).

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{134}Cs

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by P.R. Pascholati, V.R. Vanin (Universidade de São Paulo, Brazil) and E. Browne (Lawrence Berkeley National Laboratory, USA), September 2002; cut-off date: November 2001.

Recommended data

Half-life

$T_{1/2}$ = 753.5(10) d

SELECTED GAMMA RAYS

E_{γ} (keV)	P_{γ} per decay
563.243(3)	0.0837(3)
569.327(3)	0.1538(4)
604.720(3)	0.97650(18)
795.83(3)	0.855(3)
801.945(4)	0.0870(3)
1365.186(4)	0.03017(12)

Input data

HALF-LIFE

Half-life (d)	Reference
754.5(2)	[H1]
753.88(15)	[H2]
754.50(7)[a]	[H3]
745(11)[b]	[H4]
753.1(6)	[H5]
751.7(15)	[H6]
753.5(10)	

[a] Uncertainty increased to (12) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]
563.243(3)	8.0(12)	8.5(8)	8.96(84)	8.7(10)	8.60(46)	8.86(45)
569.327(3)	12.0(15)	14.6(14)	15.81(110)	15.0(16)	13.30(70)	16.0(10)
604.720(3)	100	100(5)	98.04	98.0	97.50(300)	98.1(60)
795.83(4)	—	90(9)	87.79(660)	88.4(91)	87.00(447)	86.0(43)
801.945(4)	—	9.0(15)	8.94(80)	9.2(10)	7.90(42)	8.70(44)
1167.961(4)	—	1.99(17)	1.96(22)	1.9(2)	2.01(14)	1.86(10)
1365.186(4)	—	3.46(30)	3.25(32)	3.3(3)	3.47(19)	3.23(17)

E_γ (keV) [1]	[8]	[9]	[10]	[11]	[12]	Evaluated [13]
563.243(3)	8.38(5)	—	8.57(3)	8.36(3)	8.54(7)	8.567(22)
569.327(3)	15.43(11)	—	15.78(6)	15.39(5)	15.75(3)	15.753(25)
604.720(3)	97.56(32)	97.6(5)	100.0(4)	97.65(20)	100.0(7)	100.00(22)
795.83(4)	85.44(38)	84.0(3)	87.5(3)	85.4(2)	—	87.54(22)
801.945(4)	8.73(4)	—	8.89(3)	8.69(3)	—	8.914(23)
1167.961(4)	1.805(26)	—	1.827(8)	1.790(6)	—	1.833(7)
1365.186(4)	3.04(4)	—	3.074(13)	3.014(10)	—	3.090(10)

Evaluated emission probabilities are the weighted averages calculated according to the limitation of relative statistical weights method; no value has a relative weighting factor greater than 0.50.

Comments:

Absolute emission probabilities were calculated from $\Sigma P_{\gamma+ce}(604.72 + 1167.96\text{ keV}) = 1.00$, and NF of 0.009765(22) derived from decay scheme constraints (with an uncertainty of ±0.22 in the relative P_γ(604.72 keV) of 100.00).

Although the 1167.96 keV γ ray emission probability was required in the calculation of the NF, this low intensity transition has deliberately not been included in the recommended set of selected γ rays.

However, the absolute P_γ(604.72 keV) of 0.97650(18) with such a small uncertainty was determined from consideration of the γ ray and conversion electron emission probabilities that directly feed the ground state of ^{134}Ba:

$$P_\gamma(604.72\text{ keV}) + P_{ce}(604.72\text{ keV}) + P_\gamma(1167.96\text{ keV}) + P_{ce}(1167.96\text{ keV}) = 1.00,$$

leading to absolute P_γ(604.72 keV) = 0.97650(18).

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Detailed tables and comments can be found in Refs [1, 13] and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{137}Cs

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA) and E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), January 1999.

Recommended data

Half-life

$T_{1/2}$ = 1.099 (4) × 10^4 d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
661.657(3) [a]	0.8499(20) [b]

[a] From Ref. [1].

[b] Emission probability is from the combination of two methods of determination:
(1) Direct comparison of the γ-emission rate and source decay rate by [2–4]; P_γ is 0.852(5).
(2) P_γ(661 keV) = {1.0 – [P_β(0) – P_γ(283 keV)]}/[1.0 + α(661 keV)] = 0.8495(22), where P_β(0) = 0.0569(19) from an evaluation of data from Refs [5–12], and α(661 keV) = 0.1102(19) from analysis of values from Refs [2, 3, 8, 10, 12], as listed in Ref. [13]. The adopted average of these two results is 0.8499(20).

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Ba	L	3.954–5.973	0.0090(5)
Ba	$K\alpha_2$	31.8174	0.0195(4)
Ba	$K\alpha_1$	32.1939	0.0359(7)
Ba	$K\beta_1'$	36.31–36.67	0.01055(22)
Ba	$K\beta_2'$	37.26–37.43	0.00266(8)

Input data

HALF-LIFE

Half-life (d)	Reference
10970(20)	[H1]
10940.8(69)	[H2]
11015.0(200)	[H3]
10967.8(45)	[H4]
10941(7)	[H5]
11009(11)	[H6]
10906(33)	[H7]
11118(19)	[H8]
11021.1(41)	[H9]
11023(37)	[H10]
11191(157)	[H11]
1.099(4) × 10^4	

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{133}Ba

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by V.P. Chechev and N.K. Kuzmenko (V.G. Khlopin Radium Institute, Russian Federation), April 2000.

Recommended data

Half-life

$T_{1/2}$ = 3848.7(12) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
53.1622(6)	0.0214(3)
79.6142(12)	0.0265(5)
80.9979(11)	0.329(3)
276.3989(12)	0.0716(5)
302.8508(5)	0.1834(13)
356.0129(7)	0.6205(19)
383.8485(12)	0.0894(6)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Cs	L	3.80–5.70	0.160(8)
Cs	$K\alpha_2$	30.625	0.340(4)
Cs	$K\alpha_1$	30.973	0.628(7)
Cs	$K\beta_1'$	34.92–35.26	0.182(2)
Cs	$K\beta_2'$	35.82–35.97	0.046(1)

Input data

HALF-LIFE

Half-life (d)	Reference
3848.9(7)[a]	[H1]
3841(5)	[H2]
3853.6(36)	[H3]
3885.9(129)	[H4]
3848.0(11)	[H5]
3850(55)	[H6]
4127(60)[b]	[H7]
3981(37)[b]	[H8]
3848.7(12)	

[a] Uncertainty increased to (11) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]
53.162	3.8(8)	3.3(5)	4.2(2)[a]	3.2(4)	3.78(9)	2.91(5)
79.614	3.8(4)	—	4.0(4)	5.5(7)[a]	4.9(6)	4.54(7)
80.998	53(4)	—	58.2(15)	52(7)	60(7)	53.7(17)
276.399	11.0(7)[a]	12.0(4)[a]	11.8(3)	11.6(8)	11.61(17)	11.2(3)
302.851	30(2)	30.6(9)[a]	29.8(8)	29.4(2)	29.75(29)	29.3(5)
356.013	≡100	100	100	100	100	100
383.848	14.5(1)	14.2(5)	14.3(10)	14.3(10)	14.18(26)	14.03(26)[a]

E_γ (keV) [1]	[8]	[9]	[10]	[11]	[12]	[13]
53.162	3.54(5)	—	—	—	3.0(4)	3.49(8)
79.614	3.9(2)	—	3.7(4)	—	5.6(15)[a]	4.29(12)
80.998	52.6(10)	—	56(6)	—	52(4)	55.8(16)
276.399	11.4(3)	11.6(5)	11.35(25)	11.43(23)	11.7(8)	11.41(16)
302.851	30.2(6)	29.6(11)	29.4(6)	29.3(6)	29.87(21)	29.4(3)
356.013	100	100	100	100	100	100
383.848	14.4(3)	14.9(6)[a]	14.3(3)	14.5(3)	14.4(11)	14.33(21)

E_γ (keV) [1]	[14]	[15]	[16]	[17]	[18]	[19]
53.162	3.54(18)	3.57(12)	—	—	2.96(9)	3.6(5)
79.614	3.1(3)[a]	4.16(18)	—	—	4.67(14)	3.7(5)
80.998	49.2(26)	54.6(17)	—	—	55.3(16)	52.3(7)
276.399	11.7(4)	11.4(3)	11.69(16)	11.57(7)	—	11.51(8)
302.851	29.8(4)	28.8(8)	29.9(4)	29.55(18)	—	29.51(23)
356.013	100	100	100	100	100	100
383.848	14.36(20)	14.3(5)	14.79(27)[a]	14.36(9)	—	13.99(9)[a]

E_γ (keV) [1]	[20]	[21]	CRP-1 [22]	CRP-2 [22]	CRP-3 [22]	CRP-4 [22]
53.162	3.48(7)	—	—	3.56(14)	3.53(8)	3.53(7)
79.614	3.77(9)	—	—	—	4.20(12)	4.18(11)
80.998	51.2(4)	—	—	53.1(19)	54.8(12)	54.6(12)
276.399	11.3(2)	11.64(13)	11.7(4)	11.7(3)	11.51(14)	11.48(14)
302.851	29.2(3)	29.31(40)	29.9(11)	30.1(9)	29.5(3)	29.5(4)
356.013	100	100	100	100	100	100
383.848	14.5(2)	14.52(17)	14.5(5)	14.4(5)	14.37(16)	14.41(16)

E_γ (keV) [1]	CRP-5 [22]	CRP-6 [22]	CRP-7 [22]	CRP-8 [22]	CRP-9 [22]	CRP-10 [22]
53.162	3.9(7)	3.45(8)	3.56(8)	—	—	—
79.614	4.00(15)	4.73(12)	4.73(12)	—	—	—
80.998	51.5(19)	57.6(14)	58.9(15)	—	—	—
276.399	11.5(3)	11.68(28)	11.50(28)	11.22(27)	11.22(24)	11.48(25)
302.851	29.5(9)	29.7(7)	29.6(7)	293(6)	29.3(5)	29.3(5)
356.013	100	100	100	100	100	100
383.848	14.2(5)	14.5(4)	14.3(4)	14.53(28)	14.26(25)	14.20(22)

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

E_γ (keV) [1]	CRP-11 [22]	CRP-12 [22]	CRP-13 [22]	CRP-14 [22]	CRP-15 [22]	CRP-16 [22]
53.162	—	3.69(18)	2.92(16)	3.53(8)	3.36(18)	3.26(17)
79.614	—	4.37(16)	—	4.39(11)	—	—
80.998	—	55.3(18)	—	55.9(12)	—	—
276.399	11.57(19)	11.53(16)	11.9(4)	11.61(13)	11.7(5)	11.7(4)
302.851	29.4(4)	29.5(4)	30.2(11)	29.6(4)	29.6(10)	29.7(6)
356.013	100	100	100	100	100	100
383.848	14.34(26)	14.36(20)	14.6(5)	14.34(18)	14.3(4)	14.3(3)

E_γ (keV) [1]	CRP-17 [22]	CRP-18 [22]	CRP-19 [22]	Evaluated
53.162	3.53(5)	3.53(6)	3.62(6)	3.45(5)
79.614	—	4.05(8)	4.15(12)	4.27(8)[b]
80.998	—	55.1(9)	55.8(9)	53.1(5)[c]
276.399	11.61(12)	11.49(21)	11.57(17)	11.54(7)[b]
302.851	29.7(3)	29.4(6)	29.5(4)	29.55(18)[b]
356.013	100	100	100	100
383.848	14.53(13)	14.51(22)	14.40(20)	14.41(9)[b]

[a] Rejected value.
[b] Least uncertainty of experimental values.
[c] The adopted value has been changed slightly from the weighted average in order to achieve a precise balance of the ground state intensity. Such a small change for one γ ray supports the adopted experimental value of 0.6205(19) for the absolute emission probability of the 356 keV γ ray, and confirms the decay scheme. The adopted uncertainty of 0.5 is external.

Comments:

Relative γ ray emission probabilities have been measured as part of a cooperative exercise involving 15 laboratories [22], and denoted as 'CRP' in the above table); weighted mean data were derived in conjunction with the other listed measurements.

Absolute γ ray emission probabilities have been computed from the evaluated relative emission probabilities and the absolute emission probability of the 356.01 keV γ ray. The latter has been obtained as a result of the international intercomparison reported in Ref. [22].

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{139}Ce

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA) and E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), September 1996.

Recommended data

Half-life

$T_{1/2}$ = 137.642(20) d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
165.8575(11)[a]	0.7990(4)[b]

[a] From Ref. [1], single γ ray that depopulates the first excited state of ^{139}La.
[b] γ transition assumed to be 100% M1 (% E2 of zero); internal conversion coefficients of α_K = 0.2146(10) and α_{tot} = 0.2516(7) adopted from Ref. [2]: TP(165.86 keV)/[1 + α_{tot}(165.86 keV)]= 0.7990(4).

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
La	L	4.124–6.252	0.120(6)
La	$K\alpha_2$	33.0344(2)	0.225(3)
La	$K\alpha_1$	33.4421(1)	0.412(4)
La	$K\beta_1'$	37.721–38.095	0.1230(18)
La	$K\beta_2'$	38.730–38.910	0.0311(6)

Input data

HALF-LIFE

Half-life (d)	Reference
137.734(91)	[H1]
137.8(2)	[H2]
137.65(3)	[H3]
137.59(4)	[H4]
137.66(4)	[H5]
137.2(4)	[H6]
137.642(20)	

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{141}Ce

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), October 1998.

Recommended data

Half-life

$T_{1/2}$ = 32.503(14) d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
145.4433(14)[a]	0.4829(20)[b]

[a] From Ref. [1].

[b] The number of photons per disintegration has been calculated using the transition probability ($P_{\gamma+ce}$), internal conversion coefficients and atomic data [6]. The γ ray emission probability is the weighted mean of four values (based on absolute activity determinations): 0.4844(41) [2]; 0.482(3) [3]; 0.485(4) [4]; and 0.480(5) [5], to give a weighted mean of 0.4829(20). For more details see Ref. [6].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Pr	L	4.45–6.81	0.0243(10)
Pr	$K\alpha_2$	35.5506(2)	0.0474(11)
Pr	$K\alpha_1$	36.0267(2)	0.0865(12)
Pr	$K\beta_1'$	40.65–41.05	0.0263(5)
Pr	$K\beta_2'$	41.77–41.97	0.00674(18)

Input data

HALF-LIFE

Half-life (d)	Reference
32.510(24)	[H1]
32.51(10)	[H2]
32.50(3)	[H3]
32.500(13)[a]	[H4]
32.45(13)	[H5]
32.503(14)	

[a] Uncertainty increased to (19) to ensure a weighting factor not greater than 0.50.

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Detailed tables and comments can be found in Refs [6, 7], and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{144}Ce–^{144}Pr

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld and R. Dersch (Physikalisch-Technische Bundesanstalt, Germany), July 2002.

Recommended data

Half-life (^{144}Ce)

$T_{1/2}$ = 285.1(6) d

SELECTED GAMMA RAYS

Parent	E_γ (keV)	P_γ per decay
^{144}Ce	33.568(10)	0.00235(12)
^{144}Ce	40.98(10)	0.0041(25)
^{144}Ce	80.12(5)	0.0152(10)
^{144}Ce	133.515(4)	0.1109(16)
^{144}Pr	696.505(4)	0.01342(14)
^{144}Pr	1489.148(3)	0.00296(5)
^{144}Pr	2185.645(5)	0.00680(18)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Pr	L	4.45–6.81	0.0142(14)
Pr	$K\alpha_2$	35.5506(3)	0.0256(11)
Pr	$K\alpha_1$	36.0267(4)	0.0469(19)
Pr	$K\beta_1'$	40.65–41.05	0.0141(6)
Pr	$K\beta_2'$	41.77–41.97	0.00360(15)

Emission probabilities per decay of KX rays were calculated from the data set described in Ref. [21].

Input data

HALF-LIFE

Half-life (d)	Reference
286.14(9)	[H1]
284.558(38)[a]	[H2]
284.45(15)	[H3]
285.8(1)	[H4]
284.8(3)	[H5]
284.9(8)	[H6]
285.1(6)	

[a] Uncertainty increased to (60) to ensure a weighting factor not greater than 0.50.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES OF ^{144}Ce

E_γ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]
33.6	2.0(5)	2.3(3)	1.4(5)	2.62(19)	—	—
41.0	4.4(15)	5(4)	4.6(23)	3.6(5)	—	—
80.1	14.8(13)	16(2)	14.3(14)	10.2(11)	15.0(4)	13.4(9)
133.5	≡100	100	100	100	100	100

E_γ (keV) [1]	[8]	[9]	[10]	Evaluated [21]
33.6	2.14(17)	1.77(26)	1.8(2)	2.12(10)
41.0	3.76(65)	3.22(22)	1.38(20)	3.7(23)
80.1	13.6(10)	12.6(10)	12.25(51)	13.7(13)
133.5	100	100	100	100

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES OF ^{144}Pr

E_γ (keV) [1]	[11]	[12]	[13]	[14]	[15]	[16]
696.5	≡100	100	100	100	100	100
1489.1	20	17(2)	19.5(2)	20.2(21)	17.7(5)	22(2)
2185.6	51	50(5)	46(7)	49.5(50)	48(9)	64(6)

E_γ (keV) [1]	[4]	[17]	[6]	[7]	[18]	[19]
696.5	100	100	100	100	100	100
1489.1	19.5(14)	20.7(3)	20(4)	20.27(21)	21.8(9)	19.9(2)
2185.6	49.5(4)	51.7(10)	49.9(10)	52.3(7)	55.7(22)	51.5(7)

E_γ (keV) [1]	[20]	Evaluated [21]
696.5	100	100
1489.1	22.0(12)	22.1(24)
2185.6	56.1(25)	50.7(12)

Comments:

Evaluated emission probabilities are the weighted averages calculated according to the limitation of relative statistical weights method; no value has a relative weighting factor greater than 0.50.

Absolute emission probabilities for the γ rays with energies of 133.5 keV (from ^{144}Ce decay) and 696.5 keV (from ^{144}Pr decay) were obtained from Ref. [17], with values of 0.1109(16) and 0.01342(14), respectively. All absolute emission probabilities are given per decay of ^{144}Ce by considering ^{144}Ce and ^{144}Pr to be in equilibrium.

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Detailed tables and comments can be found in Refs [21, 22], and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{153}Sm

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA) and E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), September 2001.

Recommended data

Half-life

$T_{1/2}$ = 1.938(10) d

SELECTED GAMMA RAYS

E_γ (keV)[a]	P_γ per decay
69.67301(18)	0.0473(3)
83.36716(17)	0.00192(7)
89.48593(21)	0.00158(15)
97.43095(17)	0.00772(18)
103.18007(13)	0.293(3)
172.85295(21)	0.000737(20)

[a] From Ref. [1].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Eu	L	5.18–8.03	0.1004(15)
Eu	$K\alpha_2$	40.9024	0.163(3)
Eu	$K\alpha_1$	41.5427	0.293(4)
Eu	$K\beta_1'$	46.90–48.27	0.0920(14)
Eu	$K\beta_2'$	48.39–48.50	0.0236(11)

Input data

HALF-LIFE

Half-life (d)	Reference
1.9284(29)	[H1]
1.92854(17)	[H2]
1.928554(58)[a]	[H3]
1.9458(21)	[H4]
1.9479(38)	[H5]
1.950(4)	[H6]
1.938(10)	

[a] Uncertainty increased to (170) to ensure a weighting factor not greater than 0.50.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[2]	[3]	[4]	[5]	[6]	[7]
69.6	17.3(10)	—	16.2(14)	16.26(21)	16.2(5)	16.39(18)
75.4	0.61(4)	—	1.10(12)	1.17(5)	0.55(2)	75.5(23)
83.3	0.75(4)	—	0.63(6)	0.68(4)	0.63(2)	6.95(20)
89.4	0.58(3)	—	0.32(4)	—	0.59(2)	—
97.4	2.63(13)	—	2.33(20)	2.84(4)	2.55(4)	2.79(6)
103.1	≡100.0	100	100	100	100	100
172.8	0.21(2)	0.24(5)	0.28(3)	0.270(4)	0.250(4)	0.253(11)

E_γ (keV)	[8]	Evaluated
69.6	15.91(17)	16.18(11)
75.4	0.80(7)	0.66(9)
83.3	0.72(4)	0.655(25)
89.4	0.534(24)	0.54(5)
97.4	2.583(24)	2.64(6)
103.1	100.0	100.0
172.8	0.2450(24)	0.252(7)

Comments:

Evaluated emission probabilities are the weighted averages calculated according to the limitation of relative statistical weights method; no value has a relative weighting factor greater than 0.50.

Relative emission probability data for the 75.4 keV γ transition are discrepant; therefore, this γ ray has been removed from the recommended list of data.

Absolute emission probabilities have been measured for several γ rays [6, 8, 9]; average values from these references are P_γ(69 keV) = 0.0470(5) and P_γ(103 keV) = 0.2926(32). The above relative emission probabilities have been normalized to P_γ(103 keV) = 0.2926(32) (which was subsequently redefined as 0.293(3)).

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{152}Eu

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by V.R. Vanin, R.M. Castro (Universidade de São Paulo, Brazil) and E. Browne (Lawrence Berkeley National Laboratory, USA), October 2001; cut-off date: August 2000.

Recommended data

Half-life

$T_{1/2}$ = 4941(7) d

SELECTED GAMMA RAYS

Decay mode (daughter)	E_γ (keV)	P_γ per decay
ε (^{152}Sm)	121.7817(3)	0.2841(13)
ε (^{152}Sm)	244.6974(8)	0.0755(4)
β^- (^{152}Gd)	344.2785(12)	0.2658(12)
β^- (^{152}Gd)	411.1165(12)	0.02237(10)
ε (^{152}Sm)	443.965(3)[a]	0.03125(14)
β^- (^{152}Gd)	778.9045(24)	0.1296(6)
ε (^{152}Sm)	867.380(3)	0.04241(23)
ε (^{152}Sm)	964.072(18)[a]	0.1462(6)
ε (^{152}Sm)	1085.837(10)	0.1013(6)
β^- (^{152}Gd)	1089.737(5)	0.01731(10)
ε (^{152}Sm)	1112.076(3)	0.1340(6)
ε (^{152}Sm)	1212.948(11)	0.01415(9)
β^- (^{152}Gd)	1299.142(8)	0.01632(9)
ε (^{152}Sm)	1408.013(3)	0.2085(9)

[a] Unresolved doublet.

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Sm	L	5.61–7.18	0.130(4)
Sm	$K\alpha_2$	39.5229	0.208(3)
Sm	$K\alpha_1$	40.1186	0.377(5)
Sm	$K\beta_1'$	45.289–45.731	0.1178(19)
Sm	$K\beta_2'$	46.575–46.813	0.0304(8)

Input data

HALF-LIFE

Half-life (d)	Reference
4934.1(23)	[H1]
4948(7)	[H2]
4945.5(23)	[H3]
4944.4(41)	[H4]
4943(4)	[H5]
4792(37)[a]	[H6]
4785(55)[a]	[H7]
4821(110)[a]	[H8]
4941(7)	

[a] Rejected as an outlier.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[3]	[4]	[5]	[6]	[7]	[8]
121.7817(3)	145.0(41)	138.5(64)	132.9(40)	144.6(47)	141.0(40)	140.6(28)
244.6974(8)	39.4(13)	36.2(18)	35.8(10)	36.4(12)	36.6(11)	35.8(6)
344.2785(12)	128.2(36)	128.2(59)	128.2(38)	128.2(42)	127.2(13)	128.2(26)
411.1165(12)	10.14(54)	10.32(51)	10.77(38)	10.59(27)	10.71(11)	10.55(22)
443.965(3)[b]	—	13.2(8)	13.5(5)	13.6(8)	—	—
443.965(3)[b]	—	1.15(38)	1.67(26)	1.28(26)	—	—
443.965(3)[c]	15.47(33)	14.36(86)	15.13(57)	14.87(81)	15.00(15)	14.95(13)
778.9045(24)	—	59.7(29)	62.6(14)	59.9(7)	62.6(6)	62.5(12)
867.380(3)	—	19.23(90)	20.09(49)	19.31(35)	20.54(21)	20.29(51)
963.390(12)	—	—	0.628(103)	0.487(103)	—	—
964.072(18)[d]	—	67.44(333)	69.86(179)	68.08(179)	70.40(70)	70.45(141)
1085.837(10)	—	47.69(282)	50.64(154)	47.59(86)	48.70(50)	49.62(128)
1089.737(5)	—	8.00(64)	8.46(77)	7.90(37)	8.26(9)	8.59(26)
1109.178(12)	—	—	0.897(385)	0.808(179)	—	—
1112.076(3)[e]	—	63.59(321)	65.77(185)	63.99(87)	65.00(70)	65.64(128)
1112.076(3)	—	—	64.87(179)	63.18(86)	—	—
1212.948(11)	—	6.55(35)	7.05(26)	6.74(26)	6.67(7)	6.72(14)
1299.142(8)	—	7.71(40)	8.23(41)	7.88(44)	7.76(8)	7.97(19)
1408.013(3)	—	99.5(50)	103.6(27)	97.7(28)	100.0(10)	99.9(19)

E_γ (keV) [1]	[9]	[10]	[11]	[12]	[13]	[14]
121.7817(3)	136.99(13)	136.7(7)	139.0(10)	136.2(16)	136.6(18)	133.5(18)
244.6974(8)	36.2(3)	36.5(4)	36.5(3)	35.9(6)	38.0(5)	—
344.2785(12)	127.1(7)	126.9(9)	128.2(8)	127.5(9)	128.2(17)	128.2(18)
411.1165(12)	10.84(7)	10.73(10)	10.80(10)	10.70(10)	10.82(15)	10.72(23)
443.965(3)[b]	—	—	—	—	—	—
443.965(3)[b]	—	—	—	—	—	—
443.965(3)[c]	15.01(11)	14.81(13)	14.90(20)	14.80(20)	15.06(22)	15.18(22)
778.9045(24)	62.16(22)	62.1(5)	62.2(4)	61.9(8)	62.1(9)	62.5(13)
867.380(3)	20.33(10)	20.36(17)	20.40(30)	19.90(40)	20.33(27)	20.45(42)
963.390(12)	—	—	—	—	—	—
964.072(18)[d]	70.14(23)	71.03(40)	70.50(60)	69.20(90)	69.67(95)	70.50(149)
1085.837(10)	48.15(16)	47.84(31)	49.60(40)	48.70(80)	49.19(67)	49.60(94)
1089.737(5)	8.35(4)	8.19(10)	—	8.20(10)	7.97(51)	8.19(17)
1109.178(12)	1.000(50)	—	—	0.880(20)	—	—
1112.076(3)[e]	65.67(22)	65.45(78)	65.90(50)	65.80(90)	65.23(99)	62.47(112)
1112.076(3)	64.67(21)	—	—	64.90(9)	—	—
1212.948(11)	6.85(5)	—	6.83(5)	6.70(8)	6.97(18)	6.85(15)
1299.142(8)	7.80(5)	—	7.88(6)	7.80(10)	7.94(19)	8.08(36)
1408.013(3)	100.0(3)	100.0(6)	100.0(5)	100.0(3)	99.2(11)	102.6(14)

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

E_γ (keV) [1]	[15][a]	[17]	[18]	[19]	[20]	[21]
121.7817(3)	136.9(39)	135.0(19)	135.7(8)	136.4(5)	131.5(43)	135.8(9)
244.6974(8)	36.8(9)	35.5(5)	35.5(3)	36.3(2)	36.2(10)	35.9(5)
344.2785(12)	128.2(29)	128.9(15)	127.2(8)	127.4(6)	123.9(28)	127.6(4)
411.1165(12)	10.70(29)	10.46(16)	10.67(7)	10.80(6)	10.27(22)	10.75(4)
443.965(3)[b]	—	—	—	—	—	—
443.965(3)[b]	—	—	—	—	—	—
443.965(3)[c]	13.78(39)	14.68(21)	14.84(9)	14.96(7)	14.35(4)	15.07(6)
778.9045(24)	63.7(14)	62.4(8)	62.6(4)	62.25(19)	—	62.12(23)
867.380(3)	20.92(48)	—	—	—	—	—
963.390(12)	—	—	—	—	—	—
964.072(18)[d]	67.96(193)	69.62(84)	69.82(42)	70.10(23)	—	70.41(22)
1085.837(10)	47.96(106)	48.89(59)	48.61(29)	49.13(19)	47.43(60)	48.83(14)
1089.737(5)	8.19(19)	—	—	—	—	—
1109.178(12)	—	—	—	—	—	—
1112.076(3)[e]	—	—	—	—	—	—
1112.076(3)	—	64.28(77)	64.45(32)	65.25(27)	64.00(80)	65.26(20)
1212.948(11)	6.70(19)	—	—	—	—	—
1299.142(8)	—	—	—	—	—	—
1408.013(3)	—	100.0(12)	100.0(5)	100.0(3)	100.0(15)	100.0(3)

E_γ (keV) [1]	[22]	[23]	[24]	[25]	[26]	[27]
121.7817(3)	—	133.4(14)	—	139.2(29)	137.0(10)	—
244.6974(8)	—	36.3(3)	36.7(11)	—	35.7(4)	35.7(4)
344.2785(12)	130.6(29)	130.4(12)	127.1(11)	—	127.2(10)	126.7(11)
411.1165(12)	10.77(12)	10.90(12)	10.71(11)	10.90(23)	10.72(10)	10.90(33)
443.965(3)[b]	—	—	—	—	—	—
443.965(3)[b]	—	—	—	—	—	—
443.965(3)[c]	15.25(12)	15.33(18)	14.88(15)	15.3(26)	14.95(13)	14.73(43)
778.9045(24)	62.6(4)	62.4(12)	62.6(6)	61.8(12)	61.9(4)	61.1(9)
867.380(3)	—	—	—	—	—	—
963.390(12)	—	—	—	—	—	—
964.072(18)[d]	70.40(60)	69.80(90)	70.30(70)	69.90(100)	70.30(40)	70.90(100)
1085.837(10)	49.10(40)	47.90(60)	48.70(50)	48.90(50)	48.40(30)	—
1089.737(5)	—	—	—	—	—	—
1109.178(12)	—	—	—	—	—	—
1112.076(3)[e]	—	—	—	—	—	—
1112.076(3)	65.70(70)	64.70(40)	64.30(60)	66.70(80)	64.90(50)	67.20(90)
1212.948(11)	—	—	—	—	—	—
1299.142(8)	—	—	—	—	—	—
1408.013(3)	100.0(9)	100.0(9)	100.0(10)	100.0(12)	100.0(5)	100.0(12)

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

E_γ (keV) [1]	[28]	[29]	[30]	[31]	[32]	[33]
121.7817(3)	136.4(30)	132.5(29)	134.8(20)	136.8(41)	135.5(20)	138.9(43)
244.6974(8)	—	36.3(7)	36.4(4)	37.9(12)	35.6(5)	—
344.2785(12)	126.2(34)	128.9(24)	128.8(13)	132.7(40)	126.6(13)	133.9(55)
411.1165(12)	10.62(67)	10.72(26)	10.86(12)	11.21(39)	10.52(14)	11.18(53)
443.965(3)[b]	—	—	—	—	—	—
443.965(3)[b]	—	—	—	—	—	—
443.965(3)[c]	14.64(89)	15.15(32)	15.22(15)	—	14.89(19)	16.15(73)
778.9045(24)	61.0(10)	62.0(10)	62.4(5)	61.2(19)	61.3(7)	64.2(21)
867.380(3)	—	—	—	—	—	—
963.390(12)	—	—	—	—	—	—
964.072(18)[d]	69.30(100)	68.40(110)	70.10(50)	69.80(220)	70.00(80)	71.20(230)
1085.837(10)	48.50(90)	—	48.59(30)	50.70(150)	48.00(50)	50.00(120)
1089.737(5)	—	—	—	—	—	—
1109.178(12)	—	—	—	—	—	—
1112.076(3)[e]	—	—	—	—	—	—
1112.076(3)	64.50(110)	65.50(100)	65.30(50)	64.70(200)	65.40(80)	66.50(150)
1212.948(11)	—	—	—	—	—	—
1299.142(8)	—	—	—	—	—	—
1408.013(3)	100.0(15)	100.0(23)	100.0(7)	100.0(30)	100.0(10)	100.0(29)

E_γ (keV) [1]	[34]	Evaluated [36][f]
121.7817(3)	134.9(12)	136.35(25)
244.6974(8)	36.4(2)	36.23(8)
344.2785(12)	126.4(9)	127.53(20)
411.1165(12)	10.57(8)	10.735(20)
443.965(3)[b]	—	13.46(9)
443.965(3)[b]	—	1.53(9)
443.965(3)[c]	14.81(16)	14.99(3)
778.9045(24)	62.0(5)	62.17(9)
867.380(3)	—	20.35(7)
963.390(12)	—	0.644(14)
964.072(18)[d]	69.90(50)	69.55(10)
1085.837(10)	—	48.63(20)
1089.737(5)	—	8.30(3)
1109.178(12)	—	0.892(18)
1112.076(3)[e]	—	65.19(9)
1112.076(3)	64.20(70)	64.30(9)

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

E_γ (keV) [1]	[34]	Evaluated [36][f]
1212.948(11)	—	6.79(3)
1299.142(8)	—	7.83(3)
1408.013(3)	100.0(12)	100.00(12)

[a] Evaluators considered the precision of the values given in Ref. [15] as unwarranted; these uncertainties have been doubled.
[b] Components of an unresolved doublet assigned an energy of 443.965(3) keV from Ref. [2].
[c] Relative emission probability is the sum of the components of the unresolved doublet.
[d] Weighted average energy of an unresolved doublet of energies 963.390(12) and 964.079(18) keV from Ref. [2]; relative emission probability is the sum of the components.
[e] Relative emission probability includes the contribution from the weakest component of the doublet.
[f] Upper detection limits of Ref. [35] were taken into account when evaluating the full decay scheme.

Comments:

Evaluated relative emission probabilities are the weighted averages calculated according to the limitation of relative statistical weights method; no value has a relative weighting factor greater than 0.50.

These relative emission probabilities have been normalized to P_γ(1408 keV) = 0.2085(9), which was determined from an intercomparison of measured absolute emission probabilities produced by participants from various laboratories and coordinated by the ICRM [16].

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^{154}Eu

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by V.P. Chechev and N.K. Kuzmenko (V.G. Khlopin Radium Institute, Russian Federation), December 2002.

Recommended data

Half-life

$T_{1/2}$ = 3138.1(14) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
123.0706(9)[a]	0.404(5)
247.9288(7)[a]	0.0689(7)
591.755(3)[a]	0.0495(5)
692.4205(18)[a]	0.0179(3)
723.3014(22)[a]	0.2005(21)
756.8020(23)[a]	0.0453(5)
873.1834(23)[a]	0.1217(12)
996.262(6)[b]	0.1050(10)
1004.725(7)[b]	0.1785(17)
1246.121(4)[a]	0.00862(8)
1274.429(4)[a]	0.349(3)
1596.4804(28)[a]	0.01783(17)

[a] From Ref. [1].
[b] Averaged experimental data [2–4].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Gd	L	5.36–8.10	0.071(3)
Gd	$K\alpha_2$	42.3093	0.072(2)
Gd	$K\alpha_1$	42.9967	0.130(3)
Gd	$K\beta_1'$	48.556–49.053	0.041(1)
Gd	$K\beta_2'$	49.961–50.219	0.0108(3)

Input data

HALF-LIFE

Half-life (d)	Reference
3138.1(11)[a]	[H1]
3138.2(61)	[H2]
3138(2)	[H3]
3105(183)	[H4]
3138.1(14)	

[a] Uncertainty increased to (19) to ensure a weighting factor not greater than 0.50.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[5]	[6]	[7]	[8]	[9]
123.071	–	116(6)	–	–	118.5(13)
247.929	–	20.1(10)	20.51(20)	20.51(20)	19.91(14)
591.755	14.44(31)	14.8(8)	13.62(24)	13.62(24)	14.35(6)
692.420	5.07(13)	4.97(30)	4.86(8)	4.86(8)	5.182(29)
723.301	56.5(12)	60.1(31)	55.40(41)	55.40(41)	58.19(27)
756.802	12.71(23)	12.9(6)	12.51(11)	12.51(11)	13.18(8)
873.183	33.72(75)	34.8(17)	33.6(25)	33.6(25)	35.18(16)
996.26	29.39(71)	29.4(15)	29.7(21)	29.7(21)	30.09(15)
1004.72	50.4(11)	50.6(25)	50.93(32)	50.93(32)	52.04(25)
1246.12	2.54(7)	2.40(22)	2.35(5)	2.35(5)	2.49(4)
1274.43	≡100	100	100	100	100
1596.48	–	5.15(26)	5.19(8)	5.19(8)	5.247(30)

E_γ (keV) [1]	[10]	[11]	[12]	[4]	[2]
123.071	111.7(16)	122.1(36)	117.0(11)	114.1(20)	116.5(12)
247.929	19.615(98)	23.04(59)	19.82(16)	19.72(32)	19.8(2)
591.755	14.05(14)	15.84(66)	14.19(11)	14.14(15)	14.21(11)
692.420	5.14(5)	5.75(15)	–	5.10(9)	5.09(4)
723.301	57.23(46)	64.9(21)	57.6(4)	57.2(6)	57.3(4)
756.802	12.89(13)	13.61(20)	–	12.99(15)	12.9(11)
873.183	34.66(21)	35.7(13)	34.95(31)	34.65(30)	34.81(28)
996.26	30.87(12)	31.0(19)	29.9(3)	30.14(30)	29.78(23)
1004.72	52.05(31)	54.84(225)	51.9(5)	51.8(6)	51.55(40)
1246.12	2.52(5)	2.51(12)	–	2.48(3)	2.449(23)
1274.43	100	100	100	100	100
1596.48	5.237(84)	4.54(18)	5.08(5)	5.13(8)	5.078(40)

E_γ (keV) [1]	[13]	[3]	[14]	Evaluated
123.071	115.6(15)	113.0(15)	115.4(7)	115.9(8)
247.929	19.65(44)	19.5(2)	19.857(93)	19.76(9)
591.755	14.18(31)	14.0(14)	14.338(117)	14.18(7)
692.420	5.13(12)	5.04(5)	5.085(59)	5.12(3)
723.301	57.78(89)	56.9(6)	58.107(276)	57.46(25)
756.802	13.02(24)	12.8(2)	13.035(127)	12.98(8)
873.183	35.01(44)	34.5(4)	34.342(266)	34.87(9)
996.26	30.29(51)	29.9(3)	29.206(269)	30.1(1)
1004.72	52.07(89)	51.6(4)	51.233(276)	51.17(13)
1246.12	2.45(8)	2.48(2)	2.403(48)	2.470(11)
1274.43	100	100	100	100
1596.48	5.12(17)	5.08(5)	5.083(22)	5.11(3)

Comments:

Gamma ray energies have been adopted from Ref. [1], apart from the 996.26 and 1004.72 keV energies obtained by averaging experimental data [2–4].

Absolute γ ray emission probabilities have been calculated using a normalization factor of 0.003489(34) and the evaluated relative emission probabilities listed in the table. The normalization factor was obtained from an intensity balance of the γ ray transitions (γ + ce) to the ground states of ^{154}Gd and ^{154}Sm, assuming both are not populated directly in the ε and β^- decay of ^{154}Eu to ^{154}Gd and ^{154}Sm, respectively.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{155}Eu

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by V.P. Chechev and V.O. Sergeev (V.G. Khlopin Radium Institute, Russian Federation), October 2001.

Recommended data

Half-life

$T_{1/2}$ = 1736(6) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
26.531(21)	0.00316(22)
45.2990(10)	0.0131(5)
60.0086(10)	0.0122(5)
86.0591(10)	0.00154(17)
86.5479(10)	0.307(3)
105.3083(10)	0.211(6)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Gd	L	5.36–8.10	0.075(5)
Gd	$K\alpha_2$	42.3093	0.0670(13)
Gd	$K\alpha_1$	42.9967	0.1205(23)
Gd	$K\beta_1'$	48.556–49.053	0.0384(11)
Gd	$K\beta_2'$	49.961–50.219	0.0098(3)

Input data

HALF-LIFE

Half-life (d)	Reference
1739(8)	[H1]
1738.97(49)[a]	[H2]
1709(18)	[H3]
1655(51)[b]	[H4]
1812(4)[b]	[H5]
1698(73)	[H6]
1736(6)	

[a] Uncertainty increased to (730) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1–10]	[1]	[14]	[15]	[3]	[4]	[13]
26.53	≈4[a]	—	≈1[a]	1.03(6)[a]	—	1.00(10)
45.299	2.3[a]	—	2.8(7)[a]	4.18(17)[a]	3.6(7)	4.1(3)
60.009	4.0[a]	5.1(20)[a]	3.8(2)	3.60(10)[a]	4.3(3)	3.9(9)
86.059	—	—	0.50(5)	—	0.49(5)	—
86.548	≡100	100	100	100	100	100
105.308	64[a]	65.7(65)	67.9(35)	66.8(27)[a]	68.3(27)	68(4)

E_γ (keV) [1–10]	[7]	[9]	[12]	[16]	Evaluated
26.53	1.10(13)	1.03(6)	—	—	1.03(6)
45.299	3.95(40)	4.21(20)	4.36(12)	4.3(10)	4.27(12)
60.009	3.8(4)	3.60(10)	3.99(12)	3.9(9)	3.96(12)
86.059	0.54(11)	—	—	—	0.50(5)
86.548	100	100	100	100	100
105.308	69.9(35)	66.8(27)	68.5(14)	69.5(16)	68.8(14)[b]

[a] Value rejected; no quoted uncertainty.
[b] Value of 69.1(9) from Ref. [17] has also been included in the analysed data set.

Comments:

Gamma ray energies have been obtained by averaging the experimental data [1–10].

Absolute emission probability of the 86.55 keV γ ray was obtained by averaging the experimental data of 0.311(4) [11] and 0.305(3) [12] to give a value of 0.307(3). The resulting normalization factor of 0.00307(3) and the relative emission probabilities listed above were used to calculate the absolute emission probabilities of the γ rays.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{166}Ho

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), March 1999.

Recommended data

Half-life

$T_{1/2}$ = 1.1165(13) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
80.576(2)	0.0655(8)
1379.437(6)	0.00933(16)
1581.833(7)	0.00186(4)
1662.439(6)	0.00118(5)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Er	L	6.15–9.43	0.076(4)
Er	$K\alpha_2$	48.2215(3)	0.0291(10)
Er	$K\alpha_1$	49.1282(4)	0.0516(17)
Er	$K\beta_1'$	55.50–56.04	0.0168(6)
Er	$K\beta_2'$	57.21–57.46	0.00436(18)

Input data

HALF-LIFE

Half-life (d)	Reference
1.11526(18)[a]	[H1]
1.11779(21)	[H2]
1.1250(17)[b]	[H3]
1.1163(13)	[H4]
1.1165(13)	

[a] Uncertainty increased to (21) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

REFERENCES — HALF-LIFE

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[1]	Evaluated
80.6	6.67(43)	—	7.04(30)	6.72(70)	7.22(8)	6.56(40)	7.02(14)
1379.4	≡1	1	1	1	1	1	1
1581.8	0.206(10)	0.195(10)	0.215(10)[a]	0.197(7)	0.199(5)	0.197(5)	0.1994(28)
1662.4	0.129(7)	0.125(6)	0.099(5)[a]	0.130(5)	0.127(4)	0.130(2)[b]	0.126(5)

[a] Classified as an outlier.
[b] Uncertainty increased slightly.

Evaluated emission probabilities are the weighted averages calculated according to the limitation of relative statistical weights method; no value has a relative weighting factor greater than 0.50.

The absolute emission probability (per disintegration) of 80.6 keV γ ray was determined from the following data: 0.0655(30) [4]; 0.0625(60) [5]; 0.0660(40) [7]; and 0.0655(8) [8, 9]. A value of 0.0655(8) [10, 11] has been adopted that was combined with the relative emission probability of the 80.6 keV transition to give a normalization factor of 0.00933(16).

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Detailed tables and comments can be found in Refs [10, 11], and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{166m}Ho

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), July 1999.

Recommended data

Half-life

$T_{1/2} = 4.4(7) \times 10^5$ d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
80.5725(13)	0.1266(23)
184.4107(11)	0.725(5)
215.871(7)	0.0266(17)
259.736(10)	0.01078(10)
280.4630(23)	0.2954(25)
300.741(3)	0.0373(4)
365.768(6)	0.0246(4)
410.956(3)	0.1135(18)
451.540(4)	0.02915(14)
464.798(6)	0.0125(4)
529.825(4)	0.094(4)
570.995(5)	0.0543(20)
611.579(6)	0.0131(21)
670.526(4)	0.0534(21)
691.253(7)	0.0132(7)
711.697(3)	0.549(12)
752.280(4)	0.122(3)
810.286(4)	0.573(11)
830.565(4)	0.0972(18)
950.988(4)	0.02744(19)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Er	L	6.15–9.43	0.201(9)
Er	$K\alpha_2$	48.2215(3)	0.1071(18)
Er	$K\alpha_1$	49.1282(4)	0.190(3)
Er	$K\beta_1'$	55.50–56.04	0.0617(12)
Er	$K\beta_2'$	57.21–57.46	0.0161(5)

Input data

HALF-LIFE

Half-life (d)	Reference
$4.4(7) \times 10^5$	[H1]
$4.4(7) \times 10^5$	

Comment: only one published half-life measurement.

REFERENCE — HALF-LIFE

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]
80.6	14.5(29)	14.55(47)	17.1(9)	14.48(48)	16.83(42)	16.7(10)
184.4	≡100	100	100	100	100	100
215.9	3.8(4)	4.15(7)	3.6(4)	3.94(9)	3.96(8)	4.1(2)[b]
259.7	1.8(5)[a]	1.42(10)	1.50(11)	1.77(12)[a]	1.52(5)	—
280.5	39.5(28)	43.6(6)[a]	40.7(29)	38.61(46)	39.63(126)	40.2(18)
300.7	4.8(4)	5.45(8)	5.12(37)	4.77(9)	4.92(12)	4.97(22)
365.7	2.9(3)[a]	3.72(8)	3.44(25)	2.93(6)	3.25(10)	3.30(11)
411.0	15.8(12)	16.8(3)[a]	15.8(12)	15.50(19)	14.77(30)	15.27(50)
451.5	3.5(7)	4.30(9)	4.18(30)	3.48(7)[a]	3.84(13)	3.99(13)
464.9	2.0(4)	1.66(8)	1.68(14)	2.00(7)	1.50(8)	—
529.8	10.3(10)[a]	13.00(42)	13.9(10)	10.16(32)[a]	12.36(25)	12.78(42)
570.9	6.8(7)	7.08(16)	7.86(56)	6.77(14)	7.04(14)	7.45(24)
611.6	1.4(10)	1.59(32)	1.90(15)	1.48(27)	1.67(9)	—
670.6	7.0(7)	7.35(30)	7.88(56)	7.01(25)	6.98(16)	7.37(24)
691.3	1.9(4)	1.62(8)	2.09(15)[a]	1.85(9)	1.60(10)[a]	1.800(59)
711.7	72.5(60)	71.5(10)	80.2(57)[a]	71.65(68)	71.10(142)	74.5(25)
752.3	16.1(12)	15.20(34)[a]	17.9(13)	16.06(40)	15.98(32)	16.57(54)
810.3	76(8)	76.40(110)	85.7 61)[a]	76.38(82)	75.71(151)	78.1(28)
830.6	12.5(10)	12.90(32)	14.5(11)	12.07(28)	12.83(26)	13.26(44)
951.0	3.6(6)	3.16(13)[a]	4.15(30)[a]	3.50(14)[a]	3.74(16)	3.68(12)

E_γ (keV) [1]	[8]	[9]	[10]	[11]	[12]	[13]
80.6	17.51(61)	16.56(8)	17.8(4)	16.97(13)	17.2(8)	16.59(39)
184.4	100	100	100	100	100	100
215.9	3.54(13)	4.04(4)	3.67(9)	3.60(13)	4.14(17)[b]	3.61(13)
259.7	1.446(52)	—	1.53(3)	1.52(3)	1.47(5)	1.50(5)
280.5	40.79(141)	41.26(28)	41.0(5)	40.6(5)	40.4(15)	40.9(8)
300.7	5.12(18)	5.22(4)	5.17(8)	5.11(8)	5.04(19)	5.13(10)
365.7	3.327(117)	3.30(3)	3.49(6)	3.46(6)	3.33(12)	3.44(7)
411.0	15.25(53)	15.65(10)	15.9(2)	15.5(4)	15.3(5)	15.93(28)
451.5	4.02(15)	3.85(5)	4.17(5)	4.04(11)	4.00(14)	4.12(9)
464.9	1.651(61)	—	1.67(3)	1.73(7)	1.59(5)	1.69(6)
529.8	13.10(45)	12.48(10)	13.3(2)	13.18(34)	12.83(39)	13.46(26)
570.9	7.53(27)	7.22(6)	7.65(9)	7.64(20)	7.42(24)	7.81(15)
611.6	1.951(72)	—	1.86(4)	1.86(12)	1.85(7)	1.95(11)

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

E_γ (keV) [1]	[8]	[9]	[10]	[11]	[12]	[13]
670.6	7.37(26)	7.28(6)	7.53(9)	7.16(20)	7.32(22)	7.60(14)
691.3	1.871(69)	—	1.87(4)	1.86(9)	1.79(6)	1.84(5)
711.7	74.48(258)	72.37(39)	75.7(8)	75.33(177)	73.8(32)	76.4(14)
752.3	16.57(56)	16.26(12)	17.0(2)	17.08(43)	16.5(5)	16.98(33)
810.3	78.66(273)	76.94(44)	80.1(8)	79.31(177)	78.2(26)	80.3(12)
830.6	13.34(47)	12.99(10)	13.5(2)	13.51(35)	13.3(4)	13.62(26)
951.0	3.71(14)	3.65(4)	3.89(6)	3.87(12)	3.74(12)	3.85(8)

E_γ (keV) [1]	[14]	[15]	[16]	[17]	[18]	Evaluated
80.6	17.00(22)	16.7(5)	17.6(4)	16.050(120)	17.18(15)	17.46(20)
184.4	100	100	100	100	100	100
215.9	3.594(37)	3.60(9)	3.49(14)	3.447(26)	3.566(85)	3.67(24)
259.7	1.529(34)	1.507(34)	1.45(5)	1.434(25)	1.480(12)	1.487(9)
280.5	41.41(51)	41.8(9)	39.8(9)	40.634(167)	40.66(29)	40.75(21)
300.7	5.339(58)	5.29(12)	4.98(13)	5.079(39)	5.118(36)	5.15(4)
365.7	3.589(45)	3.51(9)	3.34(9)	3.439(47)	3.404(24)	3.39(4)
411.0	16.49(19)	16.02(36)	15.0(4)	15.424(74)	15.81(11)	15.65(22)
451.5	4.235(60)	4.11(10)	3.89(13)	4.023(30)	4.062(42)	4.02(5)
464.9	1.729(35)	1.73(4)	1.66(7)	2.027(31)	1.665(19)	1.73(6)
529.8	13.19(15)	—	12.6(4)	13.380(126)	13.33(10)	13.0(6)
570.9	7.964(91)	—	7.27(23)	7.505(71)	7.71(6)	7.49(27)
611.6	2.097(26)	—	1.86(11)	1.952(60)	1.911(36)	1.81(29)
670.6	7.718(84)	—	6.98(22)	7.618(45)	7.56(6)	7.36(28)
691.3	1.872(40)	—	1.78(9)	1.914(17)	1.862(21)	1.82(10)
711.7	77.51(62)	—	72.0(19)	76.30(35)	76.3(6)	74.7(16)
752.3	17.16(14)	—	16.2(5)	16.973(84)	16.98(12)	16.6(4)
810.3	80.81(59)	—	76.1(20)	80.52(38)	80.3(6)	79.1(14)
830.6	13.87(18)	—	12.9(4)	13.639(79)	13.64(10)	13.41(23)
951.0	3.898(48)	—	3.68(12)	3.789(25)	3.793(30)	3.785(21)

[a] Rejected as an outlier.
[b] 214.8 and 215.8 keV doublet.

Evaluated relative emission probabilities are the weighted averages calculated according to the limitation of relative statistical weights method; no value has a relative weighting factor greater than 0.50. These weighted means are listed in the last column of the table, except P_γ(81 keV) for which a value was derived from a nuclear-level balance calculation [19]. There is only one other transition to the ground state that is very weak (P_γ(786 keV)).

Absolute emission probabilities were calculated from $\Sigma P_{\gamma+ce} = 1.0$ to give a normalization factor of 0.00725(3).

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Detailed tables and comments can be found in Refs [19, 20], and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{170}Tm

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by V.P. Chechev and N.K. Kuzmenko (V.G. Khlopin Radium Institute, Russian Federation), April 2000.

Recommended data

Half-life

$T_{1/2}$ = 127.8(8) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
78.59(2)	0.000034(3)
84.25474(8)	0.0248(9)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Yb	L	6.55–10.14	0.0322(13)
Yb	$K\alpha_2$	51.3541	0.0095(4)
Yb	$K\alpha_1$	52.3887	0.0167(7)
Yb	$K\beta_1'$	59.1593–59.8045	0.0055(3)
Yb	$K\beta_2'$	60.962–61.309	0.00144(7)

Input data

HALF-LIFE

Half-life (d)	Reference
127.10(31)	[H1]
128.6(3)	[H2]
128(1)	[H3]
134.2(8)[a]	[H4]
125(2)	[H5]
127.8(8)	

[a] Rejected as an outlier.

REFERENCES — HALF-LIFE

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Gamma rays: Energies and measured emission probabilities

Comments:

— Gamma ray energies of 78.59 and 84.25 keV have been adopted from Refs [1] and [2], respectively.
— The absolute emission probability of the 84.25 keV γ ray has been obtained by averaging the experimental data of 0.0254(6) [3], 0.0256(4) [4] and 0.0237(4) [5].

— The absolute emission probability of the 78.59 keV γ ray was obtained by averaging the results of measurements of the ratio of emission probabilities: P_γ(78.59 keV)/ P_γ(84.25 keV) of 0.00122(24) [6], 0.0015(2) [7] and 0.00140(8) [8].

X rays: measured emission probabilities

Absolute XK(Yb), XL(Yb) emission probabilities have been computed using the ratio of emission probabilities P_X/P_γ(84.25 keV) determined in Refs [7, 8]. Measured results of Ref. [9] for

XK(Yb) [$K\alpha_2$ – 1.00(2), $K\alpha_1$ – 1.69(4), $K\beta_1'$ – 0.54(2), $K\beta_2'$ – 0.14(1)]

agree with the adopted values [10, 11].

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Detailed tables and comments can be found in Refs [10, 11] and on
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{169}Yb

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by M.-M. Bé (Commissariat l'Énergie Atomique, France) and E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), March 2001.

Recommended data

Half-life

$T_{1/2}$ = 32.016(6) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
63.12044(4)	0.4405(24)
93.61447(8)	0.02571(17)
109.77924(4)	0.1736(9)
118.18940(14)	0.01870(10)
130.52293(6)	0.1138(5)
177.21307(6)	0.2232(10)
197.95675(7)	0.3593(12)
261.07712(9)	0.01687(8)
307.73586(10)	0.10046(45)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Tm	L	6.34–9.78	0.494(8)
Tm	$K\alpha_2$	49.773	0.529(8)
Tm	$K\alpha_1$	50.742	0.935(13)
Tm	$K\beta_1'$	57.304–57.925	0.306(6)
Tm	$K\beta_2'$	59.100–59.357	0.0795(21)

Emission probabilities of X rays were calculated from the data set described in Ref. [2]; they are in good agreement with measured values.

Input data

HALF-LIFE

Half-life (d)	Reference
32.001(34)	[H1]
32.0147(93)	[H2]
31.88(45)[a]	[H3]
32.032(2)	[H4]
32.015(9)	[H5]
32.022(8)	[H6]
31.97(2)	[H7]
32.016(6)	

[a] Rejected as an outlier.

REFERENCES — HALF-LIFE

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[3]	[3]	[3]	[3]	[3]	[3]
63.12044(4)	122.7(14)	115.9(29)	123.5(31)	123(6)	121.4(39)	121.4(15)
93.61447(8)	7.12(9)	6.86(16)	7.28(21)	7.05(32)	6.87(24)	7.44(15)
109.77924(4)	47.97(42)	46.0(9)	48.8(11)	47.2(21)	46.1(16)	48.9(11)
118.18940(14)	—	5.17(12)	—	5.33(25)	5.15(18)	5.13(9)
130.52293(6)	31.56(25)	31.2(6)	32.4(7)	31.4(14)	31.2(10)	30.7(6)
177.21307(6)	61.92(49)	61.9(13)	62.7(16)	62.6(28)	62.2(19)	63.1(8)
197.95675(7)	100.0(7)	100.0(20)	100.0(25)	100.0(44)	100.0(30)	100.0(16)
261.07712(9)	4.643(40)	4.65(10)	4.84(12)	4.60(20)	4.70(18)	5.00(9)[a]
307.73757(9)	27.95(18)	27.4(6)	28.5(6)	28.1(12)	28.3(9)	29.67(46)[a]

E_γ (keV) [1]	[3]	[3]	[4]	[5]	[6]	[7]
63.12044(4)	123.3(8)	121.2(33)	121(3)	116(6)	124.2(24)	124.9(17)
93.61447(8)	7.195(41)	6.72(18)	6.5(3)	7.1(4)	7.22(15)	7.28(10)
109.77924(4)	48.46(31)	48.3(10)	47.4(15)	48.5(15)	48.6(9)	48.9(5)
118.18940(14)	5.205(34)	—	4.94(26)[a]	5.31(16)	5.17(9)	5.24(5)
130.52293(6)	31.81(16)	32.4(7)	30.7(13)	32.0(10)	31.3(5)	31.68(25)
177.21307(6)	61.95(36)	62.4(13)	63(4)	62.2(19)	62.3(11)	62.4(5)
197.95675(7)	100.0(6)	100.0(21)	≡100	100(3)	≡100	100.0(8)
261.07712(9)	4.654(46)	4.73(13)	4.8(5)	4.69(14)	4.67(11)	4.75(3)
307.73757(9)	28.01(14)	28.2(6)	28.3(11)	27.5(8)	28.1(8)	27.94(20)

E_γ (keV) [1]	[8]	[9]	[10]	Evaluated [2]
63.12044(4)	120(3)	120(5)	—	122.6(5)
93.61447(8)	7.31(13)	6.6(5)	7.01(9)	7.156(40)
109.77924(4)	49.0(7)	47.1(10)	48.80(57)	48.33(18)
118.18940(14)	5.26(8)	5.13(10)	5.18(7)	5.204(22)

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

E_γ (keV) [1]	[8]	[9]	[10]	Evaluated [2]
130.52293(6)	31.7(5)	31.6(10)	31.60(36)	31.67(10)
177.21307(6)	61.7(11)	62.2(10)	61.89(71)	62.13(20)
197.95675(7)	≡100	≡100	100.00(79)	100.00(33)
261.07712(9)	4.66(7)	4.66(10)	4.69(5)	4.695(17)
307.73757(9)	27.5(4)	27.1(10)	28.09(32)	27.96(9)

[a] Omitted due to large deviation from mean.

Comments:

- Euromet exercise [3]: Arbitrary code numbers were assigned to the participants; these data are listed as relative values, although quoted absolutely in the original study. Some participants have published their results elsewhere; however, these publications have not been quoted as independent references in this evaluation.
- Absolute emission probability of the 197.9 keV γ ray is the weighted mean of the measured values: 0.3626(18); 0.373(5); 0.357(6); 0.363(11); 0.359(8); 0.3549(39); 0.3606(15); 0.359(5); 0.360(5); 0.3514(28); and 0.355(4) (see also Ref. [2]).

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Detailed tables and comments can be found in Ref. [2] and on
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{192}Ir

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Browne (Lawrence Berkeley National Laboratory, USA), March 1997.

Recommended data

Half-life

$T_{1/2}$ = 73.822(9) d

SELECTED GAMMA RAYS

E_γ (keV)[a]	P_γ per decay
205.79430(9)	0.0334(4)
295.95650(15)	0.2872(14)
308.45507(17)	0.2968(15)
316.50618(17)	0.8275(21)
468.06885(26)	0.4781(24)
484.5751(4)	0.03189(24)
588.5810(7)	0.04517(22)
604.41105(25)	0.0820(4)
612.46215(26)	0.0534(8)

[a] From Ref. [1].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Os	L	7.82–12.92	0.01525(25)
Os	$K\alpha_2$	61.4873(7)	0.01211(25)
Os	$K\alpha_1$	63.0011(6)	0.0209(5)
Os	$K\beta_1'$	71.078–71.895	0.00710(21)
Os	$K\beta_2'$	73.387–73.808	0.00180(6)
Pt	L	9.4–13.8	0.0396(6)
Pt	$K\alpha_2$	65.123(4)	0.0266(5)
Pt	$K\alpha_1$	66.833(2)	0.0455(8)
Pt	$K\beta_1'$	75.369–76.234	0.0158(3)
Pt	$K\beta_2'$	77.786–78.341	0.00411(10)

Input data

HALF-LIFE

Half-life (d)	Reference
73.810(19)	[H1]
73.814(17)[a]	[H2]
73.84(5)[a]	[H2]
73.831(8)[b]	[H3]
74.02(6)[c]	[H4]
73.822(9)	

[a] Values determined independently, but reported in the same publication.
[b] Uncertainty increased to (13) to ensure a weighting factor not greater than 0.50.
[c] Rejected as an outlier.

REFERENCES — HALF-LIFE

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[2]	[3][a]	[4]	[5]	[6]	[7]
205.79	3.86(8)	3.90(45)	4.02(6)	4.01(6)	3.982(16)	3.93(7)
295.96	34.64(35)	35.6(13)	34.54(36)	34.69(17)	34.65(14)	34.81(66)
308.46	35.77(36)	37.1(8)	36.00(36)	35.87(19)	35.89(15)	36.34(73)
316.51	100.0(10)	100.0(10)	100.0(8)	100.0(5)	100.0(4)	100.0(10)
468.07	58.0(9)	59.7(20)	57.61(48)	57.76(23)	57.8(3)	58.24(97)
484.58	3.81(5)	4.10(21)	3.86(4)	3.828(18)	3.867(22)	3.62(7)
588.58	5.52(10)	5.46(20)	5.45(5)	5.423(21)	5.48(3)	5.47(9)
604.41	10.04(26)	10.9(6)	9.89(7)	9.79(4)	10.00(6)	10.39(18)
612.46	6.55(13)	6.7(4)	6.41(5)	6.365(25)	6.54(4)	6.77(12)

E_γ (keV)	[8]	[9]	[10]	[11]	[12]	Evaluated
205.79	4.22(3)	—	4.01(10)	3.08(6)[a]	4.055(22)	4.03(5)[b]
295.96	34.94(18)	—	34.7(7)	34.52(60)	34.62(16)	34.70(14)[c]
308.46	35.81(20)	—	35.8(7)	35.77(62)	35.84(16)	35.86(15)[c]
316.51	100.0(5)	100.0(5)	100.0(10)	100.0(10)	100.0(4)	100.0(5)[c]
468.07	58.01(41)	—	57.2(12)	56.97(99)	57.76(24)	57.77(23)[c]

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES (cont.)

E_γ (keV)	[8]	[9]	[10]	[11]	[12]	Evaluated
484.58	3.92(3)	—	3.77(8)	3.818(67)	3.899(27)	3.854(26)[b]
588.58	5.56(5)	—	5.36(14)	5.395(95)	5.468(21)	5.458(21)[c]
604.41	10.10(9)	—	9.77(23)	9.87(17)	9.949(39)	9.91(4)
612.46	6.61(6)	—	6.34(16)	6.25(11)	6.488(28)	6.45(9)[b]

[a] All data rejected from Ref. [3] as statistical outliers.
[b] Uncertainty expanded by the limited relative statistical weight method.
[c] Uncertainty set equal to or greater than the lowest value in the input data to avoid overestimation due to possible data correlation.

Comments:

Electron capture decay occurs to excited levels of ^{192}Os (BF_{EC} of 0.048(1)), and β^- decay to excited levels of ^{192}Pt (BF_β of 0.952(1) (revised, Aug. 2003)).

Relative emission probabilities are the weighted averages calculated according to the limited relative statistical weights method. Uncertainties associated with some of these recommended data have been increased, as explained in the footnotes to the above table.

Absolute emission probabilities (per disintegration) were determined from the sum of the relative γ ray emission probabilities (photons + electrons) to the ground states of ^{192}Os and ^{192}Pt — there is no direct β^- or (EC + β^+) decay to the ground states of these daughter nuclei, and therefore this sum should equal 1.00. These decay data and their corresponding total internal conversion coefficients of Rösel et al. [13] were also used to determine β^- and EC decay branches to individual nuclear levels.

Thus, the normalization factor for the decay scheme was calculated from the equation:

$$NF \times [TP(316\ keV) + TP(612\ keV) + TP(1378\ keV) + TP(205\ keV) + TP(489\ keV)] = 1.0$$

where NF is the gamma ray normalization factor, and $TP(E_\gamma) = P_\gamma(1 + \alpha_T)$ is the relative total (photon + electron) emission probability for a γ ray of energy E_γ with total internal conversion coefficient α_T. Hence:

$$N \times 120.850 = 1.0,$$
$$N = 0.008275(40).$$

Uncertainty in NF has been quadratically included in the uncertainties of the absolute emission probabilities of the γ rays listed in the table of selected γ rays. However, a cancellation effect (covariance) has been considered that reduces the contribution for those γ rays that populate the ground states of ^{192}Pt and ^{192}Os.

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{198}Au

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), July 1998.

Recommended data

Half-life

$T_{1/2}$ = 2.6950(7) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
411.80205(17)	0.9554(7)
675.8836(7)	0.00806(7)
1087.6842(7)	0.00159(3)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Hg	L	8.72–14.85	0.0120(5)
Hg	$K\alpha_2$	68.8952(12)	0.00809(8)
Hg	$K\alpha_1$	70.8196(12)	0.01372(12)
Hg	$K\beta_1'$	79.82–80.76	0.00466(8)
Hg	$K\beta_2'$	82.43–83.03	0.00136(4)

Input data

HALF-LIFE

Half-life (d)	Reference
2.69573(14)[a]	[H1]
2.68373(504)[b]	[H2]
2.6966(7)	[H3]
2.6935(4)	[H4]
2.695(3)	[H5]
2.6946(10)	[H6]
2.696(4)	[H7]
2.697(2)	[H8]
2.693(5)	[H9]
2.6950(7)	

[a] Uncertainty increased to (33) to ensure a weighting factor not greater than 0.50.

[b] Rejected as an outlier.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]
411.8	≡100	100	100	100	100	100
675.9	1.5	1.4(1)	1	1.3	0.842(56)	1.11(5)
1087.7	0.4	0.25(5)	0.2	0.25	0.170(12)	0.26(2)

E_γ (keV) [1]	[8]	[9]	[10][a]	[11][b]	Evaluated [12]
411.8	100	100	100	100	100
675.9	1.0	0.75	0.841(5)	0.846(11)	0.844(7)
1087.7	0.28	0.15	0.1664(22)	0.165(4)	0.166(3)

[a] Redefined from 100.0(4) to 100.
[b] Redefined from 100.0(8) to 100.

Absolute emission probabilities were calculated from:

$$P_{\gamma+ce}(412\ \text{keV}) + P_{\gamma+ce}(1088\ \text{keV}) - P_\beta(1372\ \text{keV}) = 1.0$$

Evaluated total internal conversion coefficients and P_β(1372 keV) = 0.00025(5) [6] were adopted to give a normalization factor of 0.009554(7).

REFERENCES — RADIATIONS

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[13] BÉ, M.-M., et al., Table de Radionuclides, CEA Saclay, Gif-sur-Yvette (1999).

Detailed tables and comments can be found in Refs [12, 13], and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{203}Hg

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by A.L. Nichols (IAEA and AEA Technology, UK), January 2002.

Recommended data

Half-life

$T_{1/2}$ = 46.594(12) d

SELECTED GAMMA RAY

E_γ (keV)	P_γ per decay
279.1952(10)[a]	0.8148(8)

[a] From Ref. [1].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Tl	L	8.953–14.738	0.0543(9)
Tl	$K\alpha_2$	70.8325(8)	0.0375(4)
Tl	$K\alpha_1$	72.8725(8)	0.0633(6)
Tl	$K\beta_1'$	82.118–83.115	0.0215(4)
Tl	$K\beta_2'$	84.838–85.530	0.0064(2)

Input data

HALF-LIFE

Half-life (d)	Reference
46.619(27)	[H1]
46.612(19)	[H2]
46.60(1)	[H3]
46.582(2)[a]	[H4]
46.76(8)[b]	[H5]
47.00(3)[b]	[H6]
46.594(12)	

[a] Uncertainty increased to (9) to ensure a weighting factor not greater than 0.50.
[b] Rejected as an outlier.

REFERENCES — HALF-LIFE

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[H6] LAGOUTINE, F., GALLIC, Y.L., LEGRAND, J., Int. J. Appl. Radiat. Isot. **19** (1968) 475.

Gamma ray: Energy and emission probability

Comments:

- A recommended γ ray energy of 279.1952 keV has been adopted from Ref. [1].
- The 279.1952 keV γ ray is of mixed (25%M1 + 75%E2) multipolarity, and α_{tot} = 0.2271(12) and α_K = 0.1640 (10) have been adopted from Ref. [2], in good agreement with specific measurements [3–6].
- Beta particle emission probabilities were calculated from the limit of 0.0001(1) set on the β transition to the ½$^+$ ground state of ^{203}Tl [7, 8], to give 0.9999(1) for the transition to the first excited state of ^{203}Tl (5/2$^-$ → 3/2$^+$).
- As defined above, transition probability of 0.9999(1) for the 279.1952 keV γ ray was used in conjunction with α_{tot} to calculate an absolute emission probability of 0.8148(8).

X rays: Energies and emissions

Calculated using the evaluated γ ray data, and atomic data from Refs [9–11].

REFERENCES — RADIATIONS

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{201}Tl

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Schönfeld (Physikalisch-Technische Bundesanstalt, Germany), May 1997.

Recommended data

Half-life

$T_{1/2}$ = 3.0422(17) d

SELECTED GAMMA RAYS

E_γ (keV)[a]	P_γ per decay
135.312(34)	0.02604(22)
167.450(30)	0.1000(10)

[a] From Ref. [1].

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Hg	L	8.72–14.85	0.427(18)
Hg	$K\alpha_2$	68.8952(11)	0.273(5)
Hg	$K\alpha_1$	70.8196(12)	0.464(7)
Hg	$K\beta_1'$	79.82–80.76	0.157(4)
Hg	$K\beta_2'$	82.43–83.03	0.0461(13)

Input data

HALF-LIFE

Half-life (d)	Reference
3.0486(30)	[H1]
3.0380(18)	[H2]
3.0400(28)	[H3]
3.0456(15)	[H4]
3.0408(14)	[H5]
3.0422(17)	

REFERENCES — HALF-LIFE

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]	Evaluated [8]
135.3	26.5(13)	26.5(10)	26.4(3)	26.5(4)	27.2(5)	25.65(18)	26.04(22)
167.4	≡100	100.0(17)	100.0(11)	100.0(10)	100.0(12)	100	100.0(10)

Comments:

Relative emission probabilities are the weighted averages calculated according to the limitation of relative statistical weights method; no value has a relative weighting factor greater than 0.50.

The absolute emission probability for the 167 keV transition of P_γ(167 keV) = 0.1000(10) was adopted, as determined by Coursey et al. [7] from absolute activity measurements.

REFERENCES — RADIATIONS

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[9] BÉ, M.-M., et al., Table de Radionuclides, CEA Saclay, Gif-sur-Yvette (1999).

Detailed tables and comments can be found in Refs [8, 9] and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{207}Bi

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by M.-M. Bé (Commissariat à l'Énergie Atomique, France), March 1998.

Recommended data

Half-life

$T_{1/2} = 1.18(3) \times 10^4$ d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
569.698(2)	0.9776(3)
1063.656(3)	0.7458(49)
1770.228(9)	0.0687(3)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Pb	L	9.18–15.84	0.332(14)
Pb	$K\alpha_2$	72.805	0.2169(24)
Pb	$K\alpha_1$	74.970	0.365(4)
Pb	$K\beta_1'$	84.451–85.470	0.1246(23)
Pb	$K\beta_2'$	87.238- 88.003	0.0376(10)

Emission intensities of X rays were calculated from the data set described in Ref. [14] and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

Input data

HALF-LIFE

Half-life (d)	Reference
11523(19)[a]	[H1]
11944(292)	[H2]
12199(292)	[H3]
13880(1461)	[H4]
$1.18(3) \times 10^4$	

[a] Uncertainty increased to (210) to ensure a weighting factor not greater than 0.50.

REFERENCES — HALF-LIFE

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]
569.7	≡100	100	100	100	100	100
1063.7	78.4(24)	74.0(20)	78.7(40)	75.6(5)	77.70(45)	75.5(23)
1770.2	7.07(35)	—	7.5(4)[a]	—	—	6.95(20)

E_γ (keV) [1]	[8]	[9]	[10]	[11]	[12]	Evaluated [13]
569.7	100	100	100	100	100	100
1063.7	75.79(25)	76.5(5)	76.584(367)	76.4(5)	77.7(14)	76.29(50)
1770.2	7.026(29)	—	7.023(68)	—	7.11(13)	7.028(26)

[a] Rejected as outlier.

Comments:

— Evaluated emission probabilities are the weighted averages calculated according to the limitation of relative statistical weights method; no value has a relative weighting factor greater than 0.50.

— Absolute emission probabilities were calculated from $\Sigma(P_{\gamma+ce}) = 1.0$ to the ground state level, giving a normalization factor of 0.009776(3).
— Internal conversion coefficients have been deduced from experimental values [13, 14].

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Detailed tables and comments can be found in Refs [13, 14], and on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{226}Ra with daughters

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by R.G. Helmer (Idaho National Laboratory, USA), August 2002.

Recommended data

Half-life (^{226}Ra)

$T_{1/2} = 5.862(22) \times 10^5$ d

SELECTED GAMMA RAYS (ONLY γ RAYS WITH EMISSION PROBABILITIES GREATER THAN 0.010 ARE INCLUDED.)

Parent	E (keV)	P per decay
^{214}Pb	53.2275(21)[a]	0.01066(14)
^{226}Ra	186.211(13)[a]	0.03533(28)
^{214}Pb	241.997(3)[a]	0.0719(6)
^{214}Pb	295.224(2)[a]	0.1828(14)
^{214}Pb	351.932(2)[a]	0.3534(27)
^{214}Bi	609.316(3)[b]	0.4516(33)
^{214}Bi	665.453(22)[a]	0.01521(11)
^{214}Bi	768.367(11)[b]	0.04850(38)
^{214}Bi	806.185(11)[b]	0.01255(11)
^{214}Bi	934.061(12)[a]	0.03074(25)
^{214}Bi	1120.287(10)[a]	0.1478(11)
^{214}Bi	1155.19(2)[a]	0.01624(14)
^{214}Bi	1238.110(12)[a]	0.05785(45)
^{214}Bi	1280.96(2)[a]	0.01425(12)
^{214}Bi	1377.669(12)[a]	0.03954(33)
^{214}Bi	1401.516(14)[c]	0.01324(11)
^{214}Bi	1407.993(7)[b]	0.02369(19)
^{214}Bi	1509.217(8)[b]	0.02108(21)
^{214}Bi	1661.316(13)[b]	0.01037(10)
^{214}Bi	1729.640(12)[b]	0.02817(23)
^{214}Bi	1764.539(15)[b]	0.1517(12)
^{214}Bi	1847.420(25)[a]	0.02000(18)
^{214}Bi	2118.536(8)[b]	0.01148(11)
^{214}Bi	2204.071(21)[b]	0.0489(10)
^{214}Bi	2447.673(10)[b]	0.01536(15)

[a] From Ref. [1].
[b] From Ref. [2].
[c] From Ref. [3].

Input data

HALF-LIFE

Half-life (d)	Reference
584035(853)[a]	[H1]
585131(3204)	[H2]
590609(4135)	[H3]
592436(4749)	[H4]
$5.862(22) \times 10^5$	

[a] Uncertainty increased to (2250) to ensure a weighting factor not greater than 0.50.

REFERENCES — HALF-LIFE

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

Eγ (keV)	[4]	[5]	[6] [a]	[7]	[8]	[3]	Evaluated
53.2	—	—	—	—	2.329(23)	2.384(20)	2.360(27)
186.21	8.7(11)	9.2(10)	8.58(5)	7.6(8)	7.812(31)	7.85(5)	7.824(26)
241.99	17.5(17)	16.1(24)	16.23(10)	16.1(10)	15.90(5)	15.98(6)	15.93(4)
295.22	40(4)	42(5)	41.85(26)	40.8(12)	40.36(12)	40.61(13)	40.48(9)
351.93	86(9)	82(11)	81.5(5)	78.5(24)	78.16(23)	78.34(23)	78.25(16)
609.32	≡100	100	100	100	100	100	100
665.45	3.6(4)	3.36(37)	3.51(20)	3.33(10)	3.359(17)	3.386(21)	3.369(13)
768.37	11.4(12)	11.9(17)	10.91(8)	10.39(31)	10.66(5)	10.768(29)	10.740(29)
806.18	3.0(4)	2.92(43)	2.90(22)	2.76(11)	2.788(22)	2.777(14)	2.780(12)
934.06	7.3(7)	7.0(9)	6.88(5)	6.70(20)	6.783(34)	6.834(36)	6.806(25)
1120.29	34(3)	—	33.13(22)	32.3(10)	32.71(10)	32.77(12)	32.73(8)
1155.19	4.0(5)	—	3.5(4)	4.3(7)	3.594(36)	3.595(17)	3.595(15)
1238.11	14.9(15)	—	12.87(9)	12.7(4)	12.83(6)	12.80(4)	12.810(33)
1280.96	3.6(5)	—	3.17(17)	3.15(11)	3.147(28)	3.159(16)	3.156(14)
1377.67	9.9(11)	—	8.82(25)	8.52(25)	8.69(4)	8.794(30)	8.755(35)
1401.52	3.5(4)	—	2.91(16)	3.0(4)	2.924(20)	2.934(13)	2.932(11)
1407.99	6.2(7)	—	5.37(6)	5.5(5)	5.233(26)	5.250(19)	5.245(15)
1509.22	5.5(5)	—	4.76(5)	4.63(15)	4.61(6)	4.682(31)	4.668(31)
1661.32	2.72(25)	—	2.33(12)	2.37(22)	2.271(34)	2.299(14)	2.296(14)
1729.64	7.5(7)	—	6.60(4)	6.33(15)	6.226(31)	6.245(32)	6.238(25)
1764.54	40(4)	—	34.48(25)	33.3(10)	33.54(10)	33.63(9)	33.59(7)
1847.42	5.3(5)	—	4.57(6)	4.35(13)	4.448(36)	4.419(28)	4.429(25)
2118.54	3.03(29)	—	2.56(3)	2.65(25)	2.536(20)	2.548(21)	2.543(15)
2204.07	12.38(27)	—	11.02(9)	11.1(3)	10.74(5)	10.75(9)	10.83(20)
2447.67	4.0(4)	—	3.42(3)	3.30(10)	3.402(24)	3.409(36)	3.402(21)

[a] Data rejected as outliers.

Evaluated emission probabilities are the weighted averages calculated according to the limitation of relative statistical weights method, and using the data from Refs [3–5, 7, 8]; no value has a relative weighting factor greater than 0.50.

Absolute emission probabilities for specific γ rays have been measured by several authors [9–13]. Generally, the uncertainties in the relative emission probabilities from these authors have larger uncertainties than those for the relative values in the above table. Therefore, the above relative emission probabilities have been normalized simply by use of P_γ(609 keV) = 0.4516(33) from the average of the values from Refs [9–13].

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{228}Th with daughters

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by A.L. Nichols (IAEA and AEA Technology, UK), January 2004.

Recommended data

Half-life (^{228}Th)

$T_{1/2}$ = 698.60(23) d

SELECTED GAMMA RAYS

Parent	E (keV)	P per decay [f]
^{228}Th	84.373(3)[a]	0.0117(5)
^{212}Pb	115.183(5)[b]	0.00623(22)
^{228}Th	131.612(4)[a]	0.00124(6)
^{228}Th	215.985(4)[a]	0.00226(20)
^{212}Pb	238.632(2)[b]	0.436(3)
^{224}Ra	240.986(6)[c]	0.0412(4)
^{208}Tl	277.37(3)[d]	0.0237(11)
^{212}Pb	300.09(1)[b]	0.0318(13)
^{220}Rn	549.76(4)[c]	0.00115(15)
^{208}Tl	583.187(2)[e]	0.3055(17)
^{212}Bi	727.33(1)[b]	0.0674(12)
^{212}Bi	785.37(9)[b]	0.0111(1)
^{208}Tl	860.56(3)[d]	0.0448(4)
^{212}Bi	1620.74(1)[b]	0.0151(3)
^{208}Tl	2614.511(10)[e]	0.3585(7)

[a] From Ref. [1].
[b] From Ref. [2].
[c] From Ref. [3].
[d] From Ref. [4].
[e] From Ref. [5].
[f] Per ^{228}Th decay; equilibrium assumed, with two decay modes for ^{212}Bi (α and β^-), and α branching fraction of 0.3593(7).

SELECTED X RAYS

Origin		E_X (keV)[a]	P_X per decay[b]
Ra	Ll	10.622	0.00166(9)
Ra	Lα	12.196–12.339	0.0286(15)
Ra	Lβη	13.662–15.447	0.047(3)
Ra	Lγ	17.848–18.412	0.0102(6)
Bi	L	9.420–15.709	0.145(4)
Bi	$K\alpha_2$	74.8157(9)	0.107(3)
Bi	$K\alpha_1$	77.1088(10)	0.179(5)
Bi	$K\beta_1'$	86.835–87.862	0.0612(20)
Bi	$K\beta_2'$	89.732–90.522	0.0187(7)
Pb	L	9.184–15.216	0.0104(2)[c]
Pb	$K\alpha_2$	72.8049(8)	0.0077(2)[c]
Pb	$K\alpha_1$	74.9700(9)	0.0130(3)[c]
Pb	$K\beta_1'$	84.451–85.470	0.0044(2)[c]
Pb	$K\beta_2'$	87.238–88.003	0.00134(5)[c]
Tl	Ll	8.953	0.00169(9)
Tl	Lα	10.172–10.268	0.0326(17)
Tl	Lβη	10.994–12.643	0.0272(15)
Tl	Lγ	14.291–14.738	0.0050(2)

[a] From Refs [6–8].
[b] Per ^{228}Th decay, assuming equilibrium.
[c] Corrected for a ^{212}Bi α branching fraction of 0.3593(7) in order to express per ^{228}Th decay after calculating per ^{208}Tl decay (see ^{212}Bi below).

Input data

HALF-LIFE

Half-life (d)	Reference
698.60(36)	[H1]
698.77(32)	[H2]
697.8(7)	[H3]
698.60(23)	

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^{228}Th

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E (keV)	[9][a]	[10][b]	[11]	Evaluated
84.37	100(5)	100(5)	100.0(16)	100.0(16)
131.61	10.25(50)	8.9(10)	10.70(15)	10.6(2)
215.99	19.8(11)	15.8(11)	20.78(25)	19.3(15)

[a] Converted from absolute emission probability data (absolute P_γ(84.37 keV) = 0.0121(6)).
[b] Converted from probability data published relative to P_γ(238.63 keV) for ^{212}Pb of 0.430(20).

Comments:

- The normalization factor (NF) was calculated for the γ ray emission probabilities by averaging the values determined by three different routes to give a recommended value of 0.000117(5).
- A comprehensive decay scheme was evaluated and constructed (9 α particles and 14 γ rays); weighted mean values were adopted when judged appropriate (as above), while other emission probabilities were derived from the proposed decay scheme.

Further detailed tables and comments (including α particle data) can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{224}Ra

GAMMA RAY: MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITY

E_γ (keV)	[12]	[13][a]	[10]	[14]	[15]
240.99	0.0395(13)	0.039(7)	0.039(2)	0.0404(17)	0.0405(9)

E_γ (keV)	[16]	[11]	[17]	Evaluated
240.99	0.0405(9)	0.0417(4)	0.0411(12)	0.0412(4)[b]

[a] Converted from probability data published relative to P_γ(2614.51 keV) for ^{208}Tl of 1.00.
[b] Weighted mean value of 0.0412(3); uncertainty adjusted to lowest measured value of ±0.0004 to give 0.0412(4).

Comments:

- Alpha particle emission probabilities to the first excited states of ^{220}Rn have been directly measured [12, 16, 18, 19], and these data can be used to calculate the α particle emission probability directly to the ground state of ^{220}Rn. A weighted mean value of 0.9500(4) can be determined for P_α(5685.50 keV) to the ground state, and a value of 0.0501(4) for P_α(5448.81 keV) to the first excited state.
- If P_α(5685.50 keV) of 0.9500(4) is adopted, the γ ray NF = 0.00947(8) and P_γ(240.99 keV) is 0.0390(3).
- Thus, a discrepancy arises between measurements of the absolute emission probability of the 240.99 keV γ ray and measurements of the direct α particle emission probability to the ground state of ^{220}Rn.
- The γ ray data were judged to be more reliable, and therefore P_γ(240.986 keV) of 0.0412(4) was recommended. This problem cannot be resolved on the basis of the known measurements, and further spectroscopic measurements are required to resolve the discrepancies between the α particle and γ ray data.

Further detailed tables and comments (including α particle data) can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{220}Rn

GAMMA RAY: MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITY

E_γ (keV)	[13][a]	[9][b]	[11]	Evaluated
549.76	0.00104(32)	0.000991(83)	0.00130(3)	0.00115(15)

[a] Converted from probability data published relative to P_γ(2614.51 keV) for ^{208}Tl of 1.00.
[b] Converted from absolute emission probability in measurements that include P_γ(240.99 keV) for ^{224}Ra of 0.0395.

Further detailed tables and comments (including α particle data) can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{212}Pb

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[20]	[21]	[13][a]	[22][b]	[10][c]
115.18	[observed]	1.4(3)	1.3(3)	1.4(1)	1.65(12)
238.63	≡100	≡100	≡100	100(3)	100(5)
300.09	7.7(4)	6.9(4)	7.7(15)	6.3(2)	6.7(5)

E_γ (keV)	[14][d]	[15][d]	[11][e]	[17][d]	Evaluated
115.18	—	—	1.37(2)	—	1.43(5)
238.63	100(3)	100(1)	100(1)	100(2)	100(1)
300.09	7.5(2)	7.3(1)	7.6(1)	7.6(3)	7.3(3)

[a] Converted from probability data published relative to P_γ(2614.51 keV) for ^{208}Tl of 1.00.
[b] Converted from probability data published relative to P_γ(583.19 keV) for ^{208}Tl of 0.85.
[c] Converted from probability data published relative to P_γ(238.63 keV) of ^{212}Pb specified as 0.430(20).
[d] Converted from absolute emission probabilities.
[e] Converted from probability data published relative to P_γ(583.19 keV) for ^{208}Tl of 1.000(6).

A weighted mean normalization factor of 0.00436(3) was calculated for the γ ray emission probabilities from the measurements of Refs [10, 11, 14, 15, 17]:

238.63 keV GAMMA RAY: MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITY

E_γ (keV)	[10]	[14]	[15]	[11]	[17]	Evaluated
238.63	0.430(20)	0.435(12)	0.440(6)	0.433(4)	0.441(10)	0.436(3)

A comprehensive decay scheme was evaluated and constructed (6 γ rays and 3 β particles).

Further detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{212}Bi

GAMMA RAYS: MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITIES

E_γ (keV)	[23][a]	[24][b]	[25][c]	[26][d]	[13][d]	[22][e]
727.33	0.0711(45)	[0.0785] (727.33 + 785.37)	0.076(15)	—	0.063(6)	0.076(3)
785.37	0.0109(17)		—	—	0.010(2)	0.0117(6)
1620.74	0.0180(13)	0.0157(5)	0.019(4)	0.0174(18)	0.014(1)	—

E_γ (keV)	[10][f]	[14][g]	[15][g]	[11][h]	[17][g]	Evaluated
727.33	0.070(4)	0.0656(15)	0.0700(18)	0.0662(4) [i]	0.0693(18) [j]	0.0674(12)
785.37	0.0102(7)	0.0107(5)	—	0.0111(1)	0.0105(5)	0.0111(1)
1620.74	—	0.0138(8)	—	0.0149(3) [i]	0.0144(9)	0.0151(3)

[a] Converted from probability data expressed in terms of ^{212}Bi β^- decay mode only.
[b] Converted from probability data expressed in terms of (727.33 + 785.37) keV γ rays of ^{212}Bi.
[c] Converted from probability data expressed in terms of ^{212}Po α decay.
[d] Converted from probability data published relative to P_γ(2614.51 keV) for ^{208}Tl of 1.00.
[e] Converted from probability data published relative to P_γ(583.19 keV) for ^{208}Tl of 0.85.
[f] Converted from probability data published relative to P_γ(238.63 keV) of ^{212}Pb specified as 0.430(20).
[g] Published as absolute emission probabilities.
[h] Converted from probability data published relative to P_γ(583.19 keV) for ^{208}Tl of 1.000(6).
[i] Uncertainty increased to ensure a weighting factor not greater than 0.50.
[j] Unresolved overlap with another γ ray emission, and therefore not included in the weighted mean analysis.

Comments:

^{212}Bi undergoes α decay to ^{208}Tl (BF_α = 0.3593(7)) and β^- decay to ^{212}Po (BF_β = 0.6407(7)).

The α branching fraction was calculated as the weighted mean of the measurements of Refs [23–25, 27], with the uncertainty increased to include the most precise value of 0.3600(3).

	[23]	[24]	[25]	[27]	Evaluated
BF_α	0.3596(6)	0.3581(4)	0.36(1)	0.3600(3)[a]	0.3593(7)

[a] Uncertainty increased slightly to ensure a weighting factor not greater than 0.50.

A comprehensive decay scheme was evaluated and constructed (8 α particles, 3 long range α particles, 7 β^- particles and 23 γ rays).

Further detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBABILITIES

E_γ (keV)	[28]	[23]	[29-1][a]	[29-2][a]	[30][b]	[31]	[32]
277.37	6.9(8)	8.6 [i]	—	7.2(7)	—	6.5(4)	6.9(5)
583.19	86.4(56)	85.1(40)	81(5) [j]	84(5)	85.7(18)	86(4)	85(4)
860.56	11.4(12)	14.2(6) [j]	15.3(20) [j]	15.2(15) [j]	—	12.0(8)	13(1)
2614.51	≡100	[100]	≡100	≡100	100(2)	≡100	≡100

E_γ (keV)	[13]	[33]	[34]	[35][c]	[22]	[10][d]	[14][e]
277.37	6.6(13)	6.2(7)	6.8(3)	—	6.1(2)	6.8(3)	6.5(2)
583.19	85.0(85)	86.0(4)	86(3)	84.4(11)	85 [i]	[85.2(3)][k]	85.8(22)
860.56	11.8(12)	11.5(10)	12.0(4)	12.48(13)	13.9(6) [j]	11.9(6)	12.8(3)
2614.51	≡100	[100]	≡100	100.0(14)	[100]	—	100(3)

E_γ (keV)	[15][f]	[11][g]	[17][h]	[36][h]	Evaluated
277.37	6.3(1)	6.34(5)	7.4(2)[l]	7.01(12)	6.6(3)
583.19	[85.2(3)][k]	84.0(5)	[85.2(3)][l]	88(3)	85.2(3)
860.56	—	12.41(8)	12.5(4)	12.8(7)	12.5(1)
2614.51	—	100(2)	—	100.0(13)	100(2)

[a] Two sets of measurements reported in Ref. [29]: single spectra [29-1]; coincidence spectra [29-2].
[b] Converted from average values of measured probability data published relative to P_γ(583.19 keV) for ^{208}Tl of 1.00.
[c] Converted from probability data published relative to P_γ(583.19 keV) for ^{208}Tl of 1.00.
[d] Converted from probability data published relative to P_γ(583.19 keV) for ^{208}Tl of 0.300(14).
[e] Converted from absolute emission probabilities; unresolved overlap between specific emissions (involving 277.37 and 583.19 keV γ rays) that was only corrected in the case of the 583.19 keV transition.
[f] Converted from probability data published relative to P_γ(583.19 keV) for ^{208}Tl of 0.308(6).
[g] Converted from probability data published relative to P_γ(583.19 keV) for ^{208}Tl of 1.000(6).
[h] Converted from absolute emission probabilities.
[i] No quoted uncertainty; not included in weighted mean analysis.
[j] Rejected as an outlier.
[k] Measurements did not include the 2614.51 keV γ ray; therefore a relative emission probability of 85.2(3) was used for the 583.19 keV γ ray to convert other data in this study to comparable relative values — under these circumstances, P_γ(583.19 keV) was not included in the weighted mean analysis.
[l] Unresolved overlap with another γ ray emission, and measurement did not include the 2614.51 keV γ ray; therefore, a relative emission probability of 85.2(3) was used for the 583.19 keV γ ray to convert other data in this study to comparable relative values — under these circumstances, P_γ(277.37 keV) and P_γ(583.19 keV) were not included in the weighted mean analyses.

Comments:

- NF of 0.009979(1) was calculated for the relative emission probabilities of the gamma rays, assuming no direct β^- decay to the ground state of ^{208}Pb: transition probability $P_{\gamma+ce}$(2614.51 keV) = 1.00; α_{tot}(2614.51 keV E3 γ transition) = 0.00210(6) interpolated from the tables of Ref. [37]; NF = 1.00/[(1 + 0.00210(6)) P_γ^{rel}(2614.51 keV)]= 0.009979(1).
- P_γ per ^{228}Th decay were calculated from relative P_γ values as evaluated above, NF of 0.009979(1), and α branching fraction of ^{212}Bi to ^{208}Tl of 0.3593(7).
- A comprehensive decay scheme was evaluated and constructed (17 β^- particles and 29 γ rays); weighted mean values adopted when judged appropriate (as above), while other emission probabilities were derived from the proposed decay scheme.
- 510.7 keV γ ray occurs in the decay of ^{208}Tl, with P_γ(510.7 keV) of 0.0810(7) per ^{228}Th decay; however, this transition has not been included in the selected set of recommended

γ rays because of the extremely close proximity of this emission to any annihilation radiation (511 keV).

Further detailed tables and comments can be found on
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

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All detailed tables and comments can be found on
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{234m}Pa

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by A.L. Nichols (IAEA and AEA Technology, UK), August 2002.

Recommended data

Half-life

$T_{1/2}$ = 0.000805(11) d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
258.24(7)[a]	0.000726(9)
742.814(22)[b]	0.00096(3)
766.358(20)[b]	0.00318(5)
786.272(22)[b]	0.00054(1)
1001.025(22)[b]	0.00832(10)

[a] Derived from Ref. [1].
[b] From Ref. [2].

Input data

HALF-LIFE

Half-life (d)	Reference
0.0008215(257)	[H1]
0.0007917(69)	[H2]
0.000868(69)	[H3]
0.0008160(21)[a]	[H4]
0.000805(11)	

[a] Uncertainty increased to (67) to ensure a weighting factor not greater than 0.50.

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GAMMA RAYS: MEASURED AND EVALUATED RELATIVE EMISSION PROBA0BILITIES

E_γ (keV)	[3]	[4]	[5]	[6]	[7]
258.24(7)[a]	7(2)	8.8(2)	9.7(4)	3.6(2)[c]	—
742.814(22)[b]	13(2)	11.5(2)	9.6(4)	5.4(2)[c]	11.6(7)
766.358(20)[b]	37(7)	37.8(4)	35.1(14)	40.0(9)	39.9(8)
786.272(22)[b]	5(1)	6.6(1)	5.8(2)	7.2(3)	6.6(5)
1001.025(22)[b]	100	100(1)	100	100	100.0(9)

E_γ (keV)	[8]	[9]	[10]	[11]	Evaluated
258.24(7)[a]	8.70(4)	8.6(6)	—	9.1(2)	8.73(4)
742.814(22)[b]	11.28(8)[d]	10.4(5)	—	12.7(2)	11.5(3)
766.358(20)[b]	38.4(2)[e]	37.6(11)	36(1)	—	38.2(4)
786.272(22)[b]	6.60(6)[f]	5.9(4)	—	—	6.5(1)
1001.025(22)[b]	100.0(6)	100(2)	100	(100)	100.0(4)

[a] Derived from the energies of the relevant nuclear levels of Ref. [1].
[b] From Ref. [2].
[c] Rejected as an outlier.
[d] Uncertainty increased from 0.08 to 0.13 by the evaluator.
[e] Uncertainty increased from 0.2 to 0.3 by the evaluator.
[f] Uncertainty increased from 0.06 to 0.08 by the evaluator.

Comments:

^{234m}Pa undergoes both isomeric transition and beta decay. However, the nuclear level energy of ^{234m}Pa is poorly defined (second excited state, with spin and parity of (0–)), and Q_{IT} can only be estimated as 78.9(20) keV. Studies to quantify the two branching fractions are sparse, and are based on the measurements of BF_{IT} in Refs [12–15]: BF_{IT} of 0.0016(2) was adopted as the weighted mean of five measurements, with the uncertainty set marginally above the smallest uncertainty of the values used to calculate the average. BF_{β} of 0.9984(2) was simply calculated from the value adopted for BF_{IT}.

BRANCHING FRACTIONS

Reference	BF_{IT}	BF_{β}
[12]	0.00150(15)	—
[13]	0.0018(2)	—
[14]	0.0013(3)	—
[15]	0.0015(5)	—
[15]	0.0019(6)	—
Recommended	0.0016 ± 0.0002	0.9984 ± 0.0002

Two gamma transitions with energies of 5(2) and 73.92(2) keV are attributed to the IT-decay mode. The 5 keV gamma transition has not been observed, and the energy was estimated from the proposed decay scheme and an assumed energy limit of detection of ~7 keV (i.e. (5 ± 2) keV).

Nine measurements of the absolute emission probability of the 1001.025 keV γ ray have been considered in the derivation of a recommended value for the normalization factor [4, 6–10, 16–18]. After detailed assessments of the data, the uncertainties assigned originally to the emission probabilities of Refs [4, 7, 8] were increased by 2% to bring them in line with the other studies and ensure the inclusion of systematic uncertainties in these particular measurements. Three of the measurements are significantly higher than the other six studies (values greater than 0.00900): 0.00920 [6]; 0.00910 [10]; and 0.00924 [18]. The absolute emission probability reported in Ref. [6] was not included in the weighted mean analysis because the study did not include any quantification of the uncertainty, while the equivalent measurements of P_{γ}^{abs}(1001.025 keV) in Refs [10, 18] were also set aside because of their large deviations from the other studies. The remaining six data sets were used to determine an absolute emission probability for the 1001.025 keV γ ray, and hence the normalization factor [4, 7–9, 16, 17]. All LWEIGHT analyses are listed in the table below. The decision was taken to adopt an absolute emission probability P_{γ}^{abs}(1001.025 keV) of 0.00832(10), and therefore a normalization factor and uncertainty of 0.0000832(10), with $\chi^2/(N–1)$ of 0.35. While the more disparate data have been discarded as noted above, there is a sufficient number of such measurements above 0.00900 to recommend further studies of P_{γ}^{abs}(1001.025 keV) to confirm the recommended value of 0.00832(10) per decay, a key parameter in the decay scheme of ^{234m}Pa.

ABSOLUTE EMISSION PROBABILITY OF THE 1001.025 keV GAMMA RAY

Reference	P_γ^{abs}	Quoted ΔP_γ^{abs}	Recommended ΔP_γ^{abs}	$\chi^2/(N-1)$
[4]	0.00828	0.00008	0.00025[a]	—
[6]	0.00920	—	0.00020[b]	—
[7]	0.00834	0.00007	0.00024[c]	—
[8]	0.00839	0.00005	0.00023[c]	—
[16]	0.00818	0.00030	0.00030	—
[17]	0.00788	0.00043	0.00043	—
[9]	0.00845	0.00021	0.00021	—
[10]	0.00910	0.00025[d]	0.00025[d]	—
[18]	0.00924	0.00017	0.00017	—
Evaluated[e]	0.00840	0.00008	—	5.33
	0.00872	—	0.00016	4.22
	0.00872	—	0.00052[f]	4.22
[4]	0.00828	0.00008	0.00025[a]	—
[7]	0.00834	0.00007	0.00024[c]	—
[8]	0.00839	0.00005	0.00023[c]	—
[16]	0.00818	0.00030	0.00030	—
[17]	0.00788	0.00043	0.00043	—
[9]	0.00845	0.00021	0.00021	—
Evaluated[e]	0.00835	0.00004	—	0.63
	0.00832	—	0.00010	0.35

[a] Uncertainty quoted only in terms of random uncertainties as 0.00008; assumed to require addition of 2% systematic uncertainty to give an overall uncertainty of 0.00025.
[b] Uncertainty has been estimated from comments made in Ref. [6].
[c] Uncertainty increased by 2% to ensure inclusion of systematic uncertainty, and to align with the majority of other studies.
[d] Value of 0.0091(5) is quoted at 2σ level of uncertainty in Ref. [10]; adjusted to 1σ level of uncertainty.
[e] Weighted mean values as calculated using LWEIGHT.
[f] Uncertainty adjusted to include the most precise value.

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^{241}Am

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by V.P. Chechev and N.K. Kuzmenko (V.G. Khlopin Radium Institute, Russian Federation), October 2002.

Recommended data

Half-life

$T_{1/2} = 1.5785(23) \times 10^5$ d

SELECTED GAMMA RAYS

E_γ	P_γ per decay
26.3446(2)	0.0240(3)
33.1963(3)	0.00121(3)
59.5409(1)	0.3578(9)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Np	Ll	11.89(2)	0.00848(10)
Np	Lα	13.90(2)	0.1303(10)
Np	Lβη	17.81(2)	0.1886(15)
Np	Lγ	20.82(2)	0.0481(4)

Input data

HALF-LIFE

Half-life (d)	Reference
157788(73)[a]	[H1]
155706(767)	[H2]
158080(566)	[H3]
158153(2557)	[H4]
159468(1096)	[H5]
158044(256)	[H6]
$1.5785(23) \times 10^5$	

[a] Uncertainty increased to (220) to ensure a weighting factor not greater than 0.50.

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Gamma rays: Energies and absolute emission probabilities

26.345 and 59.541 keV γ ray energies were adopted from Ref. [1], while the 33.196 keV γ ray energy has been calculated from the difference between the 26.345 and 59.541 keV γ transition energies.

Absolute γ ray emission probabilities have been adopted from the detailed analysis of Johnston [2] undertaken to determine the optimum values of the low energy photons in the decay of ^{241}Am (including XL rays). The decay scheme balance for the lower levels of ^{237}Np is better in Ref. [2] than other previous attempts.

XL RAYS: MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITIES

E_X (keV)	[3]	[4]	[5]	[6]	[7]
11.89	0.0081(7)	0.0087(6)	0.0086(2)	—	0.00806(40)
13.90	0.126(9)	0.135(12)	0.1320(25)	—	0.132(7)
17.81	0.191(14)	0.191(14)	0.1925(40)	0.1946(16)	0.192(10)
20.82	0.0475(35)	0.0475(35)	0.0485(15)	—	0.0494(25)

E_X (keV)	[8]	[9]	[10]	[11]	Evaluated
11.89	0.0087(3)	0.0083(3)	0.00837(10)	0.00864(12)	0.00848(10)
13.90	0.132(3)	0.127(4)	0.1301(10)	0.1303(13)	0.1303(10)
17.81	0.1978(36)	0.183(6)	0.1861(15)	0.1839(19)	0.1886(15)
20.82	0.0496(20)	0.048(2)	0.04815(38)	0.0474(8)	0.0481 (4)

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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{243}Am

Half-life evaluated by M.J. Woods (National Physical Laboratory, UK), September 2003.

Decay scheme evaluated by E. Browne (Lawrence Berkeley National Laboratory, USA) and R.G. Helmer (Idaho National Laboratory, USA), September 2004.

Recommended data

Half-life

$T_{1/2} = 2.692(8) \times 10^6$ d

SELECTED GAMMA RAYS

E_γ (keV)	P_γ per decay
43.53(2)	0.0589(10)
74.66(2)	0.672(12)

SELECTED X RAYS

Origin		E_X (keV)	P_X per decay
Np	Ll	11.871	0.00445(14)
Np	Lα	13.761–13.946	0.0705(20)
Np	Lη	15.861	0.00126(4)
Np	Lβ	16.109–17.992	0.0818(16)
Np	Lγ	20.784–21.491	0.0197(4)

Input data

HALF-LIFE

Half-life (d)	Reference
2687510(15341)	[H1]
2695545(12419)	[H2]
2691893(14610)	[H3]
$2.692(8) \times 10^6$	

REFERENCES — HALF-LIFE

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GAMMA RAYS: EVALUATED ENERGIES, AND MEASURED AND EVALUATED ABSOLUTE EMISSION PROBABILITIES

E_γ (keV)[a]	[6]	[3][b]	[7]	[8]	[9]	[10]
43.53(2)	0.04(1)	0.053	0.05(1)	0.055(3)	—	0.053(12)
74.66(2)	0.69(3)	0.61	—	0.66(3)	0.59(4)	0.60(4)

E_γ (keV)[a]	[2]	[11]	[12]	[5]	Evaluated
43.53(2)	0.0620(30)	0.0604(13)	0.0593(10)	0.0572(17)	0.0589(10)
74.66(2)	0.680(20)	0.685(15)	0.667(12)	0.684(13)	0.672(12)

[a] Weighted average of values from Refs [1, 2], complemented with data from Refs [3–5].
[b] Uncertainties of at least 10%; not included in weighted mean analysis.

Comments:

Recommended absolute emission probabilities are weighted averages of data from Refs [2, 5–12]. A comprehensive decay scheme was evaluated and constructed from the published α particle and γ ray decay data, including the derivation of absolute γ ray transition probabilities from the evaluated emission probabilities, theoretical internal conversion coefficients of Rösel et al. [13], and the multipolarities specified in Ref. [14].

Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

X rays: Energies and emission probabilities

X ray energies are taken from Ref. [15]. Emission probabilities are the evaluators' values calculated using the EMISSION program, Version 3.04 [16], with atomic data from Ref. [17], and the recommended ray emission probabilities.

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Further detailed tables and comments can be found on
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

Annex III

GAMMA RAY STANDARDS FOR DETECTOR EFFICIENCY CALIBRATION AT HIGH ENERGIES

B. Mariański, A. Marcinkowski

The Andrzej Soltan Institute for Nuclear Studies, Poland

III–1. DETECTOR EFFICIENCY CALIBRATION AT HIGH ENERGIES

A precise determination of the efficiency of a germanium detector up to about 2.7 MeV may be achieved with either a ^{24}Na or ^{228}Th source, or to 3.6 MeV with a ^{56}Co source. A description is given in this annex of some sources of radiation that can be used to extend the efficiency calibration beyond 10 MeV. Except for one radioactive nuclide (^{66}Ga) these sources of radiation are based on specific nuclear reactions. While other reactions can also be used, only thermal neutron capture, proton capture and proton inelastic scattering reactions are considered in this assessment. Thus, such calibrations can be extended up to 11 MeV by means of neutron capture γ rays, as described in Ref. [III–1].

Although different types of calibration source may involve specific difficulties or limitations, some general problems can be noted. One problem is the source–detector geometry: if an absolute efficiency curve is determined from spectra of one type of reaction and used for spectra from another type of reaction or from radioactive decay, care must be taken to maintain the same source–detector geometry (i.e. source distance, size and γ ray attenuation must be the same, or appropriate corrections have to be made). This may prove to be a difficult task if the reaction has a low cross-section requiring a large target, high projectile current, or long irradiation time.

III–2. HIGH ENERGY GAMMA RAYS

Some general comments are required concerning the high energy γ ray data. These data have generally been of lower accuracy than the data that describe the decay of radioactive nuclides. The main reason for this difference is that they have normally been obtained in experiments without metrological goals in mind. Most of these data were taken from a single reference and had not been subject to detailed evaluation. Furthermore, when a number of data sets were available they were often of variable quality that compromised evaluation efforts. However, the quality of such data has improved in recent years, and some significant advances have been made since IAEA-TECDOC-619 was published in 1991 [III–2].

III–3. ^{66}Ga

^{66}Ga is the only radionuclide that has been applied in the energy region above 3600 keV. This nuclide has a half-life of 9.3 hours and can be produced by ^{63}Cu(α, n), ^{66}Zn(p, n) and ^{64}Zn(α, 2n) reactions. Using new ^{35}Cl(n, γ) data as calibration standards (see Section III–4.2), new relative intensities have been determined for 21 γ rays emitted by ^{66}Ga to good accuracy [III–3, III–4]. These new data are in good agreement with ENSDF data [III–5] and the set of data from Raman et al. [III–6], as well as with the data obtained at the Lawrence Berkeley National Laboratory [III–4] by calibrating their HPGe detector with absolute sources of ^{60}Co, ^{137}Cs and ^{13}C(^{238}Pu) [γ rays of energy 6.12863 MeV from the decay of ^{16}O]. Both the evaluated relative intensities and absolute emission probabilities of the main γ rays from the decay of ^{66}Ga are listed in Table III–1 [III–7]. All the uncertainties shown in the various tables follow the notation given by 0.15862(44), which represents 0.15862 ± 0.00044.

III–4. THERMAL NEUTRON CAPTURE REACTIONS

Neutron capture reactions at thermal energies have proved to be useful tools in the efficiency

TABLE III–1. ABSOLUTE EMISSION PROBABILITIES PER DECAY AND RELATIVE PROBABILITIES OF 21 γ RAYS FROM THE DECAY OF ^{66}Ga [III–7]

E_γ (keV)	$P_{\gamma i}$ [a]	$P_{\gamma i}/P_{\gamma 1039keV}$
686.080(6)	0.00252(22)	0.00681(20)
833.5324(21)	0.059(5)	0.1595(6)
1039.220(3)	0.37(3)	1.000(3)
1333.112(5)	0.0117(9)	0.03162(13)
1418.754(5)	0.0061(5)	0.01649(8)
1508.158(7)	0.0055(4)	0.01486(7)
1898.823(8)	0.0039(3)	0.01054(8)
1918.329(5)	0.0199(16)	0.05378(23)
2189.616(6)	0.053(4)	0.1432(6)
2422.525(7)	0.0188(15)	0.05081(24)
2751.835(5)	0.227(18)	0.6135(26)
3228.800(6)	0.0151(12)	0.04081(22)
3380.850(6)	0.0146(12)	0.03946(23)
3422.040(8)	0.0086(7)	0.02324(16)
3432.309(7)	0.00288(24)	0.00778(10)
3766.850(9)	0.00149(13)	0.00403(15)
3791.004(8)	0.0109(9)	0.02946(24)
4085.853(9)	0.0127(10)	0.03432(20)
4295.187(10)	0.038(3)	0.1027(8)
4461.202(9)	0.0084(7)	0.0227(3)
4806.007(9)	0.0186(15)	0.0503(3)

[a] Uncertainties of $P_{\gamma i}$ are relative to the uncertainty of $P_{\gamma 1039keV}$.

calibration of high energy γ ray detectors. Gamma ray emission probabilities (P_γ) from these sources are usually known to an accuracy suitable for that purpose (e.g. Ref. [III–2]). Care is needed to maintain the source–detector geometry between measurements, especially if the efficiency curve from the capture reaction is to be used for radioactive sources. Furthermore, the two sources may be difficult to match if the neutron beam does not irradiate the target uniformly. Therefore, the safest approach would be to accept the absolute efficiencies from radioactive sources and extend the efficiency curve towards high energies by normalization of the relative efficiencies obtained from nuclear reactions in the region of overlap.

TABLE III–2. TOTAL NEUTRON CAPTURE CROSS-SECTION AT THERMAL ENERGY

Reaction	σ_C (b)	Ref.
^{14}N(n, γ)^{15}N	0.0803(6)	[III–8]
^{35}Cl(n, γ)^{36}Cl	43.60(46)	[III–9]
^{48}Ti(n, γ)^{49}Ti	8.5(2)	[III–10]
^{52}Cr(n, γ)^{53}Cr	0.86(3)	[III–11]
^{53}Cr(n, γ)^{54}Cr	18.6(6)	[III–12]

The emission probability of a γ ray is related to the total capture cross-section σ_C:

$$\sigma_\gamma = \sigma_C \frac{\Gamma_\gamma}{\Gamma} \quad \text{(III–1)}$$

at thermal energy $\Gamma = \Gamma_\gamma = \Sigma_i \Gamma_{\gamma i}$, with the γ_i rays being the primary γ transitions from the capturing state. The relationship

$$\sigma_{\gamma j} = \sigma_C P_{\gamma j} \quad \text{(III–2)}$$

also holds for the secondary γ_j rays of known emission probability $P_{\gamma j}$. The total neutron capture cross-sections for the target nuclei of interest have been brought together in Table III–2. Both the ^{14}N(n, γ)^{15}N [III–8, III–13] and ^{35}Cl(n, γ)^{36}Cl [III–6, III–14 to III–16] reactions are of particular interest since the γ ray intensities were measured with metrological goals in mind.

III–4.1. ^{14}N(n, γ)^{15}N reaction

Data from the ^{14}N(n, γ)^{15}N reaction in Refs [III–8, III–13] are of even quality (see Table III in Ref. [III–8]), and therefore the evaluated γ ray intensities were obtained as weighted averages in which no adopted uncertainty was deemed to be lower than the lowest measured uncertainty. In Table III–3, unweighted mean values are listed as UWM, while the recommended least squares weighted mean data are denoted by LWM. There are only two γ rays ranging from 1885 to 8310 keV that have emission probabilities $P_{\gamma i}$ (per neutron capture) known to an accuracy better than 1%, while the uncertainties in the emission probabilities of the two highest energy γ rays of 9149 and 10829 keV amount to 4.1% and 1.5%, respectively.

TABLE III–3. EVALUATED THERMAL NEUTRON CAPTURE CROSS-SECTIONS ($\sigma_{\gamma i}$) FOR SELECTED γ_i RAYS FROM THE $^{14}N(n, \gamma)^{15}N$ REACTION, AND CORRESPONDING γ_i RAY EMISSION PROBABILITIES $P_{\gamma i}$(abs) PER NEUTRON CAPTURE AS EVALUATED ON THE BASIS OF DATA FROM REFS [III–8, III–13]

$E_{\gamma i}$ (keV)	$P_{\gamma i}$(abs)				$\sigma_{\gamma i}$ (mb)
	[III–13]	[III–8]	UWM	LWM recommended	
1678.293(25)	0.0723(18)	0.0796(9)[a]	0.076(4)	0.076(4)	6.1(3)
1681.228(50)	0.0154(15)	0.0164(4)	0.0159(5)	0.0163(4)	1.31(3)
1884.780(18)	0.1866(25)	0.1877(20)	0.1872(20)	0.1873(20)	15.04(20)
1999.679(27)	0.0399(9)	0.0411(5)	0.0405(6)	0.0408(5)	3.28(5)
2520.443(22)	0.0579(7)	0.0558(9)	0.0569(11)	0.0571(10)	4.59(8)
2830.805(36)	0.0173(3)	0.0171(4)	0.0172(3)	0.0172(3)	1.38(3)
3531.982(20)	0.0924(9)	0.0894(11)	0.0909(15)	0.0912(15)	7.32(13)
3677.737(17)	0.1489(15)	0.1452(16)	0.1471(19)	0.1472(19)	11.82(18)
4508.783(14)	0.1654(17)	0.1671(17)	0.1663(17)	0.1663(17)	13.35(17)
5269.162(17)	0.3003(20)	0.2986(30)	0.2995(20)	0.2998(20)	24.07(24)
5297.826(20)	0.2131(18)	0.2123(22)	0.2127(18)	0.2128(18)	17.08(19)
5533.391(18)	0.1975(21)	0.1958(21)	0.1967(21)	0.1967(21)	15.80(21)
5562.059(21)	0.1065(12)	0.1068(12)	0.1067(12)	0.1067(12)	8.57(12)
6322.433(16)	0.1867(14)	0.1823(22)	0.1845(22)	0.1854(20)	14.89(20)
7298.980(32)	0.0973(9)	0.0939(12)	0.0956(17)	0.0961(16)	7.72(14)
8310.156(39)	0.0422(5)	0.0412(9)	0.0417(5)	0.0420(5)	3.37(5)
9148.95(9)	0.0148(6)	0.0148(6)	0.0148(6)	0.0148(6)	1.19(5)
10829.110(59)	0.1365(21)	0.143(6)	0.1398(33)	0.1372(21)	11.02(19)

[a] Uncertainty adjusted to (18) based on the chi-squared test.

The thermal neutron capture cross-sections $\sigma_{\gamma i}$ in Table III–3 were calculated from Eq. (III–2), with σ_C taken from Table III–2.

III–4.2. $^{35}Cl(n, \gamma)^{36}Cl$ reaction

Table III–4 lists the γ_i ray emission cross-sections ($\sigma_{\gamma i}$) for the $^{35}Cl(n, \gamma)^{36}Cl$ reaction calculated according to Eq. (III–2), with the evaluated emission probabilities $P_{\gamma i}$ (per neutron capture) given in the seventh column. The uncertainties in the emission probabilities $P_{\gamma i}$ from the $^{35}Cl(n, \gamma)^{36}Cl$ reaction measured in Ref. [III–14] include the systematic contributions. As many as 21 of the 24 γ ray emission probabilities in this reference have uncertainties lower than 3%, and the data of Molnár et al. [III–15] and Raman et al. [III–6] are even more precise. On the other hand, data sets in Refs [III–17 to III–21] have much larger uncertainties and were disregarded in deriving the weighted mean emission probabilities. While Refs [III–6, III–14 to III–16] quote their γ ray emission probabilities on an absolute scale, such measurements are made on a relative basis. Therefore, prior to analysis all of these data sets were converted to values relative to the preferred 1951.1 keV γ ray. The resulting data are listed in Table III–4: the sixth column contains the least squares weighted mean values of the relative emission probabilities from Refs [III–6, III–14 to III–16] for which no adopted uncertainty was deemed to be lower than the lowest measured uncertainty. Krusche et al. have studied the $^{35}Cl(n, \gamma)^{36}Cl$ reaction in considerable detail [III–21] and placed 326 γ transitions in the ^{36}Cl decay scheme out of almost 400 emissions observed. These assigned transitions contain 99% of the γ ray flux of the reaction, and those populating the ground state can be defined with confidence to sum to 1.00 (100%) in deriving an accurate NF of 0.001935(8). This value has been used in conjunction with the relative γ ray emission probabilities to calculate the absolute γ ray emission probabilities listed in column 7 of Table III–4.

The ratios of emission probabilities $P_{\gamma i}/P_{\gamma j}$ are usually more accurate than the absolute values of $P_{\gamma i}$. Such relative emission probabilities of the γ rays from the $^{35}Cl(n, \gamma)^{36}Cl$ reaction were measured by Molnár et al. [III–15, III–22]; the authors claim an accuracy better than 1%. The ratios of the emission probabilities for 36 γ rays relative to the 1164.9 keV γ ray are shown in Table III–5, in which the values of 20 of these ratios were determined to an accuracy of better than 1.0%. Please note that the $P_{\gamma i}$ data listed

TABLE III–4. THERMAL NEUTRON CAPTURE CROSS-SECTIONS ($\sigma_{\gamma i}$) FOR SELECTED γ_i RAYS FROM THE $^{35}Cl(n, \gamma)^{36}Cl$ REACTION, AND CORRESPONDING EVALUATED γ_i RAY EMISSION PROBABILITIES $P_{\gamma i}$(abs) PER NEUTRON CAPTURE AS EVALUATED FROM REFS [III–6, III–14 TO III–16]

$E_{\gamma i}$ (keV)	$P_{\gamma i}$(rel)[a]					$P_{\gamma i}$(abs)	$\sigma_{\gamma i}$ (b)
	[III–14]	[III–16]	[III–6]	[III–15]	LWM recommended		
517.07006(23)	125.32(722)	—	117.82(248)	119.83(78)	119.71(78)	0.2316(18)	10.10(13)
786.2970(4)	54.25(180)	—	51.49(149)	54.03(47)	53.83(51)	0.1042(11)	4.54(7)
788.4230(4)	84.17(186)	—	81.19(198)	85.63(78)	84.9(10)	0.1643(18)	7.16(11)
1131.244(12)	9.86(29)	—	—	9.90(5)	9.90(5)	0.0192(1)	0.837(10)
1164.8579(5)	140.28(371)	—	134.65(248)	140.86(62)	140.5(10)	0.2719(17)	11.85(15)
1601.068(17)	17.97(46)	—	19.01(30)	19.13(11)	19.06(18)	0.0369(4)	1.61(2)
1951.1278(14)	100(3)	100(3)	100(2)	100.0(6)	100.0(6)	0.1935(12)	8.44(10)
1959.343(8)	64.78(144)	67.16(200)	64.36(149)	64.76(47)	64.84(47)	0.1255(10)	5.51(7)
2676.31(3)	8.11(20)	7.91(25)	—	8.42(6)	8.37(10)	0.0162(2)	0.706(11)
2863.82(3)	29.76(57)	32.64(70)	27.92(45)	28.74(16)[b]	29.09(76)	0.0563(14)	2.45(7)
2975.25(4)	5.39(13)	5.92(15)	—	5.95(7)[c]	5.78(18)	0.0112(4)	0.488(18)
3061.83(4)	18.16(34)	18.21(40)	17.08(30)	17.81(11)	17.79(16)	0.0344(3)	1.500(21)
4440.38(5)	5.40(12)	5.50(13)	—	5.95(6)[d]	5.70(25)	0.0110(5)	0.480(22)
4979.72(5)	18.65(50)	18.61(40)	—	19.47(16)	19.29(24)	0.0373(5)	1.63(3)
5517.21(6)	8.71(22)	8.46(20)	—	8.84(7)	8.79(8)	0.0170(2)	0.741(12)
5715.20(6)	27.39(77)	27.61(55)	26.39(50)	28.74(26)[e]	27.88(86)	0.0539(17)	2.35(8)
5902.69(6)	5.69(16)	—	—	5.87(7)	5.84(7)	0.0113(1)	0.493(7)
6110.80(6)	106.14(335)	101.00(199)	102.97(198)	104.22(94)	103.66(94)	0.2006(20)	8.75(13)
6619.57(7)	40.38(83)	40.45(95)	37.57(74)	39.98(36)	39.71(53)	0.0768(11)	3.35(6)
6627.78(7)	24.19(57)	24.63(65)	21.98(45)	23.17(26)[f]	23.20(49)	0.0449(10)	1.96(5)
6977.79(7)	11.81(33)	11.24(25)	11.09(25)	11.71(16)	11.50(16)	0.0223(3)	0.972(17)
7413.92(8)	54.25(124)	51.24(109)	49.50(124)	52.00(73)	51.80(80)	0.1002(16)	4.37(8)
7790.28(8)	42.86(98)	41.04(95)	40.84(109)	42.01(52)	41.83(52)	0.0809(11)	3.53(6)
8578.53(9)	14.13(29)	13.73(35)	13.51(35)	13.95(21)	13.89(21)	0.0269(4)	1.173(21)

[a] Relative to the 1951.1 keV γ ray.
[b] Uncertainty adjusted to (32) based on the chi-squared test.
[c] Uncertainty adjusted to (10) based on the chi-squared test.
[d] Uncertainty adjusted to (9) based on the chi-squared test.
[e] Uncertainty adjusted to (33) based on the chi-squared test.
[f] Uncertainty adjusted to (31) based on the chi-squared test.

TABLE III–5. EMISSION PROBABILITIES OF γ RAYS FROM THERMAL NEUTRON CAPTURE BY ^{35}Cl RELATIVE TO THE 1164.9 keV γ RAY, AS DETERMINED FROM REFS [III–15, III–22]

$E_{\gamma i}$ (keV)	$P_{\gamma i}/P_{\gamma 1165keV}$
292.175(5)	0.01001(12)
436.220(5)	0.0347(3)
517.07006(23)	0.851(7)
632.434(7)	0.01249(19)
786.2970(4)	0.384(4)
788.4230(4)	0.608(6)
936.915(10)	0.01933(17)
1131.244(12)	0.0703(5)
1164.8579(5)	1.000(6)
1327.400(14)	0.0451(3)
1601.068(17)	0.1358(10)
1951.1278(14)	0.710(5)
1959.343(8)	0.460(4)
2034.63(2)	0.0268(5)
2676.31(3)	0.0598(5)
2845.49(3)	0.0392(3)
2863.82(3)	0.2040(14)
2975.25(4)	0.0422(5)
3015.94(4)	0.0368(3)
3061.83(4)	0.1265(10)
3116.02(8)	0.0334(3)
3428.83(4)	0.0305(3)
3981.06(5)	0.0372(8)
4082.70(6)	0.0295(6)
4440.38(5)	0.0422(4)
4979.72(5)	0.1382(13)
5517.21(6)	0.0628(6)
5715.20(6)	0.2040(21)
5902.69(6)	0.0417(5)
6110.80(6)	0.740(7)
6619.57(7)	0.284(3)
6627.78(7)	0.1644(20)
6977.79(7)	0.0831(12)
7413.92(8)	0.369(5)
7790.28(8)	0.298(4)
8578.53(9)	0.0990(15)

in Table III–4 are the average emission probabilities of the measured values from four laboratories, while the $P_{\gamma i}/P_{\gamma 1165keV}$ ratios in Table III–5 originate from one set of measurements only; furthermore, the two sets of relative emission probabilities are quoted relative to different γ ray emissions. Ratios of emission probabilities for pairs of cascading γ rays were calculated from the data in Table III–4 (see Section III–4.5 and Table III–9). Both the γ ray energies and their uncertainties in Tables III–4 and III–5 were taken from Molnár et al. [III–23], who adapted the data of Krusche et al. [III–21] and Kessler et al. [III–24].

III–4.3. $^{47,48,49}Ti(n, \gamma)^{48,49,50}Ti$ reactions

The ^{48}Ti (n, γ)^{49}Ti reaction may also be useful with γ rays at energies of 6418, 6556 and 6760 keV, and emission probabilities that can be related to the probabilities of the accompanying low energy γ rays of 342, 1382 and 1586 keV, respectively. Measured γ ray yields of Ref. [III–25] have been normalized to a Q value of 8.14243 MeV, and a resulting NF of 1.0084 was adopted in determining the data listed in Table III–6 from Ref. [III–26]. As shown in this table, the emission probabilities of the higher intensity γ rays have been determined to a statistical accuracy of better than 3%, although a systematic uncertainty of 5% was attributed to the data of Ref. [III–25].

TABLE III–6. EVALUATED THERMAL NEUTRON CAPTURE CROSS-SECTIONS ($\sigma_{\gamma i}$) FOR SELECTED γ_i FROM THE $^{48}Ti(n, \gamma)^{49}Ti$ REACTION AND CORRESPONDING γ_i RAY EMISSION PROBABILITIES (($P_{\gamma i}$) PER NEUTRON CAPTURE) FROM REF. [III–26]

$E_{\gamma i}$ (keV)	$\sigma_{\gamma i}$ (b)	$P_{\gamma i}$
341.69(3)	2.13(5)	0.250(2)
1381.72(3)	7.33(25)	0.862(21)
1498.63(3)	0.419(15)	0.0493(13)
1585.95(3)	0.88(3)	0.1029(30)
1761.96(3)	0.459(17)	0.0540(16)
4881.32(5)	0.387(10)	0.0455(5)
6418.38(7)	2.62(7)	0.308(3)
6555.83(7)	0.436(11)	0.0513(5)
6760.06(7)	3.97(10)	0.467(4)

TABLE III–7. EMISSION PROBABILITIES OF γ RAYS FROM THERMAL NEUTRON CAPTURE IN NATURAL TITANIUM RELATIVE TO THE 1381.7 keV γ RAY [III–22]

$E_{\gamma i}$ (keV)	Target	$P_{\gamma i}/P_{\gamma 1382keV}$
137.46(3)	^{48}Ti	0.01218(10)
341.69(3)	^{48}Ti	0.3786(14)
983.50(4)	^{47}Ti	0.02275(19)
1381.72(3)	^{48}Ti	1.000(4)
1498.63(3)	^{48}Ti	0.0570(3)
1553.79(4)	^{49}Ti	0.01882(23)
1585.95(3)	^{48}Ti	0.1178(6)
1761.96(3)	^{48}Ti	0.0600(4)
1793.47(3)	^{48}Ti	0.02928(24)
2943.12(4)	^{48}Ti	0.01221(13)
3026.76(4)	^{48}Ti	0.02674(24)
3475.62(4)	^{48}Ti	0.01950(18)
3733.75(5)	^{48}Ti	0.01612(18)
3920.44(5)	^{48}Ti	0.01629(18)
4881.32(5)	^{48}Ti	0.0559(5)
4966.74(5)	^{48}Ti	0.0365(4)
6418.38(7)	^{48}Ti	0.343(3)
6555.83(7)	^{48}Ti	0.0574(7)
6760.06(7)	^{48}Ti	0.518(5)

The relative emission probabilities of the γ rays from thermal neutron capture in a natural titanium target are listed in Table III–7, as reported in Ref. [III–22]. Ratios of these probabilities for pairs of cascading γ rays have also been calculated (see Section III–4.5 and Table III–9). Gamma ray energies in Tables III–6 and III–7 are taken from Ref. [III–23]. Please note that the sets of $P_{\gamma i}$ data listed in Tables III–6 and III–7 originate from two different laboratories, and therefore these two data listings are not fully consistent with each other.

III–4.4. ^{50,52,53}Cr(n, γ)^{51,53,54}Cr reactions

^{52,53}Cr(n, γ)^{53,54}Cr reactions were considered in Ref. [III–2] because of the possible use of the associated γ rays with relatively high energies of 7099, 7375, 7939, 8883 and 9718 keV. The relative emission probabilities of the strong γ rays from thermal neutron capture in natural chromium are given in Table III–8, as reported by Belgya and Molnár [III–27]. Most of the emission probabilities are determined to an accuracy of better than 2%, while the γ ray energies are taken from Ref. [III–23].

TABLE III–8. EMISSION PROBABILITIES OF γ RAYS FROM THERMAL NEUTRON CAPTURE BY NATURAL CHROMIUM RELATIVE TO THE 835 keV γ RAY [III–27]

$E_{\gamma i}$ (keV)	Target	$P_{\gamma i}/P_{835keV}$
564.35(6)	^{52}Cr	0.0819(4)
749.32(6)	^{50}Cr	0.4137(17)
835.03(6)	^{53}Cr	1.000(4)
1150.06(5)	^{50}Cr	0.01525(11)
1784.69(5)	^{53}Cr	0.1284(6)
1899.25(5)	^{50}Cr	0.0619(4)
2239.16(5)	^{53}Cr	0.1354(7)
2321.09(5)	^{52}Cr	0.0968(5)
2376.84(5)	^{50}Cr	0.02588(13)
2670.20(5)	^{52}Cr	0.02006(12)
3616.88(8)	^{52}Cr	0.01886(11)
3719.77(6)	^{53}Cr	0.04674(24)
4322.43(8)	^{52}Cr	0.02096(12)
5268.92(12)	^{52}Cr	0.0333(3)
5618.13(11)	^{52}Cr	0.0949(8)
5998.63(11)	^{53}Cr	0.0569(5)
6135.39(13)	^{50}Cr	0.0466(10)
6644.47(14)	^{53}Cr	0.1229(11)
7098.84(19)	^{53}Cr	0.0963(9)
7361.99(17)	^{50}Cr	0.0643(6)
7374.68(17)	^{52}Cr	0.0557(5)
7938.65(18)	^{52}Cr	0.294(3)
8511.55(20)	^{50}Cr	0.1555(21)
8882.88(22)	^{53}Cr	0.562(7)
9717.5(3)	^{53}Cr	0.200(3)

III–4.5. Ratios of cascading γ rays

The level schemes in nuclear reactions often result in the ratio of the emission probabilities of two γ rays emitted in cascade being determined more accurately than the relative intensities of the full spectrum of γ rays. Ideally, the ratio of the emission probabilities should be 1.00, which arises when the two γ rays populate and depopulate a common level, no other γ rays populate or depopulate this level, and there is no significant internal conversion or internal pair production for either γ ray. These ratios are useful for detector efficiency calibration if one of the γ rays occurs in an energy region for which the efficiency is already known, so that the efficiency can be computed at the second energy. Some γ ray emission probability ratios have been collected in Table III–9, as deduced from the reaction data given in the preceding tables. While the adoption of these data for calibration purposes depends on the availability of a thermal neutron source, the usefulness of any particular reaction has also to be assessed from the reaction cross-section, a suitable sample selection, and the lack of any interference from background γ rays (including the occurrence of the same reaction outside the target).

III–5. RESONANCE PROTON CAPTURE REACTIONS

The proton capture reaction has frequently been used as a source of γ rays for the calibration of germanium detectors. Proton capture has the advantage that simple γ ray spectra are often produced when the proton energy is chosen to coincide with a single resonance. The thermal neutron capture cross-section (σ_C) has to be replaced by the proton capture cross-section (σ_R) at the resonance energy (E_p) in order to specify Eqs (III–1) and (III–2) for a resonance:

$$\sigma_R = \frac{\lambda_p^2}{\pi}\frac{(2J+1)}{(2s_p+1)(2I_T+1)}\frac{\Gamma_p}{\Gamma^2} \qquad \text{(III–3)}$$

The resulting radiative capture cross-section at the resonance energy is given by the equation:

$$\sigma_\lambda = \frac{\lambda_p^2}{\pi}\frac{(2J+1)}{(2s_p+1)(2I_T+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma^2} \qquad \text{(III–4)}$$

The cross-section for the emission of a specific γ_i ray is expressed via the emission probability $P_{\gamma i}$:

$$\sigma_{\gamma i} = \sigma_\gamma P_{\gamma i} \qquad \text{(III–5)}$$

Using the measured resonance strengths $S_{p\gamma} = (2J + 1)\Gamma_p\Gamma_\gamma/\Gamma$ and the resonance widths Γ from Refs [III–28, III–29], the proton capture cross-sections (σ_γ) can be obtained from Eq. (III–4) as shown in Table III–10. The experimental emission probabilities $P_{\gamma i}$ for selected γ_i rays [III–28 to III–30] were used in Eq. (III–5) to calculate the corresponding emission cross-sections ($\sigma_{\gamma i}$); these results are listed in Tables III–11 to III–13.

TABLE III–9. EMISSION PROBABILITY RATIOS OF γ_1 RAYS (POPULATING) AND γ_2 RAYS (DEPOPULATING A COMMON LEVEL) AFTER THERMAL NEUTRON CAPTURE

Reaction	$E_{\gamma 1}$ (keV)	$E_{\gamma 2}$ (keV)	P1/P2	Ref.
$^{35}Cl(n, \gamma)^{36}Cl$	5715.20	2863.82	0.96(4)	[III–6. III–14 to III–16]
	5902.69	2676.31	0.698(12)	[III–6, III–14 to III–16]
	6110.80	1951.1278[a]	1.037(11)	[III–6, III–14 to III–16]
	6110.80	517.07006	0.866(10)	[III–6, III–14 to III–16]
	6619.57	1959.343	0.612(9)	[III–6, III–14 to III–16]
	6977.79	1601.068	0.603(10)	[III–6, III–14 to III–16]
	7790.28	788.4230	0.493(6)	[III–6, III–14 to III–16]
$^{48}Ti(n, \gamma)^{49}Ti$	4881.32	1498.63	0.981(10)	[III–22]
	6418.38	341.69	0.906(9)	[III–22]
	6555.83	1585.95	0.487(6)	[III–22]
	6760.06	1381.72	0.518(5)	[III–22]
$^{52}Cr(n, \gamma)^{53}Cr$	5618.13	2321.09	0.980(8)	[III–27]
$^{53}Cr(n, \gamma)^{54}Cr$	6644.47	2239.16	0.907(8)	[III–27]
	7098.84	1784.69	0.750(8)	[III–27]
	8882.88	835.03	0.562(7)	[III–27]

[a] Subsequent emission of three γ rays in cascade.

TABLE III–10. CALCULATED RESONANCE PROTON CAPTURE CROSS-SECTIONS

Reaction	E_p (keV)	Γ (eV)	$S_{p\gamma}$ (eV)	σ_γ (mb)
$^{14}N(p, \gamma)^{15}O$	1058.0(5)	3900(700)	5.7	0.69(12)
$^{23}Na(p, \gamma)^{24}Mg$	1416.85(7)	90(30)	27(6)	75(30)
$^{27}Al(p, \gamma)^{28}Si$	991.86(3)	70(14)	24(2)	81(17)

TABLE III–11. EVALUATED PROTON CAPTURE CROSS-SECTIONS ($\sigma_{\gamma i}$) FOR SELECTED γ_i RAYS FROM THE $^{14}N(p, \gamma)^{15}O$ REACTION AT RESONANCE ENERGY E_p = 1058 keV, AND CORRESPONDING EMISSION PROBABILITIES $P_{\gamma i}$ (PER PROTON CAPTURE) FROM REF. [III–30] (energies are taken from Ref. [III–31])

$E_{\gamma i}$ (keV)	$\sigma_{\gamma i}$ (mb)	$P_{\gamma i}$
3042.8(6)	0.290(50)	0.422(5)
5239.9(3)	0.299(52)	0.434(6)
8281.5(5)	0.366(62)	0.5320(25)

TABLE III–12. EVALUATED PROTON CAPTURE CROSS-SECTIONS ($\sigma_{\gamma i}$) FOR SELECTED γ_i RAYS FROM THE $^{23}Na(p, \gamma)^{24}Mg$ REACTION AT RESONANCE ENERGY E_p = 1417 keV, AND CORRESPONDING EMISSION PROBABILITIES $P_{\gamma i}$ (PER PROTON CAPTURE) FROM REF. [III–29] (energies are taken from Ref. [III–31])

$E_{\gamma i}$ (keV)	$\sigma_{\gamma i}$ (mb)	$P_{\gamma i}$
2754.028	71(28)	0.94(1)
8925.55	70(28)	0.93(1)

TABLE III–13. EVALUATED PROTON CAPTURE CROSS-SECTIONS ($\sigma_{\gamma i}$) FOR SELECTED γ_i RAYS FROM THE $^{27}Al(p, \gamma)^{28}Si$ REACTION AT RESONANCE ENERGY E_p = 992 keV, AND CORRESPONDING EMISSION PROBABILITIES $P_{\gamma i}$ (PER PROTON CAPTURE) FROM REF. [III–32] (energies are taken from Refs [III–31, III–32])

$E_{\gamma i}$ (keV)	$\sigma_{\gamma i}$ (mb)	$P_{\gamma i}$
1778.969(12)	77(17)	0.948(15)
10762.9	62(14)	0.766(15)

III–5.1. Ratios of cascading γ rays

As emphasized earlier, the ratios of the emission probabilities $P_{\gamma i}/P_{\gamma j}$ are usually determined with better accuracy than $P_{\gamma i}$ alone. Therefore, this ‘two line method’ has been used in thermal neutron capture and proton capture reactions. The resulting calibration will be completely independent of previously measured efficiencies for high energy γ rays, when a high energy and a low energy γ transition from the initial capturing state and via an intermediate state, respectively, both have 100% γ ray branching to one level, resulting in an intensity ratio $P_{\gamma 1}/P_{\gamma 2}$ = 1. Since the efficiency for the low energy γ ray arises from a well defined radioactive source, the determination of the efficiency of the high energy γ ray is straightforward. However, such situations are extremely rare and hence (p, γ) reactions on light nuclei, with their broad choice of many sharp resonances, have certain advantages over thermal neutron capture reactions. Eight cascading γ ray pairs were reported in Ref. [III–33] with uncertainties in $P_{\gamma 1}/P_{\gamma 2}$ estimated at about 2%. More recently, the intensity ratios of strong cascades in the multi-γ decay of four resonances in the $^{23}Na(p, \gamma)^{24}Mg$ and $^{27}Al(p, \gamma)^{28}Si$ reactions have been measured with an accuracy better than 1.0%, and three resonances in the $^{11}B(p, \gamma)^{12}C$ reaction with an accuracy of 1–2% [III–34]. The latter resonances extend the calibration energy range up to 13.92 MeV. All these data are included in IAEA-TECDOC-619 [III–2], and have been collected in Table III–14.

Certain experimental effects should be taken into account in the (p, γ) reactions, i.e. the width of the resonance, the energy spread of the beam and the target thickness should neither degrade the detector resolution nor alter the apparent efficiency. Since the emitted γ rays have anisotropic angular distributions with respect to the beam direction, the observed counting rate must be corrected for this variation. This correction can normally be achieved simply by undertaking measurements at an angle θ of 55° or 125° with respect to the beam direction

TABLE III–14. PROTON CAPTURE REACTIONS WITH SUBSEQUENT EMISSION OF γ_1 AND γ_2 RAYS IN CASCADE; EMISSION PROBABILITIES ARE P_1 AND P_2, AND E_P IS THE PROTON RESONANCE ENERGY, WHILE ENERGIES ARE TAKEN FROM REF. [III–31]

Reaction	E_p (keV)	$E_{\gamma 1}$ (keV)	$E_{\gamma 2}$ (keV)	P1/P2	Ref.
$^{11}B(p, \gamma)^{12}C$	675	12140	4438.03	1.000(<1)[a]	[III–34]
	1388	12790	4438.03	1.000(<1)[a]	[III–34]
	2626	13920	4438.03	1.000(<1)[a]	[III–34]
$^{14}N(p, \gamma)^{15}O$	278	5182(1)	2373(1)	1.000(38)	[III–30]
		6174.9(1)	1380.1(17)	1.000(7)	[III–30]
		6791.4(17)	763.4(17)	1.000(37)	[III–30]
	1058	5239.9(3)	3042.8(6)	1.028(12)	[III–30]
$^{23}Na(p, \gamma)^{24}Mg$	1318	11588	1368.633	0.960(2)	[III–34]
	1417	8925.55	2754.028	0.9850(11)	[III–34]
$^{27}Al(p, \gamma)^{28}Si$	767	7706	2838.67(5)	0.981(2)	[III–34]
	992	10762.9	1778.969(12)	0.806(10)	[III–34]
	1317	6580	4500	1.017(6)	[III–34]

[a] Another 1–2% uncertainty arises from the angular distribution, even when applied at $\theta = 55°$.

under the assumption that $\theta = 55°$ intensities are proportional to the 4π-integrated γ ray yields; $P_2(\cos\theta) = 0$ at this angle, which minimizes the influence of the angular distribution. P_1, P_3 and P_4 terms are assumed to be negligible, although there are reactions in which this may not occur, e.g. in the $^{11}B(p, \gamma)^{12}C$ reaction (Table III–14), the $P_1(\cos\theta)$ term does not vanish [III–34].

III–6. CONTINUUM PROTON CAPTURE BY ^{11}B

Radiative proton capture to the continuum states of the compound nucleus $^{12}C^*$ (defined as the highly excited target nucleus plus the proton projectile) can be used as a source of primary γ rays of variable energy. The most useful are the primary γ_0 rays from the direct decay of the capturing states in the continuum (contained within the energy spread of the proton beam combined with the straggling due to target thickness) to the ground state of ^{12}C. The variable energy of these γ_0 rays depends on the laboratory bombarding energy (E_p) and the binding energy of the proton in ^{12}C (B_p = 15.95717 ± 0.00033 MeV):

$$E_{\gamma 0} = E_p(11/12) + B_p \qquad \text{(III–6)}$$

The width of the γ_0 peak in the calibration spectrum depends on the target thickness and the energy resolution of the proton beam. Target thickness is the dominant factor since μg/cm^2 to tens of mg/cm^2 of target material are often used. Figure III–1 and Table III–15 contain the recommended differential cross-sections for the emission of the primary γ_0 rays from proton capture in ^{11}B measured at 90° with respect to the proton beam direction [III–35 to III–39]. The cross-sections in Ref. [III–37] were measured with an accuracy better than 6% (see Tables III–15 and III–16), and these data extend from a proton energy of 18.00 to 43.70 MeV. The studies of Ref. [III–36] range from

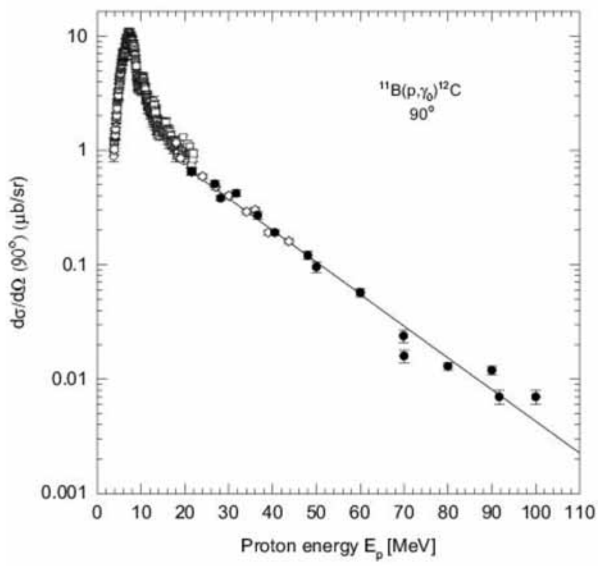

FIG. III–1. Recommended 90° differential cross-section for the $^{11}B(p, \gamma_0)^{12}C$ reaction [III–35 to III–39].

a proton energy of 13.00 to 21.80 MeV, and the cross-sections were multiplied by a factor of 1.25 in order to fit the data of Ref. [III–37] in the region of overlapping energies. Furthermore, the cross-sections from Ref. [III–35] were multiplied by a factor of 0.66 to achieve consistency. The cross-sections in Ref. [III–38] were measured at three proton energies (48.04, 69.86 and 91.68 MeV), and those of Ref. [III–39] at several energies ranging from 21.5 to 100 MeV. Both data sets are consistent with the cross-sections reported in Ref. [III–37]. Data in Ref. [III–39] were obtained at 60° with respect to the proton beam and converted into 90° data by means of the Legendre expansion coefficients from Tables III–17 and III–18. As a result, the recommended data set extends from a proton energy of 3.70 to approximately 100 MeV. An uncertainty of about ±6% was adopted for the evaluated cross-sections (solid line in Fig. III–1, and 'eval' in Table III–16), as specified in Ref. [III–37] (compare with the sixth column in Table III–15).

The Legendre polynomial expansion coefficients shown in Figs III–2 and III–3 and listed in Tables III–17 and III–18 are given as a function of the incident proton energy in the range from approximately 14.00 to 90.00 MeV.

III–7. PROTON INELASTIC SCATTERING AND THE $^{19}F(p, \alpha\gamma)^{16}O$ REACTION

The 4438.0(3) and 15099(3) keV γ rays produced in proton scattering on carbon by the $^{12}C(p, p'\gamma)^{12}C$ reaction, and the 6128.63(4) keV γ ray from the $^{19}F(p, \alpha\gamma)^{16}O$ reaction are used routinely for the energy calibration of γ ray spectra. Therefore, an attempt was made to evaluate the production cross-sections of these energy calibration standards with the aim of obtaining new intensity calibrants. Although numerous measurements of the reactions in question have been compiled and evaluated [III–41, III–42], the accuracy of the experimental data does not meet the requirements for metrological applications. The uncertainties in the measured differential cross-sections vary between 11 and 20%, and are much higher than the uncertainties of the emission probabilities of the γ rays following thermal-neutron capture or proton capture reactions. As was shown in the preceding sections, the latter are normally found to vary between 2 and 6%, although uncertainties as small as 0.5% are not uncommon.

TABLE III–15. EXPERIMENTAL DIFFERENTIAL CROSS-SECTIONS FOR THE $^{11}B(p, \gamma_0)^{12}C$ REACTION IN (μb/sr) MEASURED AT DIFFERENT LABORATORY ANGLES AS GIVEN IN REF. [III–37]

E_p (MeV)	34°	45°	60°	75°	90°	105°	120°
18	0.760(37)	1.010(51)	1.260(56)	1.200(63)	1.170(63)	0.885(45)	0.580(30)
19	0.650(34)	0.900(27)	1.030(51)	1.080(60)	0.850(50)	0.650(37)	0.480(27)
21.5	0.590(26)	0.760(42)	0.790(38)	0.740(40)	0.750(41)	0.490(28)	0.330(19)
24	0.510(29)	0.660(19)	0.640(32)	0.630(37)	0.590(33)	0.320(18)	0.200(12)
27	0.470(26)	0.580(31)	0.650(30)	0.580(31)	0.480(27)	0.290(17)	0.150(10)
30	0.520(24)	0.520(21)	0.570(26)	0.470(25)	0.400(22)	0.250(11)	0.128(8)
32	0.470(21)	0.480(25)	0.520(21)	0.470(25)	0.320(18)	0.240(14)	0.100(6)
34	0.410(21)	0.420(21)	0.460(21)	0.420(2)	0.290(16)	0.150(9)	0.078(5)
36	0.390(17)	0.460(23)	0.470(21)	0.380(18)	0.300(16)	0.130(8)	0.070(5)
39	0.330(16)	0.400(20)	0.420(19)	0.270(14)	0.190(11)	0.060(4)	0.050(4)
43.7	0.190(10)	0.370(18)	0.330(14)	0.210(11)	0.160(9)	0.040(4)	0.026(2)

TABLE III–16. RECOMMENDED 90° DIFFERENTIAL CROSS-SECTIONS FOR THE $^{11}B(p, \gamma_0)^{12}C$ REACTION

E_p (MeV)	$\sigma(\Delta\sigma)$ (μb/sr)	Ref.	E_p (MeV)	$\sigma(\Delta\sigma)$ (μb/sr)	Ref.
3.70	0.098(10)	[III–35]	5.80	6.65(67)	[III–35]
3.75	0.89(9)	[III–35]	5.85	6.92(69)	[III–35]
3.80	1.16(12)	[III–35]	5.90	7.04(70)	[III–35]
3.85	1.15(12)	[III–35]	5.95	6.82(68)	[III–35]
3.90	1.02(10)	[III–35]	6.00	6.67(67)	[III–35]
3.95	1.27(13)	[III–36]	6.05	6.90(69)	[III–35]
4.00	1.35(14)	[III–35]	6.10	6.85(69)	[III–35]
4.05	1.39(14)	[III–35]	6.15	7.01(70)	[III–35]
4.10	1.40(14)	[III–35]	6.20	6.91(69)	[III–35]
4.15	1.36(14)	[III–35]	6.25	7.03(70)	[III–35]
4.20	1.54(15)	[III–35]	6.30	7.34(73)	[III–35]
4.25	1.90(19)	[III–35]	6.35	7.76(78)	[III–35]
4.30	1.78(18)	[III–35]	6.40	7.89(79)	[III–35]
4.35	1.94(19)	[III–35]	6.45	8.55(86)	[III–35]
4.40	1.93(19)	[III–35]	6.50	8.67(87)	[III–35]
4.45	2.02(20)	[III–35]	6.55	8.53(85)	[III–35]
4.50	2.57(26)	[III–35]	6.60	9.20(92)	[III–35]
4.55	2.34(23)	[III–35]	6.65	8.75(88)	[III–35]
4.60	2.76(28)	[III–35]	6.70	9.20(92)	[III–35]
4.65	2.89(29)	[III–35]	6.75	8.87(87)	[III–35]
4.70	3.06(31)	[III–35]	6.80	8.77(88)	[III–35]
4.75	2.94(29)	[III–35]	6.85	9.29(93)	[III–35]
4.80	3.14(31)	[III–35]	6.90	9.62(96)	[III–35]
4.85	3.02(30)	[III–35]	6.95	9.29(93)	[III–35]
4.90	3.47(35)	[III–35]	7.00	9.74(97)	[III–35]
4.95	3.85(39)	[III–35]	7.05	10.07(101)	[III–35]
5.00	3.74(37)	[III–35]	7.10	10.26(103)	[III–35]
5.05	4.20(42)	[III–35]	7.15	10.46(105)	[III–35]
5.10	4.33(43)	[III–35]	7.20	10.68(107)	[III–35]
5.15	4.02(40)	[III–35]	7.25	9.84(100)	[III–35]
5.20	4.28(43)	[III–35]	7.30	10.71(107)	[III–35]
5.25	4.47(45)	[III–35]	7.35	10.01(100)	[III–35]
5.30	4.61(46)	[III–35]	7.40	10.41(104)	[III–35]
5.35	4.76(48)	[III–35]	7.45	9.82(98)	[III–35]
5.40	5.22(52)	[III–35]	7.50	9.96(100)	[III–35]
5.45	5.30(53)	[III–35]	7.55	9.77(98)	[III–35]
5.50	5.52(55)	[III–35]	7.60	9.37(94)	[III–35]
5.55	5.80(58)	[III–35]	7.65	9.53(95)	[III–35]
5.60	5.68(57)	[III–35]	7.70	9.41(94)	[III–35]
5.65	6.09(61)	[III–35]	7.75	9.27(93)	[III–35]
5.70	6.16(62)	[III–35]	7.80	9.28(93)	[III–35]
5.75	6.30(63)	[III–35]	7.85	8.76(88)	[III–35]

TABLE III–16. RECOMMENDED 90° DIFFERENTIAL CROSS-SECTIONS FOR THE $^{11}B(p, \gamma_0)^{12}C$ REACTION (cont.)

E_p (MeV)	$\sigma(\Delta\sigma)$ (μb/sr)	Ref.	E_p (MeV)	$\sigma(\Delta\sigma)$ (μb/sr)	Ref.
7.90	8.87(89)	[III–35]	10.00	3.52(35)	[III–35]
7.95	9.09(91)	[III–35]	10.05	3.41(34)	[III–35]
8.00	9.02(90)	[III–35]	10.10	3.69(37)	[III–35]
8.05	8.52(85)	[III–35]	10.15	3.82(38)	[III–35]
8.10	8.02(80)	[III–35]	10.20	3.33(33)	[III–35]
8.15	8.42(84)	[III–35]	10.25	3.91(39)	[III–35]
8.20	8.29(83)	[III–35]	10.30	4.03(40)	[III–35]
8.25	8.44(84)	[III–35]	10.35	4.42(44)	[III–35]
8.30	8.34(83)	[III–35]	10.40	4.25(43)	[III–35]
8.35	7.50(75)	[III–35]	10.45	4.11(41)	[III–35]
8.40	8.01(80)	[III–35]	10.50	3.78(38)	[III–35]
8.45	7.09(71)	[III–35]	10.55	4.21(42)	[III–35]
8.50	7.45(75)	[III–35]	10.60	3.94(39)	[III–35]
8.55	7.01(70)	[III–35]	10.65	3.79(38)	[III–35]
8.60	6.86(69)	[III–35]	10.70	3.68(37)	[III–35]
8.65	6.73(67)	[III–35]	10.75	3.56(36)	[III–35]
8.70	6.24(62)	[III–35]	10.80	3.45(35)	[III–35]
8.75	6.01(60)	[III–35]	10.85	3.43(34)	[III–35]
8.80	5.74(57)	[III–35]	10.90	3.55(36)	[III–35]
8.85	5.34(53)	[III–35]	10.95	3.21(32)	[III–35]
8.90	5.45(55)	[III–35]	11.00	3.40(34)	[III–35]
8.95	4.62(46)	[III–35]	11.05	2.83(28)	[III–35]
9.00	4.56(46)	[III–35]	11.10	2.96(30)	[III–35]
9.05	4.34(43)	[III–35]	11.15	2.85(29)	[III–35]
9.10	4.16(42)	[III–35]	11.20	3.04(30)	[III–35]
9.15	3.98(40)	[III–35]	11.25	2.88(29)	[III–35]
9.20	3.76(38)	[III–35]	11.30	3.04(30)	[III–35]
9.25	3.69(37)	[III–35]	11.35	2.88(29)	[III–35]
9.30	3.65(37)	[III–35]	11.40	2.87(29)	[III–35]
9.35	3.60(36)	[III–35]	11.45	2.83(28)	[III–35]
9.40	3.47(35)	[III–35]	11.50	2.34(23)	[III–35]
9.45	3.91(39)	[III–35]	11.55	2.51(25)	[III–35]
9.50	3.78(38)	[III–35]	11.60	2.64(26)	[III–35]
9.55	4.13(41)	[III–35]	11.65	2.51(25)	[III–35]
9.60	3.74(37)	[III–35]	11.70	2.34(23)	[III–35]
9.65	3.76(38)	[III–35]	11.75	2.46(25)	[III–35]
9.70	4.42(44)	[III–35]	11.80	2.68(27)	[III–35]
9.75	3.82(38)	[III–35]	11.85	2.55(26)	[III–35]
9.80	3.80(38)	[III–35]	11.90	2.36(24)	[III–35]
9.85	3.69(37)	[III–35]	11.95	2.59(26)	[III–35]
9.90	4.22(42)	[III–35]	12.00	2.11(21)	[III–35]
9.95	4.23(42)	[III–35]	12.05	2.34(23)	[III–35]

TABLE III–16. RECOMMENDED 90° DIFFERENTIAL CROSS-SECTIONS FOR THE $^{11}B(p, \gamma_0)^{12}C$ REACTION (cont.)

E_p (MeV)	$\sigma(\Delta\sigma)$ (μb/sr)	Ref.	E_p (MeV)	$\sigma(\Delta\sigma)$ (μb/sr)	Ref.
12.10	2.22(22)	[III–35]	13.80	1.53(15)	[III–36]
12.15	2.10(21)	[III–35]	13.90	1.78(18)	[III–36]
12.20	2.24(22)	[III–35]	14.00	1.40(14)	[III–36]
12.25	2.36(24)	[III–35]	14.10	1.58(16)	[III–36]
12.30	2.26(23)	[III–35]	14.20	1.63(16)	[III–36]
12.35	2.38(24)	[III–35]	14.30	1.35(14)	[III–36]
12.40	2.23(22)	[III–35]	14.40	1.66(17)	[III–36]
12.45	2.40(24)	[III–35]	14.50	1.75(18)	[III–36]
12.50	2.28(23)	[III–35]	14.60	1.63(16)	[III–36]
12.55	2.34(23)	[III–35]	14.70	1.50(15)	[III–36]
12.60	2.18(22)	[III–35]	14.80	1.46(15)	[III–36]
12.65	1.78(18)	[III–35]	14.90	1.58(16)	[III–36]
12.70	2.14(21)	[III–35]	15.00	1.48(15)	[III–36]
12.75	1.87(19)	[III–35]	15.10	1.66(17)	[III–36]
12.80	2.13(21)	[III–35]	15.20	1.56(16)	[III–36]
12.85	1.98(20)	[III–35]	15.30	1.59(16)	[III–36]
12.90	2.30(23)	[III–35]	15.40	1.45(15)	[III–36]
12.95	2.69(27)	[III–35]	15.50	1.75(18)	[III–36]
13.00	2.46(25)	[III–35]	15.60	1.54(15)	[III–36]
13.00	2.18(22)	[III–36]	15.70	1.74(17)	[III–36]
13.05	1.97(20)	[III–35]	15.80	1.41(14)	[III–36]
13.10	1.68(17)	[III–35]	15.90	1.40(14)	[III–36]
13.10	2.20(22)	[III–36]	16.00	1.26(13)	[III–36]
13.15	2.21(22)	[III–35]	16.10	1.51(15)	[III–36]
13.20	1.97(20)	[III–35]	16.20	1.50(15)	[III–36]
13.20	2.08(21)	[III–36]	16.30	1.35(14)	[III–36]
13.25	1.78(18)	[III–35]	16.40	1.16(12)	[III–36]
13.30	2.28(23)	[III–35]	16.50	1.43(14)	[III–36]
13.30	2.14(21)	[III–36]	16.60	1.24(12)	[III–36]
13.35	2.14(21)	[III–35]	16.70	1.26(13)	[III–36]
13.40	1.87(19)	[III–35]	16.80	1.34(13)	[III–36]
13.40	1.84(18)	[III–36]	16.90	1.20(12)	[III–36]
13.45	2.20(22)	[III–35]	17.00	1.16(12)	[III–36]
13.50	1.66(17)	[III–35]	17.10	1.15(12)	[III–36]
13.50	1.75(18)	[III–36]	17.20	1.13(11)	[III–36]
13.55	1.56(16)	[III–35]	17.30	1.14(11)	[III–36]
13.60	1.82(18)	[III–35]	17.40	1.04(10)	[III–36]
13.60	1.51(15)	[III–36]	17.50	1.08(11)	[III–36]
13.65	1.52(15)	[III–35]	17.60	1.19(12)	[III–36]
13.70	1.82(18)	[III–35]	17.70	1.19(12)	[III–36]
13.70	1.61(16)	[III–36]	17.80	1.13(11)	[III–36]
13.75	1.42(14)	[III–35]	17.90	1.09(11)	[III–36]

TABLE III–16. RECOMMENDED 90° DIFFERENTIAL CROSS-SECTIONS FOR THE $^{11}B(p, \gamma_0)^{12}C$ REACTION (cont.)

E_p (MeV)	$\sigma(\Delta\sigma)$ (μb/sr)	Ref.	E_p (MeV)	$\sigma(\Delta\sigma)$ (μb/sr)	Ref.
18.00	1.170(63)	[III–37]	22.00	0.630(37)	eval
18.10	0.90(10)	[III–36]	23.00	0.590(35)	eval
18.20	0.90(5)	[III–36]	24.00	0.590(33)	[III–37]
18.30	1.00(6)	[III–36]	25.00	0.520(31)	eval
18.40	0.94(6)	[III–36]	26.00	0.490(29)	eval
18.50	0.99(6)	[III–36]	26.80	0.51(3)	[III–39]
18.60	1.15(7)	[III–36]	27.00	0.480(27)	[III–37]
18.70	1.08(6)	[III–36]	28.00	0.430(25)	eval
18.80	1.18(7)	[III–36]	28.10	0.38(2)	[III–39]
18.90	1.08(6)	[III–36]	29.00	0.400(24)	eval
19.00	0.88(5)	[III–36]	30.00	0.400(22)	[III–37]
19.00	0.85(5)	[III–37]	31.00	0.350(21)	eval
19.10	1.11(7)	[III–36]	31.70	0.42(3)	[III–39]
19.20	1.13(7)	[III–36]	32.00	0.320(18)	[III–37]
19.30	1.00(6)	[III–36]	33.00	0.311(18)	eval
19.40	1.13(7)	[III–36]	34.00	0.290(16)	[III–37]
19.50	1.00(6)	[III–36]	35.00	0.274(16)	eval
19.60	1.29(8)	[III–36]	36.00	0.300(16)	[III–37]
19.70	0.86(5)	[III–36]	36.60	0.27(2)	[III–39]
19.80	1.05(6)	[III–36]	37.00	0.241(14)	eval
19.90	0.88(5)	[III–36]	38.00	0.226(13)	eval
20.00	1.13(7)	[III–36]	39.00	0.190(11)	[III–37]
20.10	0.96(6)	[III–36]	40.00	0.198(11)	eval
20.20	0.86(5)	[III–36]	40.50	0.19(1)	[III–39]
20.30	1.05(6)	[III–36]	41.00	0.186(11)	eval
20.40	0.90(5)	[III–36]	42.00	0.175(10)	eval
20.50	0.80(5)	[III–36]	43.00	0.164(9)	eval
20.60	1.14(7)	[III–36]	43.70	0.160(9)	[III–37]
20.70	0.90(5)	[III–36]	44.00	0.154(9)	eval
20.80	0.98(6)	[III–36]	45.00	0.144(8)	eval
20.90	1.00(6)	[III–36]	48.40	0.12(1)	[III–38]
21.00	0.94(6)	[III–36]	50.00	0.105(6)	eval
21.10	1.08(6)	[III–36]	55.00	0.0760(45)	eval
21.20	0.95(6)	[III–36]	60.00	0.0550(32)	eval
21.30	0.94(6)	[III–36]	60.00	0.057(4)	[III–39]
21.40	0.74(4)	[III–36]	65.00	0.0400(23)	eval
21.50	0.93(6)	[III–36]	69.86	0.024(3)	[III–38]
21.50	0.750(41)	[III–37]	70.00	0.016(2)	[III–39]
21.50	0.65(4)	[III–39]	75.00	0.0210(12)	eval
21.60	0.66(4)	[III–36]	80.00	0.013(1)	[III–39]
21.70	0.95(6)	[III–36]	85.00	0.0110(6)	eval
21.80	0.84(5)	[III–36]	90.00	0.012(1)	[III–39]

TABLE III–16. RECOMMENDED 90° DIFFERENTIAL CROSS-SECTIONS FOR THE $^{11}B(p, \gamma_0)^{12}C$ REACTION (cont.)

E_p (MeV)	$\sigma(\Delta\sigma)$ (μb/sr)	Ref.	E_p (MeV)	$\sigma(\Delta\sigma)$ (μb/sr)	Ref.
91.68	0.007(1)	[III–38]	100.00	0.007(1)	[III–39]
95.00	0.0060(3)	eval	105.00	0.0030(2)	eval

TABLE III–17. RECOMMENDED LEGENDRE POLYNOMIAL EXPANSION COEFFICIENT (a_0) FOR THE PRIMARY γ_0 RAYS TO THE GROUND STATE OF ^{12}C FROM THE $^{11}B(p, \gamma_0)^{12}C$ REACTION (absolute uncertainties of the evaluated data are 8–10% as adopted from Ref. [III–37])

E_p (MeV)	$a_0(\Delta a_0)$ (μb/sr)	Ref.	E_p (MeV)	$a_0(\Delta a_0)$ (μb/sr)	Ref.
14.0	1.25(14)	[III–36]	34.0	0.245(23)	[III–37]
14.5	1.24(11)	[III–36]	36.0	0.243(23)	[III–37]
15.0	1.25(15)	[III–36]	38.0	0.191(19)	eval
15.5	1.19(21)	[III–36]	39.0	0.186(17)	[III–37]
16.0	1.05(20)	[III–36]	40.0	0.173(17)	eval
16.5	1.06(19)	[III–36]	42.0	0.157(16)	eval
17.0	0.91(11)	[III–36]	43.7	0.137(13)	[III–37]
17.5	0.90(11)	[III–36]	46.0	0.130(13)	eval
18.0	0.807(81)	[III–37]	48.04	0.130(29)	[III–38]
18.0	0.82(8)	[III–40]	50.0	0.109(11)	eval
18.5	0.76(11)	[III–36]	52.5	0.098(10)	eval
19.0	0.686(68)	[III–37]	55.0	0.089(9)	eval
19.0	0.69(7)	[III–40]	57.5	0.080(8)	eval
19.5	0.74(15)	[III–36]	60.0	0.073(7)	eval
20.0	0.64(13)	[III–36]	62.5	0.066(7)	eval
20.5	0.58(18)	[III–36]	65.0	0.060(6)	eval
21.0	0.55(18)	[III–36]	67.5	0.055(6)	eval
21.5	0.518(52)	[III–37]	69.86	0.043(9)	[III–38]
22.0	0.548(52)	eval	72.5	0.046(5)	eval
23.0	0.504(39)	eval	75.0	0.042(4)	eval
24.0	0.412(39)	[III–37]	77.5	0.038(4)	eval
25.0	0.430(38)	eval	80.0	0.034(3)	eval
26.0	0.399(34)	eval	82.5	0.032(3)	eval
27.0	0.361(34)	[III–37]	85.0	0.029(3)	eval
28.0	0.346(32)	eval	87.5	0.026(3)	eval
29.0	0.324(31)	eval	90.0	0.024(2)	eval
30.0	0.312(30)	[III–37]	91.68	0.023(4)	[III–38]
32.0	0.290(27)	[III–37]			

TABLE III–18. LEGENDRE POLYNOMIAL EXPANSION COEFFICIENTS FOR THE PRIMARY γ_0 RAYS TO THE GROUND STATE OF ^{12}C FROM THE $^{11}B(p, \gamma_0)^{12}C$ REACTION

E_p (MeV)	a_1/a_0 (uncertainty)	a_2/a_0 (uncertainty)	a_3/a_0 (uncertainty)	a_4/a_0 (uncertainty)	Ref.
13.0	0.16(7)	–0.65(6)	–0.23(6)		[III–40]
14.0	0.34(2)	–0.78(5)	–0.21(4)	–0.08(4)	[III–36]
14.5	0.40(1)	–0.78(3)	–0.30(3)	–0.13(2)	[III–36]
15.0	0.34(1)	–0.80(3)	–0.19(3)	–0.05(2)	[III–36]
15.0	0.42(8)	–0.73(6)	–0.33(6)		[III–40]
15.5	0.35(2)	–0.76(3)	–0.19(4)	–0.05(2)	[III–36]
16.0	0.36(2)	–0.67(3)	–0.18(4)	–0.15(3)	[III–36]
16.0	0.35(8)	–0.80(6)	–0.12(6)		[III–40]
16.5	0.43(2)	–0.73(3)	–0.22(4)	–0.07(3)	[III–36]
17.0	0.42(2)	–0.78(3)	–0.31(4)	–0.11(3)	[III–36]
17.5	0.46(2)	–0.73(3)	–0.18(4)	–0.01(3)	[III–36]
17.7	0.42(8)	–0.78(6)	–0.21(6)		[III–40]
18.0	0.43(2)	–0.82(7)	–0.31(5)	–0.06(3)	[III–36]
18.0	0.59(8)	–0.83(6)	–0.32(6)	0.00(6)	[III–37]
18.5	0.42(2)	–0.76(7)	–0.24(5)	–0.07(3)	[III–36]
19.0	0.46(2)	–0.79(6)	–0.27(4)	–0.02(3)	[III–36]
19.0	0.32(8)	–0.61(6)	–0.52(6)	–0.07(4)	[III–37]
19.0	0.38(8)	–0.70(6)	–0.33(6)		[III–40]
19.5	0.44(2)	–0.76(9)	–0.32(5)	0.00(5)	[III–36]
20.0	0.53(2)	–0.70(8)	–0.29(6)	–0.07(4)	[III–36]
20.0	0.64(8)	–0.67(6)	–0.31(6)		[III–40]
20.0	0.50(4)	–0.71(6)			eval
20.5	0.49(3)	–0.78(9)	–0.39(6)	–0.12(5)	[III–36]
21.0	0.55(5)	–0.70(13)	–0.24(21)	0.01(16)	[III–36]
21.5	0.26(8)	–0.63(7)	–0.24(6)	0.00(6)	[III–37]
24.0	0.76(7)	–0.55(7)	–0.55(6)	–0.06(6)	[III–37]
25.0	0.70(6)	–0.63(5)			eval
27.0	0.80(7)	–0.60(6)	–0.55(6)	0.00(7)	[III–37]
30.0	0.89(7)	–0.52(6)	–0.53(6)	–0.15(7)	[III–37]
30.0	0.85(7)	–0.51(4)			eval
32.0	1.00(7)	–0.42(6)	–0.37(6)	–0.09(7)	[III–37]
34.0	1.00(7)	–0.40(7)	–0.64(7)	–0.13(7)	[III–37]
36.0	1.00(7)	–0.40(6)	–0.74(7)	–0.22(6)	[III–37]
39.0	1.05(7)	–0.21(7)	–0.93(6)	–0.57(6)	[III–37]
40.0	1.10(9)	–0.26(2)			eval
43.7	1.10(7)	–0.31(7)	–1.13(10)	–0.69(6)	[III–37]
45.0	1.20(10)	–0.13(10)			eval
48.04	1.23(13)	–0.12(8)	–0.76(22)	–0.40(20)	[III–38]
50.0	1.29(10)	0.080(1)			eval
55.0	1.37(11)	0.14(1)			eval
60.0	1.45(12)	0.28(2)			eval

TABLE III–18. LEGENDRE POLYNOMIAL EXPANSION COEFFICIENTS FOR THE PRIMARY γ_0 RAYS TO THE GROUND STATE OF ^{12}C FROM THE $^{11}B(p, \gamma_0)^{12}C$ REACTION (cont.)

E_p (MeV)	a_1/a_0 (uncertainty)	a_2/a_0 (uncertainty)	a_3/a_0 (uncertainty)	a_4/a_0 (uncertainty)	Ref.
65.0	1.52(12)	0.42(3)			eval
69.86	1.70(27)	0.59(9)	–0.76(30)	–0.30(19)	[III–38]
70.0	1.58(13)	0.56(4)			eval
75.0	1.65(13)	0.70(6)			eval
80.0	1.70(14)	0.84(7)			eval
85.0	1.76(14)	0.98(8)			eval
90.0	1.82(15)	1.11(9)			eval
91.68	1.90(30)	1.11(9)	–0.31(31)	–0.21(13)	[III–38]
95.0	1.95(15)	1.14(9)			eval

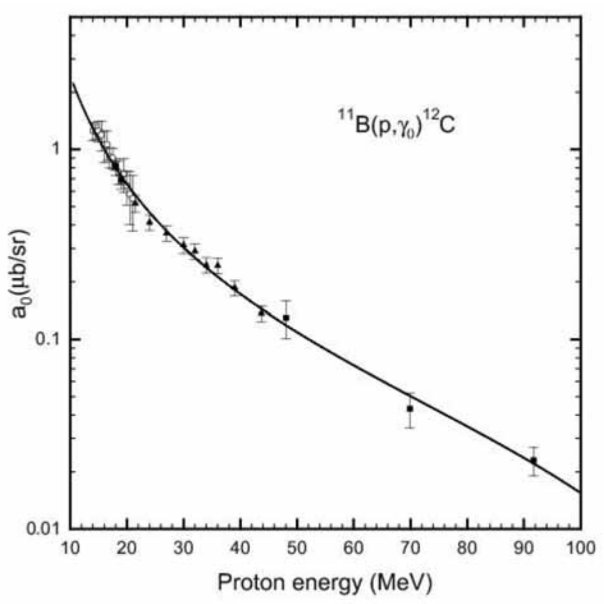

FIG. III–2. Legendre polynomial expansion coefficient a_0 for the primary γ_0 rays to the ground state of the ^{12}C from proton capture on ^{11}B; absolute normalization uncertainties are included, and the solid line is a least squares fit to the data [III–36 to III–38, III–40].

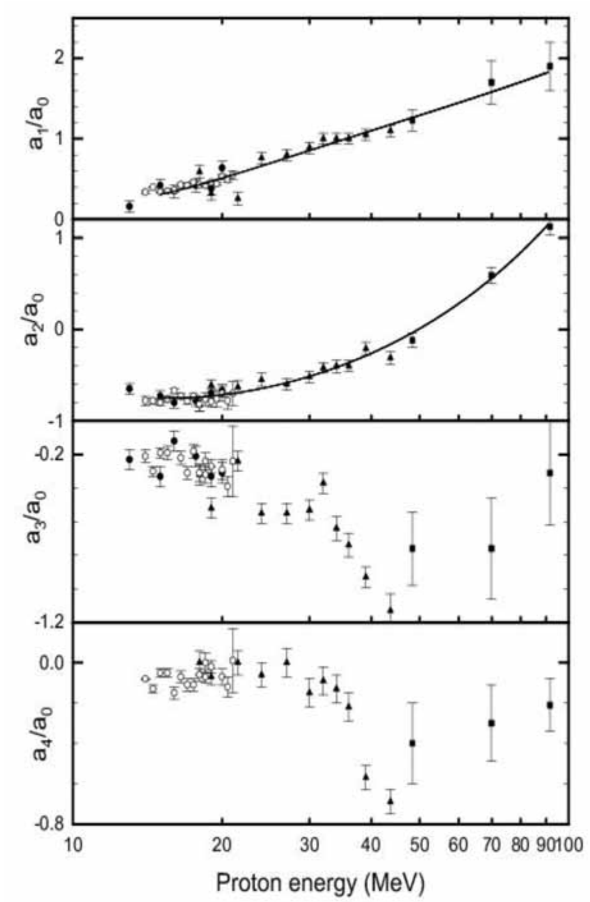

FIG. III–3. Legendre polynomial expansion coefficients for primary γ_0 rays to the ground state of ^{12}C from the $^{11}B(p, \gamma_0)^{12}C$ reaction, taken from Refs [III–36 to III–38, III–40].

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Annex IV

EVALUATION OF ANGULAR CORRELATION COEFFICIENTS FOR DETECTOR CALIBRATION BY MEANS OF THE COINCIDENCE METHOD

S. Hlaváč

Slovak Academy of Sciences, Slovakia

IV–1. γ–γ COINCIDENCE METHOD OF DETECTOR EFFICIENCY CALIBRATION

The coincidence method has been successfully used for decades in nuclear spectroscopy and various other applications as the only feasible method for the study of complex decay and level schemes of atomic nuclei. A second important and widely accepted application of the coincidence method is the determination of the absolute decay rate of standards for detector calibration. However, the coincidence method can also be applied to determine the absolute detector efficiency.

The absolute calibration of photon detectors proceeds in two steps: determination of the absolute source intensity by means of the β–γ coincidence method to give an absolutely calibrated standard that can subsequently be used to determine the absolute efficiency of the photon detector. Use of the coincidence method can potentially reduce the number of steps in the detector calibration procedure to a single step, thus reducing the error in the calibration. A useful property of the coincidence method is that one can calibrate γ ray detectors absolutely even without absolutely calibrated standards.

IV–2. PRINCIPLE OF THE γ–γ COINCIDENCE METHOD

The coincidence method is relatively simple and can be used if the source nucleus decays by two cascading photons, γ_1 and γ_2. Two detectors are set up, as shown in Fig. IV–1 together with an appropriate decay scheme.

Detectors d_1 and d_2 are used to measure gamma rays γ_1 and γ_2, respectively. The following relationships hold for the full energy rate N_2 in detector d_2 and the coincidence rate N_{12} in detector d_2 in this simple arrangement:

$$N_2 = \varepsilon_2 A$$

$$N_{12} = \varepsilon_2 \varepsilon_1^t A W(\vartheta)$$

where A is the unknown decay rate of the calibration source, ε_2 is the full energy peak efficiency of detector d_2, ε_1^t is the total efficiency of detector d_1 for γ_1, and $W(\vartheta)$ is the correlation function. From the above equations, the total efficiency ε_1^t is given by the expression:

$$\varepsilon_1^t = \frac{N_{12}}{N_2}\frac{1}{W(\vartheta)}. \quad \text{(IV–1)}$$

The full energy peak efficiency ε_1 can be determined using the known peak to total ratio f_1, $\varepsilon_1 = f_1 \varepsilon_1^t$.

Thus, the total efficiency of detector d_1 for gamma ray γ_1 can be determined from the ratio of coincidence counts to single counts of gamma ray γ_2 in detector d_2. We do not need to know the efficiency of detector d_2 in order to determine the efficiency of detector d_1. These simple relationships can be further refined to describe a realistic experimental situation with full energy peak efficiency of the calibrated detector, calibration sources with

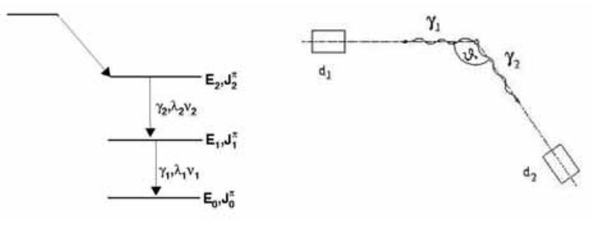

FIG. IV–1. Typical decay scheme of daughter nucleus with two cascading γ rays — note that γ_1 is the second transition in the cascade — along with the detector set-up for an efficiency measurement by means of the coincidence method (two γ rays are emitted with relative angle ϑ and detected in detectors d_1 and d_2).

more complicated decay schemes, and finite detector volumes. A two-parametric data acquisition system is advisable in order to perform a precise efficiency measurement. Further reduction of the uncertainties can be achieved if a time distribution between two coincident γ rays is also measured.

Calibration sources for use in the coincidence method need to possess slightly different decay data properties than arise for a normal calibrant. The crucial parameter is $P_{\gamma_{12}}$ (number of gamma rays γ_1 per single photon γ_2), and therefore the population of individual levels, branching ratios of electromagnetic transitions and the internal conversion coefficients need to be known in a similar manner to the traditional calibration methods. However, the number of nuclei that decay during the efficiency measurement does not need to be known absolutely and the half-life of the source does not need to be precisely defined. While the spatial and time correlations of both photons are important, the half-lives of the majority of nuclear levels in nuclei used for such calibrations are much shorter than the time resolution of commonly used photon detectors; therefore, we can assume that both photons are emitted at the same time.

The spatial correlations between two successive γ transitions are well understood, and depend on the spins and parities of all three nuclear levels involved, as well as on the multipolarities of both γ transitions. Although the general theory of correlations is rather involved, in principle the correlation function can always be reduced to the sum of Legendre polynomials $P_k(\cos \vartheta)$:

$$W(\vartheta) = \sum_{k_{even}} A_{kk} P_k(\cos\vartheta)$$

where k starts at 0 and adopts only even values, and A_{kk} are angular correlation coefficients (where $A_{00} = 1$ by definition). Since the spins of the nuclear levels of most nuclei used for detector calibration are always rather low, directional correlations are weak and the first three terms of the above sum describe the observed angular correlations satisfactorily:

$$W(\vartheta) = 1 + A_{22}P_2(\cos\vartheta) + A_{44}P_4(\cos\vartheta) \qquad \text{(IV–2)}$$

The effect of the correlations can be further reduced by undertaking a measurement at an angle of 125°, where the second Legendre polynomial $P_2(\cos \vartheta)$ equals zero. Nevertheless, the influence of angular correlations should be taken into account in the coincidence method.

IV–3. SELECTED NUCLEI

The best source to be used in the coincidence method should emit two γ rays. However, few nuclei exist with such a simple decay scheme, the best examples being ^{60}Co and ^{88}Y. Additional nuclei have been identified to enlarge the energy region in which the coincidence method can be used. After assessing the list of radionuclides recommended for the present CRP, we have selected 11 radionuclides suitable for detector calibration by means of the coincidence method. The selection criteria were as follows: a simple decay scheme with a cascade of two γ rays; high emission probability P_{γ_2} of the first transition γ_2 in the cascade; high emission probability $P_{\gamma_{12}}$ of the coincident γ_1 transition; decay involved only low spin states; low multipolarities of cascading γ rays; and broad energy range. These nuclei are summarized in Table IV–1, where the energies of the cascading γ rays as well as the emission probabilities are listed.

IV–4. CALCULATION OF ANGULAR CORRELATION COEFFICIENTS

The angular distribution of γ rays of different multipolarities emitted in transitions between individually oriented levels is well understood and has been described in detail in numerous articles [IV–1 to IV–3]. Angular correlation in a coincidence experiment is a special case of angular distribution, in which usually we take the direction of the first γ ray as the quantization axis. Since we do not have any information on the random orientation of decaying nucleus and the polarization of the γ ray the contributions of all subprocesses are summed in the derivation of angular correlation. The angular correlation of two successive γ rays is given by [IV–2]:

$$W(\vartheta) = \sum_k A_{kk}(J_2,\lambda_1,\lambda_2,J_1,J_0) P_k(\cos\vartheta)$$

$$A_{kk}(J_2,\lambda_1,\lambda_2,J_1,J_0) = F_k(J_2,\lambda_2,J_1) F_k(J_0,\lambda_1,J_1)$$

$$k_{\max} = Min\{2\lambda_1, 2\lambda_2, 2J_1\}$$

TABLE IV–1. ENERGY LEVELS E_i, γ RAY ENERGIES E_{γ_i} AND γ RAY EMISSION PROBABILITIES P_{γ_2} AND $P_{\gamma 12}$ FOR SELECTED SOURCES

Parent	E_2 (keV)	E_{γ_2} (keV)	P_{γ_2} (per decay)	E_1 (keV)	E_{γ_1} (keV)	$P_{\gamma 12}$ (per γ_2)
^{24}Na	4122.9	2754.03	0.99872	1368.7	1368.63	1.00
^{46}Sc	2009.8	1120.54	0.99986	889.3	889.27	1.00
^{60}Co	2505.8	1173.23	0.9985	1332.50	1332.49	1.00
^{66}Ga	3791.2	2751.84	0.227	1039.39	1039.22	1.00
^{75}Se	400.7	136.00	0.582	264.7	264.66	0.981(4)
^{88}Y	2734.1	898.04	0.939	1836.1	1836.05	1.00
^{94}Nb	1573.7	702.64	0.9982	871.1	871.11	1.00
^{111}In	416.7	171.28	0.9066	245.40	245.4	1.00
^{134}Cs	1400.6	795.83	0.855	604.72	604.72	1.00
^{152}Eu	1123.2	778.90	0.1296	344.3	344.28	1.00
^{207}Bi	1633.4	1063.66	0.7458	569.7	569.7	1.00

where F_k are combinations of the Clebsch-Gordan and Racah coefficients:

$$F\left(J_f,\lambda,J_i\right) = -1^{1-Ji-Jf}\sqrt{2J_i+1}\,(2\lambda+1)$$
$$\times\langle\lambda 1\lambda-1\,|\,k0\rangle W\left(J_iJ_i\lambda_i\lambda_i;kJ_f\right)$$

that take care for all vector addition rules, and $P_k(\cos\vartheta)$ are Legendre polynomials. When one of the transitions is a mixed multipole type (λ,λ'), the formal expression for $W(\vartheta)$ remains the same but the coefficients A_{kk} are calculated as a sum of generalized functions F_k for both multipolarities λ,λ' weighted by the mixing ratio δ:

$$A_{kk}\left(J_i\lambda\lambda' J_f\right) = \frac{1}{1+\delta^2}$$
$$\times\left[F_k\left(J_f\lambda\lambda J_i\right) + 2\delta F_k\left(J_f\lambda\lambda' J_i\right) + \delta^2 F_k\left(J_f\lambda'\lambda' J_i\right)\right]$$

$$F_k\left(J_f\lambda\lambda' J_i\right) = -1^{1-Ji-Jf}\sqrt{(2J_i+1)(2\lambda+1)(2\lambda'+1)}$$
$$\times\langle\lambda 1\lambda'-1\,|\,k0\rangle W\left(J_iJ_i\lambda\lambda';kJ_f\right)$$

Angular correlation coefficients were calculated according to the formulas given above. Input data for the calculations are summarized in Table IV–2.

IV–5. CORRECTIONS

Equation (IV–1) is derived on the basis of some rather simplified assumptions, and several corrections should be applied in the real experiments. Two of the most important corrections are for the finite volume of both detectors, and for coincidence summing.

The finite volume of both detectors smears the relative angle ϑ of the two detectors. Two photons emitted by the source during the same event may be detected by a single detector. Under such circumstances, the energy deposited in a single detector may be higher than the full energy peak of the single γ ray, reducing the full energy peak rate. When the coincidence summing effects are important, Eq. (IV–1) should be replaced in the case of two γ rays by the following expression:

$$N_2 = \varepsilon_2\left(E_2\right)\left(1-\varepsilon_2^t\left(E_1\right)\right)A$$
$$N_{12} = \varepsilon_1^t\left(E_1\right)\varepsilon_2\left(E_2\right)P_{\gamma 12}AW(\vartheta)F\left(\Omega_1,\Omega_2,\vartheta\right)$$

from which the following equation can be derived:

$$\varepsilon_1^t\left(E_1\right) = \frac{N_{12}}{N_1}\frac{\left(1-\varepsilon_2^t\left(E_1\right)\right)}{P_{\gamma 12}W(\vartheta)F\left(\Omega_1,\Omega_2,\vartheta\right)} \qquad \text{(IV–3)}$$

TABLE IV–2. INPUT DATA FOR CALCULATION OF THE ANGULAR CORRELATION COEFFICIENTS: $E_{\gamma i}$, $\lambda\nu$ AND δ ARE THE ENERGY, MULTIPOLARITY AND MIXING RATIO OF THE i-th γ RAY, RESPECTIVELY; J_i^π, J^π AND J_f^π ARE THE SPIN AND PARITY OF THE INITIAL, INTERMEDIATE AND FINAL STATE, RESPECTIVELY

Parent	E_{γ_2} (keV)	$\lambda_2\nu_2$	δ_2	E_{γ_1} (keV)	$\lambda_1\nu_1$	δ_1	J_2^π	J_1^π	J_0^π
^{24}Na	2754.03	[E2]	1.0	1368.63	E2	1.0	4^+	2^+	0^+
^{46}Sc	1120.55	E2	1.0	889.28	E2	1.0	4^+	2^+	0^+
^{60}Co	1173.24	E2(+M3)	–0.0025(22)	1332.5	E2	1.0	4^+	2^+	0^+
^{66}Ga	2751.85	M1+E2	–0.09(3)	1039.30	E2	1.0	1^+	2^+	0^+
^{75}Se	136.00	E1	1.0	264.66	M1+E2	–0.07(2)	$5/2^+$	$3/2^-$	$3/2^-$
^{88}Y	898.04	E1	1.0	1836.06	E2	1.0	3^-	2^+	0^+
^{94}Nb	702.62	E2	1.0	871.09	E2	1.0	4^+	2^+	0^+
^{111}In	171.28	M1+E2	–0.144(3)	245.4	E2	1.0	$7/2^+$	$5/2^+$	$1/2^+$
^{134}Cs	795.86	E2	1.0	604.7	E2	1.0	4^+	2^+	0^+
^{152}Eu	778.90	E1(+M2)	0.002(6)	344.28	E2	1.0	3^-	2^+	0^+
^{207}Bi	1063.66	M4+E5	0.03(1)	569.7	E2	1.0	$13/2^+$	$5/2^-$	$1/2^-$

where $\varepsilon_i(E_j)$ is the photopeak efficiency of detector i for gamma ray γ_j with energy E_j, $\varepsilon_i^t(E_j)$ is the total efficiency of detector i for gamma ray γ_j, $P_{\gamma 12}$ is the emission probability of gamma ray γ_1 per single emited photon γ_2, $(1 - \varepsilon_i^t(E_j))$ is a correction factor for coincidence summing in detector d_i, and $F(\Omega_1, \Omega_2, \vartheta)$ is the correction factor for the finite solid angle of both detectors Ω_1, Ω_2 at relative angle ϑ. Full energy peak efficiency is given by the relationship:

$$\varepsilon_i = f_i\, \varepsilon_i^t$$

where f_i is the peak to total ratio, measured at the given energy in a separate experiment.

Consider two HPGe detectors with 50% relative efficiency at 1.33 MeV (typical crystal diameter of 65 mm, and length 60 mm) and a distance of 25 cm from the ^{60}Co source with a relative angle of 125°: the coincidence summing correction is lower than 0.5%. Furthermore, for two detectors with 100% efficiency (typical crystal diameter of 82 mm and length 70 mm), the coincidence summing correction at the same distance is still lower than 1%.

The correlation coefficients were calculated at fixed detector angles without taking into account the finite solid angle of both detectors. Corrections for finite solid angle depend on the solid angles subtended by both detectors, the angular correlation function, and their relative angle. Typical correction factors for two identical detectors, both with either 50% or 100% relative efficiency at a distance of 25 cm from the radioactive source (^{60}Co and ^{207}Bi) and two different relative angles are given in Table IV–3.

TABLE IV–3. EXAMPLES OF FINITE SOLID ANGLE CORRECTIONS $F(\Omega_1, \Omega_2, \vartheta)$, DEFINED IN EQ. (IV–3) FOR EXPERIMENTAL SET-UPS WITH TWO DIFFERENT DETECTOR SIZES (50% AND 100% RELATIVE EFFICIENCY), AND TWO DIFFERENT RADIOACTIVE SOURCES (^{60}Co and ^{207}Bi) AT TWO RELATIVE ANGLES OF 90° AND 124.7°

Detector relative efficiency (%)	^{60}Co		^{207}Bi	
	90°	124.7°	90°	124.7°
50	0.953589	0.996079	0.886792	1.004591
100	0.954504	0.996725	0.889816	1.005005

The corrections for the finite solid angle depend on the angular correlations, size of the detectors and their relative angle (see Table IV–3). At an angle of 124.7°, at which the second Legendre polynomial equals zero, the correction is lower than 1% in all instances, whereas the correction can reach values greater than 10% at an angle of 90°. The finite solid angle correction is more dominant at larger distances and a relative angle of 90°; at shorter distances the coincidence summing effects start to become important. The best experimental practice would be to measure the efficiency at an angle of 54.7 or 124.7°, where both correlation effects as well as the correction are minimized. Corrections for coincidence summing are lower at larger source–detector distances.

All corrections can be calculated by Monte Carlo techniques. Several codes are available, probably the most advanced of them being the GESPECOR code [IV–4, IV–5].

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[IV–4] SIMA, O., ARNOLD, D., Accurate computation of coincidence summing corrections in low level gamma-ray spectrometry, Appl. Radiat. Isot. **53** (2000) 51–56.

[IV–5] SIMA, O., ARNOLD, D., DOVLETE, C., GESPECOR — A versatile tool in gamma-ray spectrometry, J. Radioanal. Nucl. Chem. **248** (2001) 359–364.

EVALUATIONS

Suitable sources with two strong cascading γ rays were identified from the CRP set of recommended decay data: ^{24}Na, ^{46}Sc, ^{60}Co, ^{66}Ga, ^{75}Se, ^{88}Y, ^{94}Nb, ^{111}In, ^{134}Cs, ^{152}Eu and ^{207}Bi. Angular correlation coefficients were evaluated for the cascade of two selected γ rays in every source, covering the energy range from 136 to 2750 keV. The correlation coefficients A_{kk} (as defined in Eq. (IV–2)) are evaluated and their recommended values given for the above mentioned sources.

^{24}Na

Recommended data:

SELECTED γ RAYS IN TRANSITIONS BETWEEN LEVELS $4^+ \rightarrow 2^+ \rightarrow 0^+$

E_γ (keV)	P_γ per decay	Multipolarity
2754.0	0.99872(8)	E2(+M3)
1368.6	0.999935(5)	E2

Angular correlation coefficients

A_{22} = 0.10204
A_{44} = 0.00907

Input data:

MEASURED, EVALUATED AND THEORETICAL ANGULAR CORRELATION COEFFICIENTS

CC	Theory
A_{22}	0.10204
A_{44}	0.00907

REFERENCES

No experimental data available.

^{46}Sc

Recommended data:

SELECTED γ RAYS IN TRANSITIONS BETWEEN LEVELS $4^+ \rightarrow 2^+ \rightarrow 0^+$

E_γ (keV)	P_γ per decay	Multipolarity
1120.5	0.99986 (+4–36)	E2
889.3	0.999833(5)	E2

Angular correlation coefficients

$A_{22} = 0.10204$
$A_{44} = 0.00907$

Input data:

MEASURED, EVALUATED AND THEORETICAL ANGULAR CORRELATION COEFFICIENTS

CC	Theory
A_{22}	0.10204
A_{44}	0.00907

REFERENCES

No experimental data available.

^{60}Co

Recommended data:

SELECTED γ RAYS IN TRANSITIONS BETWEEN LEVELS $4^+ \rightarrow 2^+ \rightarrow 0^+$

E_γ (keV)	P_γ per decay	Multipolarity
1173.2	0.9985(3)	E2(+M3)
1332.5	0.999826(6)	E2

Angular correlation coefficients

$A_{22} = 0.10204$
$A_{44} = 0.00907$

Input data

MEASURED, EVALUATED AND THEORETICAL ANGULAR CORRELATION COEFFICIENTS

CC	[1]	[2]	[3]
A_{22}	0.1015(32)	0.101(3)	0.167(1)
A_{44}	0.095(3)	0.014(4)	—

CC	[4]	Evaluated	Theory
A_{22}	0.120(52)	0.1012(22)	0.10204
A_{44}	0.043(59)	0.0658(24)	0.00907

REFERENCES

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^{66}Ga

Recommended data:

SELECTED γ RAYS IN TRANSITIONS BETWEEN LEVELS $1^+ \rightarrow 2^+ \rightarrow 0^+$

E_γ (keV)	P_γ per decay	Multipolarity
2751.8	0.227(18)	M1+E2
1039.2	0.37(3)	E2

Angular correlation coefficients

$A_{22} = -0.24552$
$A_{44} = -0.00001$

Input data:

MEASURED, EVALUATED AND THEORETICAL ANGULAR CORRELATION COEFFICIENTS

CC	[1]	Theory
A_{22}	–0.15(3)	–0.24552
A_{44}	—	–0.00001

REFERENCE

[1] SCHWARZSCHILD, A., GRODZINS, L., Phys. Rev. **119** (1960) 276.

^{75}Se

Recommended data:

SELECTED γ RAYS IN TRANSITIONS BETWEEN LEVELS $5/2^+ \rightarrow 3/2^- \rightarrow 3/2^-$

E_γ (keV)	P_γ per decay	Multipolarity
136.0	0.582(7)	E1
264.7	0.589(3)	M1+E2

Angular correlation coefficients

$A_{22} = -0.03312$
$A_{44} = 0.0000$

Input data:

MEASURED, EVALUATED AND THEORETICAL ANGULAR CORRELATION COEFFICIENTS

CC	[1]	[2]	[3]
A_{22}	–0.033(1)	–0.019(2)	0.016(30)
A_{44}	0.001(2)	–0.012(12)	—

CC	[4]	[5]	[6]
A_{22}	–0.011(9)	–0.033(4)	–0.0302(29)
A_{44}	—	0.001(9)	0.0036(56)

CC	Evaluated	Theory
A_{22}	–0.028(4)	–0.03312
A_{44}	0.0015(18)	0.0000

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^{88}Y

Recommended data:

SELECTED γ RAYS IN TRANSITIONS BETWEEN LEVELS $3^- \rightarrow 2^+ \rightarrow 0^+$

E_γ (keV)	P_γ per decay	Multipolarity
898.0	0.9390(23)	E1
1836.1	0.9938(3)	E2

Angular correlation coefficients

A_{22} = –0.0714
A_{44} = 0.0000

Input data:

MEASURED, EVALUATED AND THEORETICAL ANGULAR CORRELATION COEFFICIENTS

CC	[1]	[2]	[3]
A_{22}	–0.073(10)	–0.0784(42)	–0.0685(28)
A_{44}	–0.02(2)	0.0037(25)	–0.0045(42)

CC	[4]	Evaluated	Theory
A_{22}	–0.065(3)	–0.0692(32)	–0.0714
A_{44}	–0.002(3)	–0.0009(19)	0.0000

REFERENCES

[1] HATTULA, J., KANTELE, J., SARMANTO, A., Nucl. Instrum. Methods **65** (1968) 77.
[2] HESS, A., SCHNEIDER, H., Z. Phys. **262** (1973) 231.
[3] KLEMA, E.D., Phys. Rev. **102** (1956) 449.
[4] STEFFEN, R.M., Phys. Rev. **90** (1953) 321.

^{94}Nb

Recommended data:

SELECTED γ RAYS IN TRANSITIONS BETWEEN LEVELS $4^+ \rightarrow 2^+ \rightarrow 0^+$

E_γ (keV)	P_γ per decay	Multipolarity
702.6	0.99815(6)	E2
871.1	0.99892(3)	E2

Angular correlation coefficients

A_{22} = 0.10204
A_{44} = 0.00907

Input data:

MEASURED, EVALUATED AND THEORETICAL ANGULAR CORRELATION COEFFICIENTS

CC	[1]	[2]	[3]
A_{22}	0.101(17)	0.101(3)	0.0865(80)
A_{44}	0.023(43)	0.0121(43)	0.0243(125)

CC	[4]	Evaluated	Theory
A_{22}	0.0965(76)	0.0968(34)	0.10204
A_{44}	0.019(11)	0.0141(38)	0.00907

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^{111}In

Recommended data:

SELECTED γ RAYS IN TRANSITIONS BETWEEN LEVELS $7/2^+ \rightarrow 5/2^+ \rightarrow 1/2^+$

E_γ (keV)	P_γ per decay	Multipolarity
171.3	0.9066(25)	M1+E2
245.4	0.9409(6)	E2

Angular correlation coefficients

$A_{22} = -0.0714$
$A_{44} = 0.0000$

Input data:

MEASURED, EVALUATED AND THEORETICAL ANGULAR CORRELATION COEFFICIENTS

CC	[1]	Theory
A_{22}	–0.180(2)	0.03122
A_{44}	0.002(3)	–0.00147

REFERENCE

[1] STEFFEN, R.M., Phys. Rev. **103** (1956) 116.

^{134}Cs

Recommended data:

SELECTED γ RAYS IN TRANSITIONS BETWEEN LEVELS $4^+ \rightarrow 2^+ \rightarrow 0^+$

E_γ (keV)	P_γ per decay	Multipolarity
795.8	0.855(3)	E2
604.7	0.97650(18)	E2

Angular correlation coefficients

$A_{22} = 0.10204$
$A_{44} = 0.00907$

Input data:

MEASURED, EVALUATED AND THEORETICAL ANGULAR CORRELATION COEFFICIENTS

CC	[1]	[2]	[3]
A_{22}	0.101(8)	0.102(9)	0.095(9)
A_{44}	–0.002(12)	0.008(16)	0.009(16)

CC	Evaluated	Theory
A_{22}	0.0968(34)	0.10204
A_{44}	0.0141(38)	0.00907

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^{152}Eu

Recommended data:

SELECTED γ RAYS IN TRANSITIONS BETWEEN LEVELS $3^- \rightarrow 2^+ \rightarrow 0^+$

E_γ (keV)	P_γ per decay	Multipolarity
778.9	0.1296(6)	E1(+E2)
344.3	0.2658(12)	E2

Angular correlation coefficients

A_{22} = –0.0730
A_{44} = 0.0000

Input data:

MEASURED, EVALUATED AND THEORETICAL ANGULAR CORRELATION COEFFICIENTS

CC	[1]	[2]	[3]	[4]
A_{22}	–0.074(5)	–0.070(5)	–0.074(5)	–0.073(3)
A_{44}	0.00(0)	0.002(7)	0.000(0)	—

CC	[5]	[6]	Evaluated	Theory
A_{22}	–0.081(13)	–0.074(10)	–0.0730(19)	–0.07299
A_{44}	—	—	0.002(7)	0.0000

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^{207}Bi

Recommended data:

SELECTED γ RAYS IN TRANSITIONS BETWEEN LEVELS $13/2^+ \rightarrow 5/2^- \rightarrow 1/2^-$

E_γ (keV)	P_γ per decay	Multipolarity
1063.7	0.7458(49)	M4+E5
569.7	0.9776(3)	E2

Angular correlation coefficients

A_{22} = 0.22078
A_{44} = –0.01798

Input data:

MEASURED, EVALUATED AND THEORETICAL ANGULAR CORRELATION COEFFICIENTS

CC	[1]	[2]	[3]	[4]
A_{22}	0.235(3)	0.232(7)	0.204(5)	0.2181(32)
A_{44}	–0.029(4)	–0.022(3)	–0.004(3)	–0.0209

CC	[5]	[6]	[7]	[8]
A_{22}	0.204(6)	0.215(5)	0.220(3)	0.232(2)
A_{44}	0.025(7)	0.007(7)	–0.038(4)	–0.022(2)

CC	[9]	Evaluated	Theory
A_{22}	0.227(3)	0.224(29)	0.22078
A_{44}	–0.018(8)	–0.023(5)	–0.01798

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Annex V

COVARIANCE ANALYSIS BY MEANS OF THE LEAST SQUARES METHOD

V.R. Vanin, O.A.M. Helene

Instituto de Física, Universidade de São Paulo, Brazil

V–1. CORRELATIONS AND COVARIANCE MATRICES

A summary of the use and propagation of covariance matrices is given below. Since detector calibration is almost invariably performed within the framework of the least squares method (LSM), this procedure has been reviewed by means of a matrix approach which is adopted to account for the covariances. The determination of the correlation between γ ray intensities in spectroscopic experiments is described in Section V–8, following presentation of the necessary inputs in the earlier sections. Illustrative examples from γ ray spectroscopy are used throughout the text. Complete discussions of the related statistical issues are given in various publications such as Refs [V–1, V–2], and a concise summary can be found in Appendices E and F of Ref. [V–3].

V–2. COVARIANCE MATRIX: USE AND CALCULATION

Proper evaluation of the uncertainty of a value based on two or more correlated data must take the correlations into account. Also, the correlation between quantities depends on both their uncertainties and the correlations of the data on which they depend.

V–2.1. Covariance matrix

Correlations or covariances between many random quantities can be concisely stored in a matrix. Hence the covariance matrix of n experimental values of physical quantities z_1, z_2 ...... z_n is a square symmetric matrix **V**:

$$\boldsymbol{V} = \begin{pmatrix} \sigma_1^2 & \mathrm{cov}(z_1, z_2) & \dots & \mathrm{cov}(z_1, z_n) \\ \mathrm{cov}(z_1, z_2) & \sigma_2^2 & \dots & \mathrm{cov}(z_2, z_n) \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{cov}(z_1, z_n) & \mathrm{cov}(z_2, z_n) & \dots & \sigma_n^2 \end{pmatrix} \qquad \text{(V–1)}$$

where the diagonal element on row and column i is the variance of z_i, and the off-diagonal element on i, j is the covariance between z_i and z_j. Formally, we have

$$\mathrm{cov}(z_i, z_j) = \langle \varepsilon_i \varepsilon_j \rangle \qquad \text{(V–2)}$$

where ε_i is the error in z_i (i.e. difference between the experimental value and true (unknown) value of the physical quantity), and $\langle x \rangle$ represents the expected value of the random variable x.

The standard deviation of z_i is defined as the positive square root of the appropriate diagonal term of the covariance matrix, and the correlation coefficient between two quantities z_i and z_j is the a-dimensional quantity given by

$$\rho_{ij} = \frac{\mathrm{cov}(z_i, z_j)}{\sigma_i \sigma_j} \qquad \text{(V–3)}$$

This correlation coefficient ranges from –1 to +1, and is a measure of the linear association between the experimental results z_i and z_j. Normally, when $\rho_{ij} > 0$ and z_i is underestimated (overestimated), z_j is probably underestimated (overestimated) as well. The inverse occurs when $\rho_{ij} < 0$: if z_i is overestimated (underestimated), z_j is probably underestimated (overestimated).

The correlation coefficient between two statistically independent quantities vanishes. Even if the converse is true for normal distributed data, there are circumstances when this statement is not true (i.e. $\rho_{ij} = 0$ does not imply that z_i and z_j are statistically independent).

V–2.2. Covariance propagation formula: Linear case

Consider a set of n data stored in a column vector such that $\vec{z}^t = (z_1, z_2 ..... z_n)$, where the superscript t represents transpose, and a set of m known linear functions $w_i = w_i\,(z_1, z_2 ...... z_n)$, $i = 1, 2 ...... m$. The adopted values of w_i are given by the values of the functions calculated in the experimental point $\vec{z}$. We can write these linear relations in a matrix form as

$$\vec{w} = \vec{w}_k + \boldsymbol{D} \cdot \vec{z} \qquad \text{(V–4)}$$

where the column vector $\vec{w}$ contains the calculated values of w_i, such that $\vec{w}^t = (w_1, w_2 .....w_m)$,

$$D_{ij} = \partial w_i / \partial z_j \qquad \text{(V–5)}$$

and $\vec{w}_k$ is a column vector of exact and known values. The covariance matrix of the calculated functions w_i is given by

$$\boldsymbol{V_w} = \boldsymbol{D} \cdot \boldsymbol{V_z} \cdot \boldsymbol{D^t} \qquad \text{(V–6)}$$

where $\mathbf{V}_z$ is the covariance matrix of $\vec{z}$.

Equation (V–6) is a generalization of the popular uncertainty propagation formula and is not restricted to normal distributed data (valid whenever $\mathbf{V}_z$ is known independently of the probability distribution function of the z_i quantities). However, when the data are normally distributed, the calculated function values are also normally distributed.

V–2.3. Variance propagation in cascade crossover relations: Example

When determining the variance in the energy of the gamma crossover from the cascading γ rays, the covariance between the energies plays an important role. Consider the level scheme of Fig. V–1: the energies of the first two excited levels can be calculated on the basis of the two γ ray energies $E_{2,1}$ = 411.111(10) keV and $E_{1,0}$ = 110.455(12) keV with covariance -6.0×10^{-5} keV^2, and the covariance matrix of the level energies can be derived.

Neglecting recoil for simplicity (also does not affect the statistical behaviour of the quantities), $E_1 = E_{1,0}$ and $E_2 = E_{2,1} + E_{1,0}$. Defining

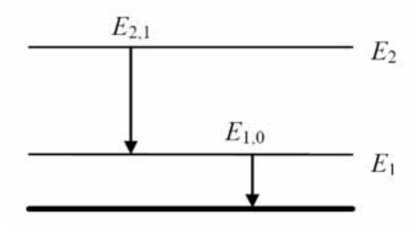

FIG. V–1. Level scheme for cascade crossover.

the data vector as $\vec{E}_\gamma^t = (E_{2,1}, E_{1,0})$, the transformation matrix is

$$\mathbf{D} = \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix}$$

and the γ ray energies covariance matrix is given by

$$\boldsymbol{V}_\gamma = \begin{pmatrix} 100 & -60 \\ -60 & 144 \end{pmatrix} \cdot 10^{-6} \text{ keV}^2$$

The level energies $\vec{E}_L^t = (E_1, E_2)$ are calculated as

$$\vec{E}_L = \boldsymbol{D} \cdot \vec{E}_\gamma = \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix} \cdot \begin{pmatrix} 411.111 \\ 110.455 \end{pmatrix} = \begin{pmatrix} 110.455 \\ 521.566 \end{pmatrix} \text{ keV}$$

with covariance matrix

$$\boldsymbol{V_L} = \boldsymbol{D} \cdot \boldsymbol{V}_\gamma \cdot \boldsymbol{D^t} = \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix} \cdot 10^{-6} \begin{pmatrix} 100 & -60 \\ -60 & 144 \end{pmatrix} \cdot \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix}$$
$$= \begin{pmatrix} 144 & 84 \\ 84 & 124 \end{pmatrix} 10^{-6} \text{ keV}^2$$

Therefore, the energy of the second excited level is 521.566(11) keV, which is the energy of the γ crossover when recoil is neglected. However, if the variance was incorrectly calculated as the sum of the variances of the two cascading γ rays neglecting covariance (100 + 144 = 244 eV^2), the standard deviation would be 16 eV and overestimated by about 40%.

V–2.4. Covariance propagation formula: Non-linear case

When the functions $w_i\,(z_1, z_2 .... z_n)$ are non-linear in z_i, the matrix **D** in the variance propagation formula is approximately given by

$$D_{ij} \cong \partial w_i / \partial z_j \tag{V–7}$$

where the derivatives are evaluated at the experimental vector values $(\hat{z}_1, \hat{z}_2 \,\ldots\ldots\, \hat{z}_n)$. Equation (V–6) becomes an approximation, which is valid when the functions are approximately linear in the range of a few σ_1 around $\hat{z}_1$, a few σ_2 around $\hat{z}_2$, etc.

V–2.5. Gamma ray relative intensity: Example

The uncertainty of the intensity ratio $r = I_1/I_2$, where I_1 and I_2 are γ ray intensities in any scale, depends on the covariance between the intensities. For example, consider $I_1 = 0.37(3)$ and $I_2 = 0.630(9)$ with correlation coefficient $\rho = 0.88$; the matrix of the derivatives (**D**) has only one row and two columns:

$$\mathbf{D} \cong \begin{pmatrix} \partial r/\partial I_1 & \partial r/\partial I_2 \end{pmatrix} = \begin{pmatrix} 1/0.630 & -0.37/0.630^2 \end{pmatrix} = \begin{pmatrix} 1.59 & -0.93 \end{pmatrix}$$

The covariance matrix of r is a 1 × 1 matrix whose single element is the variance of r. Since $\mathrm{cov}(I_1, I_2) = \rho\sigma_1\sigma_2$ and using Eq. (V-6), an approximation can be derived:

$$\sigma_r^2 \cong \begin{pmatrix} 1.59 & -0.93 \end{pmatrix} \cdot 10^{-4} \begin{pmatrix} 9.0 & 2.38 \\ 2.38 & 0.81 \end{pmatrix} \cdot \begin{pmatrix} 1.59 \\ -0.93 \end{pmatrix} = 0.0016$$

The experimental result for the ratio is 0.59(4). If the covariance term is erroneously omitted:

$$(1.59 \cdot 0.03)^2 + (-0.93 \cdot 0.009)^2 = 0.00235$$

which results in a standard deviation of ~0.05 that is overestimated by about 25%.

V–3. MATRIX APPROACH TO THE LSM: LINEAR CASE

V–3.1. Least squares estimate for the linear model

Consider a set of n experimental quantities (y_1, y_2 ...... y_n) related linearly to m parameters with true and unknown values of (a_{01}, a_{02} ...... a_{0m}), and $n \times m$ known values x_{ij}. The relationship between the experimental values and the parameters can be written as

$$\begin{aligned} y_1 &= a_{01}x_{11} + a_{02}x_{12} + \ldots + a_{0m}x_{1m} + e_1 \\ y_2 &= a_{01}x_{21} + a_{02}x_{22} + \ldots + a_{0m}x_{2m} + e_2 \\ &\vdots \\ y_n &= a_{01}x_{n1} + a_{02}x_{n2} + \ldots + a_{0m}x_{nm} + e_n \end{aligned} \tag{V–8'}$$

where e_i is the unknown experimental error of y_i with $\langle e_i \rangle = 0$, $\langle e_i^2 \rangle = \sigma_i^2$ and $\langle e_i e_j \rangle = \mathrm{cov}(y_i, y_j)$. These observational equations of the linear model can be written in matrix form as

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{pmatrix} \cdot \begin{pmatrix} a_{01} \\ \vdots \\ a_{0m} \end{pmatrix} + \begin{pmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{pmatrix} \tag{V–8}$$

Defining the vector of observations as $\vec{y}^{\,t} = (y_1, y_2 \,\ldots\ldots\, y_n)$, the vector of parameters to be estimated as $\vec{A}_0^{\,t} = (a_{01}, a_{02} \,\ldots\ldots\, a_{0m})$, the design matrix **X** formed by the independent variables as x_{ij}, and the vector of errors as $\vec{e}$, Eq. (V–8) can be rewritten as

$$\vec{y} = \boldsymbol{X} \cdot \vec{A}_0 + \vec{e} \tag{V–9}$$

Thus, for a straight line given by $y = y(x) = a + bx$ with experimental points (x_i, y_i) for $i = 1, 2, 3, 4$, the observational linear equations are

$$\begin{aligned} y_1 &= a + bx_1 + e_1 \\ y_2 &= a + bx_2 + e_2 \\ y_3 &= a + bx_3 + e_3 \\ y_4 &= a + bx_4 + e_4 \end{aligned}$$

to give the following vector of observations and design matrix:

$$\vec{y} = \begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{pmatrix} \qquad \boldsymbol{X} = \begin{pmatrix} 1 & x_1 \\ 1 & x_2 \\ 1 & x_3 \\ 1 & x_4 \end{pmatrix}$$

The LSM estimate of $\vec{A}_0$, $\tilde{\vec{A}}$ is obtained by minimizing

$$Q(\vec{A}) = (\vec{y} - \boldsymbol{X} \cdot \vec{A})^t \cdot V^{-1} \cdot (\vec{y} - \boldsymbol{X} \cdot \vec{A}) \tag{V–10}$$

with respect to all A_i. This quadratic form in A_i has the solution

$$\tilde{\vec{A}} = (\boldsymbol{X^t} \cdot \boldsymbol{V^{-1}} \cdot \boldsymbol{X})^{-1} \cdot \boldsymbol{X^t} \cdot \boldsymbol{V^{-1}} \cdot \vec{y} \qquad \text{(V–11)}$$

Using Eq. (V–6) we can verify that the covariance matrix of $\tilde{\vec{A}}$ is given by

$$\boldsymbol{V}_{\tilde{\boldsymbol{A}}} = (\boldsymbol{X^t} \cdot V^{-1} \cdot \boldsymbol{X})^{-1} \qquad \text{(V–12)}$$

The estimate given in Eq. (V–11) is more precisely determined by solving the set of linear algebraic equations

$$(\boldsymbol{X^t} \cdot \boldsymbol{V^{-1}} \cdot \boldsymbol{X}) \cdot \tilde{\vec{A}} = \boldsymbol{X^t} \cdot \boldsymbol{V^{-1}} \cdot \vec{y}$$

because they require much less calculational effort than the inversion of $(\boldsymbol{X^t} \cdot \boldsymbol{V^{-1}} \cdot \boldsymbol{X})$.

V–3.2. Properties of the least squares estimate

The LSM estimate $\tilde{\vec{A}}$ has some important and practical properties.

(a) $\tilde{\vec{A}}$ is unbiased:

As a consequence of the statistical fluctuation in the experimental data, the LSM estimate of the true value $\vec{A}_0$ fluctuates; both $\tilde{a}_i > a_{0i}$ and $\tilde{a}_i < a_{0i}$ will be calculated. However, the expected value of a_i is equal to the true (and unknown) value a_{0i} in the linear case, which is expressed by the formula $\langle a_i \rangle = a_{0i}$ and, generally,

$\langle \tilde{\vec{A}} \rangle = \vec{A}_0$.

This behavior is called unbiasedness, sometimes interpreted as the absence of systematic uncertainty. However, this property does not hold when fitting functions that are non-linear in the parameters unless some specific conditions are satisfied (see Sections V–5, V–7.1).

(b) Minimum variance:

The least squares estimate is the linear estimate with minimum variance. No other linear estimate of a_{0i} has variance smaller than the variance of the LS estimate. This result is true for any i as well as for any linear combination of the fitted parameters.

(c) Non-normal data:

Equations (V–11) and (V–12), as well as properties (a) and (b) above, are valid whether the data are normally distributed or not. Those equations are also valid when the different y_i follow different probability distributions.

(d) Normal data:

When the experimental data obey normal distributions, the adjusted parameters obey normal distributions. Property (b) above becomes stronger for normal data: there is no other estimate with smaller variance (i.e. no matter how the data have been combined, estimates of non-LSM linear combinations will be less precise).

(e) Asymptotic normality of the estimates:

The central limit theorem can be applied to the linear equations (Eq. (V–11)): for large n, every fitted parameter $\tilde{a}_i$ is normally distributed and independent of the distribution of the experimental data, assuming that many data points contribute to the estimate $\tilde{a}_i$. Although the theorem assumes that the estimates are normal only when $n \to \infty$, the probability density function of the fitted parameters is approximately normal even for a few data and especially when the data are nearly normal.

(f) Goodness of fit test:

Perhaps the χ^2 test is the most popular test of fit in experimental physics. When the experimental data follow a normal distribution, the statistics

$$\chi^2 = \left(\vec{y} - \boldsymbol{X} \cdot \tilde{\vec{A}}\right)^t \cdot V^{-1} \cdot \left(\vec{y} - \boldsymbol{X} \cdot \tilde{\vec{A}}\right) \qquad \text{(V–13)}$$

follow a chi-square distribution with $\nu = n - m$ degrees of freedom. The expected value of χ^2 is equal to ν with a standard deviation of $\sqrt{2\nu}$. A table of the χ^2 cumulative distribution must be consulted in order to use the χ^2 test. Generally, χ^2 fluctuates a few standard deviations around ν.

V–4. LSM WORKED EXAMPLES WITH LINEAR FUNCTIONS

When dealing with the LSM, the basic aim is to prepare the linear model equations (Eq. (V–8)) and identify the vector $\vec{y}$ and the matrices **X** and **V**. Some simple examples are shown in this section with correlated data or results.

V–4.1. Mean of correlated data

Consider n observations (y_1, y_2 …... y_n) of the same physical quantity with covariance matrix $\boldsymbol{V}$ given by $V_{ii} = \sigma^2$ and $V_{ij} = \rho \cdot \sigma^2$ for $i \neq j$. The linear model equations (Eq. (V–8')) are

$$
\begin{aligned}
y_1 &= y_0 + e_1 \\
y_2 &= y_0 + e_2 \\
&\vdots \\
y_n &= y_0 + e_n
\end{aligned}
\qquad \text{(V–14)}
$$

where y_0 is the true and unknown value of the physical quantity. Design matrix $\boldsymbol{X}$ is

$$\boldsymbol{X} = \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} \qquad \text{(V–15)}$$

Using Eq. (V–11), the fitted value is

$$\tilde{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \qquad \text{(V–16)}$$

which is the usual result, with the variance given by Eq. (V–12):

$$\sigma_{\tilde{y}}^2 = \frac{(\rho n - \rho + 1)\sigma^2}{n} \qquad \text{(V–17)}$$

that is not evident for $n > 1$ but shows that the precision of the mean of correlated data is limited by the correlation coefficient: when $n \to \infty$,

$$\sigma_{\tilde{y}}^2 \to \rho\sigma^2 \qquad \text{(V–18)}$$

which is a physically sound result. Incorrect asymptotic behaviour occurs when the covariances are neglected and has rather surprisingly been used to argue against using strict statistical methods in experimental physics.

V–4.2. Signal and noise measurement

Consider two observations (y_1 and y_2) of a signal (s_0) in the presence of background (b_0), and two other observations (y_3 and y_4) of the background (b_0). The determination of the adopted signal value and uncertainty can be simplified by assuming that the standard deviation of y_i is equal to 1 for every i and the data are uncorrelated.

There are two approaches to this problem:

(1) We can determine the adopted values of the signal plus background and of the background by the LSM, and then calculate the adopted value of the signal by using the difference between the two results:

$$\tilde{s} = \frac{y_1 + y_2}{2} - \frac{y_3 + y_4}{2} \qquad \text{(V–19)}$$

By using Eq. (V–6), we obtain

$$\sigma_{\tilde{s}}^2 = 1 \qquad \text{(V–20)}$$

(2) Another possibility is to apply the LSM directly for $\vec{A}_0^t = (s_0, b_0)$. Thus, we have $\vec{y}^t = (y_1, y_2, y_3, y_4)$ and

$$\boldsymbol{X} = \begin{pmatrix} 1 & 1 \\ 1 & 1 \\ 0 & 1 \\ 0 & 1 \end{pmatrix} \qquad \text{(V–21)}$$

Using Eqs (V–11), (V–12), we obtain the same results as given in Eqs (V–19), (V–20).

Both approaches give the same result and illustrate the uniqueness of the LSM: the intermediate steps adopted in the application of the LSM in the linear problem are irrelevant.

V–4.3. Using the covariances in a relative efficiency calibration

The use of covariances between γ ray emission probabilities can be demonstrated by interpolating the detection efficiency at energies between the γ lines of ^{94}Nb, and assuming that the logarithm of the efficiency is linear over the logarithm of the energy. This hypothesis is reasonable for the small energy range considered [V–4].

The efficiencies ε_1 and ε_2 at the energies of the γ ray emissions following ^{94}Nb decay of E_1 = 871.1 keV and E_2 = 702.6 keV, respectively, can be calculated from the peak areas A_i and the emission probabilities p_i:

$$\varepsilon_i = C_i \frac{A_i}{p_i} \cong C \frac{A_i}{p_i} \qquad \text{(V–22)}$$

where C_1 and C_2 are proportionality constants that include all required corrections. Although C_1 and C_2 are most likely different in a precise measurement, these values can be considered equal for both transitions in the calculation of the standard deviations; hence we assume $C_1 \neq C_2$ when calculating the efficiencies, but $C_1 = C_2 = C$ in the calculation of variances.

The efficiency relative to the value at E_1 is assumed to be given by the equation

$$\ln \frac{\varepsilon}{\varepsilon_1} = b \ln \frac{E}{E_1} \qquad \text{(V–23)}$$

and the coefficient b is related to the data by

$$b \ln \frac{E_2}{E_1} = \ln \frac{C_1 A_1}{C_2 A_2} + \ln \frac{p_2}{p_1} \cong \ln \frac{A_1}{A_2} + \ln \frac{p_2}{p_1} \qquad \text{(V–24)}$$

where the first expression is used to estimate the efficiency, and the second expression is adopted to determine the standard deviation of the efficiency using Eq. (V–6) to give

$$\sigma_b^2 = \left[\left(\frac{\sigma(A_1)}{A_1} \right)^2 + \left(\frac{\sigma(A_2)}{A_2} \right)^2 + \left(\frac{\sigma_1}{p_1} \right)^2 + \left(\frac{\sigma_2}{p_2} \right)^2 - 2\rho \frac{\sigma_1}{p_1} \frac{\sigma_2}{p_2} \right] \left(\ln \frac{E_1}{E_2} \right)^{-2} \qquad \text{(V–25)}$$

This formula was derived by assuming that the peak areas A_1 and A_2 are statistically independent, and the standard deviation of the ratio of the two emission probabilities is given by

$$\sigma\left(\frac{p_1}{p_2}\right) = \frac{p_1}{p_2} \sqrt{\left(\frac{\sigma_1}{p_1}\right)^2 + \left(\frac{\sigma_2}{p_2}\right)^2 - 2\rho \frac{\sigma_1}{p_1} \frac{\sigma_2}{p_2}} \qquad \text{(V–26)}$$

where σ_1 and σ_2 are the standard deviations, and ρ is the correlation coefficient between p_1 and p_2.

The standard deviation of the relative efficiency interpolated at energy E can be calculated from Eq. (V–23) and σ_b to be

$$\sigma\left(\frac{\varepsilon}{\varepsilon_1}\right) = \frac{\varepsilon}{\varepsilon_1} \sigma_b \ln \frac{E}{E_1} \qquad \text{(V–27)}$$

A positive correlation coefficient ρ reduces the contribution of the uncertainties of the emission probabilities to the uncertainty in the interpolated relative efficiency, because of the negative term in Eq. (V–25). However, there is no point in taking into account the covariance in the efficiency calibration for ^{94}Nb because of the negligible contribution of the uncertainties in the γ ray emission probabilities to the efficiency uncertainty. Also note the possible effect of the covariance when the relative standard deviations in p_1 and p_2 are equal and ρ approaches 1, resulting in the last three terms in the square brackets of Eq. (V–25), cancelling each other out.

V–5. FITTING NON-LINEAR FUNCTIONS BY THE LSM

V–5.1. Reduction to the linear case

The relationship between the experimental results and the parameters to be fitted is non-linear in many practical cases (i.e. observational equations are non-linear). Thus, a first order expansion of the observational equations has to be used around some starting values of the parameters to apply the LSM.

Consider the non-linear relationships between the parameters and the experimental data:

$$y_i = f_i(\vec{A}_0) = f_i(a_{01}, a_{02}, \ldots a_{0m}),\ i = 1, 2 \ldots\ldots n \qquad \text{(V–28)}$$

where f_i are known functions of the parameters. Developing f_i around starting values $(a_{s1}, a_{s2}, \ldots a_{sm})$, we obtain

$$y_i \cong f_i(a_{s1}, a_{s2}, ... a_{sm}) + \frac{\partial f_i}{\partial a_1}\Delta a_1 + \frac{\partial f_i}{\partial a_2}\Delta a_2 + ... \frac{\partial f_i}{\partial a_m}\Delta a_m \quad \text{(V–29)}$$

where the partial derivatives are calculated at the starting values $\vec{A}_S$. If the functions f_i are approximately linear in the range $a_{si}, a_{si} + \Delta a_i$ for every i, the problem reduces to the linear LSM for $\Delta\vec{A}$. Defining

$$y'_i = y_i - f_i(\vec{A}_s) = \frac{\partial f_i}{\partial a_1}\Delta a_1 + \frac{\partial f_i}{\partial a_2}\Delta a_2 + ... \frac{\partial f_i}{\partial a_m}\Delta a_m \quad \text{(V–30)}$$

reduces the analysis to the linear case, where the observational equations of the LSM [Eq. (V–8)] are written with $\vec{y}^t = (y'_1, y'_2 ...... y'_n)$,

$$x_{ij} = \left.\frac{\partial f_i}{\partial a_j}\right|_{\vec{A}_s} \quad \text{(V–31)}$$

and the derivatives are evaluated at the starting values of the parameters.

Using Eqs (V–11) and (V–12) we obtain $\Delta\vec{A}$ and the associated covariance matrix, and a better approximation of $\tilde{\vec{A}}$ is obtained, $\vec{A}_+ = \vec{A}_s + \Delta\vec{A}$. However, a single iteration is not always sufficient to reach the minimum squares, and therefore the resulting $\vec{A}_+$ value is used as a new starting value and the calculations are repeated to obtain a new correction $\Delta\vec{A}$.

V–5.2. Iterative procedure

The procedure outlined above does not converge sufficiently quickly in many cases. A better iterative method has been proposed by Marquardt [V–5], with the following steps.

(1) Use starting values $\vec{A}_S$, and calculate the sum of the squares

$$Q = \vec{y}'^t \cdot \boldsymbol{V}^{-1} \cdot \vec{y}' \quad \text{(V–32)}$$

where $\vec{y}'$ is the vector of residuals given by Eq. (V–30).

(2) Calculate the auxiliary matrix $\boldsymbol{M}(\lambda)$ using x_{ij} from Eq. (V–31)

$$M(\lambda)_{ij} = (1 + \lambda \cdot \delta_{ij}) \cdot (\boldsymbol{X}' \cdot \boldsymbol{V}^{-1} \cdot \boldsymbol{X})_{ij} \quad \text{(V–33)}$$

where $\delta_{ij} = 1$ if $i = j$, and 0 otherwise. Start the iterative procedure with $\lambda = 0.01$, and then calculate a trial vector of corrections to the starting values,

$$\Delta\vec{A} = \boldsymbol{M}(\lambda)^{-1} \cdot \boldsymbol{X}^t \cdot \boldsymbol{V}^{-1} \cdot \vec{y}' \quad \text{(V–34)}$$

(3) Calculate $\vec{A}_+ = \vec{A}_s + \Delta\vec{A}$, a new vector of residuals $\vec{y}'_+$, and

$$Q' = \vec{y}'^{\,t}_+ \cdot \boldsymbol{V}^{-1} \cdot \vec{y}'_+ \quad \text{(V–35)}$$

(4) If $Q' > Q$, reject the new value $\vec{A}_+$, increase λ by a factor of 10 and return to (2); if $Q' < Q$, accept the new value $\vec{A}_+$ as a better estimate of $\tilde{\vec{A}}$ and test convergence as described in (5).

(5) Convergence test: If $|Q' - Q| << 1$ and

$$\delta a_i << \sqrt{\left(\boldsymbol{V}_{\Delta\vec{A}}\right)_{ii}}$$

for every i, where $\boldsymbol{V}_{\Delta\vec{A}} = (\boldsymbol{X}^t \cdot \boldsymbol{V}^{-1} \cdot \boldsymbol{X})^{-1}$, the process converged. However, if one of the above conditions was not satisfied, decrease λ by a factor of 10, substitute Q' to Q, $\vec{A}_+$ to $\vec{A}_S$ and return to (2).

After convergence has been reached, the variance of the fitted parameters $\tilde{\vec{A}}$ is given by Eq. (V–12):

$$\boldsymbol{V}_{\tilde{\vec{A}}} = (\boldsymbol{X}^t \cdot \boldsymbol{V}^{-1} \cdot \boldsymbol{X})^{-1}$$

using the design matrix **X** calculated by Eq. (V–31) with the fitted parameters

$$x_{ij} = \left.\frac{\partial f_i}{\partial a_j}\right|_{\tilde{\vec{A}}} \quad \text{(V–36)}$$

V–6. LSM APPLIED TO A NON-LINEAR FUNCTION: HPGe DETECTOR EFFICIENCY CALIBRATION

V–6.1. Procedure

The logarithm of the efficiency of a HPGe detector can be well approximated by

$$y = a_1 + a_2 \cdot \ln(E/E_0) + \begin{cases} b_1 \cdot \ln^2(E/E_0) & E \le E_0 \\ b_2 \cdot \ln^2(E/E_0) & E > E_0 \end{cases} \quad \text{(V–37)}$$

Parameters a_1, a_2, b_1, b_2 and E_0 will be determined so that the function fits the experimental data listed in Table V–1 below, taking into account the correlations given in Table V–2. This exercise represents a real case of efficiency calibration for an extended source; details of the determination of the correlation matrix can be found in Ref. [V–6].

TABLE V–1. EXPERIMENTAL DETECTOR EFFICIENCY ε, AS A FUNCTION OF THE γ RAY ENERGY E

E (keV)	$\varepsilon(\sigma)$	E (keV)	$\varepsilon(\sigma)$
59.5	0.00642(29)	356.0	0.01349(64)
81.0	0.01472(93)	383.9	0.01284(63)
122.1	0.02543(63)	604.7	0.00831(27)
136.5	0.02580(77)	795.8	0.00642(21)
276.4	0.01690(81)	1173.2	0.00487(14)
302.9	0.01560(73)	1332.5	0.00436(15)

TABLE V–2. CORRELATION COEFFICIENTS BETWEEN γ RAY EFFICIENCIES (ROWS AND COLUMNS LABELLED BY ENERGY IN keV)

E_γ	60	81	122	137	277	303	356	384	605	795	1173	1332
60	1.00	0.14	0.35	0.31	0.18	0.19	0.18	0.17	0.28	0.28	0.30	0.24
81	0.14	1.00	0.26	0.21	0.19	0.19	0.19	0.17	0.20	0.20	0.22	0.17
122	0.35	0.26	1.00	0.70	0.33	0.34	0.32	0.32	0.50	0.52	0.56	0.45
137	0.31	0.21	0.70	1.00	0.29	0.28	0.28	0.27	0.43	0.45	0.48	0.39
277	0.18	0.19	0.33	0.29	1.00	0.23	0.23	0.23	0.26	0.26	0.29	0.23
303	0.19	0.19	0.34	0.28	0.23	1.00	0.23	0.24	0.26	0.27	0.29	0.23
356	0.18	0.19	0.32	0.28	0.23	0.23	1.00	0.23	0.26	0.27	0.29	0.23
384	0.17	0.17	0.32	0.27	0.23	0.24	0.23	1.00	0.25	0.25	0.28	0.22
605	0.28	0.20	0.50	0.43	0.26	0.26	0.26	0.25	1.00	0.80	0.43	0.36
795	0.28	0.20	0.52	0.45	0.26	0.27	0.27	0.25	0.80	1.00	0.45	0.34
1173	0.30	0.22	0.56	0.48	0.29	0.29	0.29	0.28	0.43	0.45	1.00	0.80
1332	0.24	0.17	0.45	0.39	0.23	0.23	0.23	0.22	0.36	0.34	0.80	1.00

The design matrix is given by

$$X_{i1} = 1$$

$$X_{i2} = \ln E_i/E_0$$

$$X_{i3} = \begin{cases} \ln^2 E_i/E_0 & \text{for } E_i \le E_0 \\ 0 & \text{for } E_i > E_0 \end{cases}$$

$$X_{i4} = \begin{cases} 0 & \text{for } E_i \le E_0 \\ \ln^2 E_i/E_0 & \text{for } E_i > E_0 \end{cases}$$

$$X_{i5} = \begin{cases} -a_2/E_0 - 2b_1/E_0 \cdot \ln E_i/E_0 & \text{for } E_i \le E_0 \\ -a_2/E_0 - 2b_2/E_0 \cdot \ln E_i/E_0 & \text{for } E_i > E_0 \end{cases}$$

Using the iterative procedure outlined in Section V–5, and choosing 4, –1, –2, 0.02 and 200 keV as the starting values for a_1, a_2, b_1, b_2 and E_0, respectively, the results listed in Table V–3 were obtained after six iterations.

V–6.2. Correlated interpolation

The efficiency at a given energy is determined from Eq. (V–37), and the standard deviation is calculated using the parameter variances and correlation coefficients of Table V–3. Interpolated efficiencies for different energies are correlated. As

TABLE V–3. FITTED PARAMETERS ALONG WITH THEIR STANDARD DEVIATIONS AND CORRELATIONS, AND TOTAL CHI-SQUARE

Parameter	Value (σ)	Correlation coefficient				
		a_1	a_2	b_1	b_2	E_0 (keV)
a_1	–3.732(30)	1				
a_2	–0.89(11)	0.57	1			
b_1	–1.83(15)	–0.62	–0.82	1		
b_2	0.008(45)	–0.58	–0.98	0.74	1	
E_0 (keV)	183(15)	–0.61	–0.95	0.94	0.89	1
χ^2	5.8					

an example, the covariance matrix of the efficiencies at 100, 200 and 300 keV is calculated. Equation (V–37) gives the logarithm of the efficiency, and we must calculate the covariance matrix of the functions $\varepsilon_1 = \exp(y(100))$, $\varepsilon_2 = \exp(y(200))$ and $\varepsilon_3 = \exp(y(300))$ from the results of the previous exercise.

Using the values in Table V–3 we can determine the efficiency values and the matrix of partial derivatives of the efficiencies with respect to the fitted parameters:

$$\boldsymbol{D} = 10^{-2}\begin{pmatrix} 2.096 & -1.263 & 0.761 & 0 & -0.015 \\ 2.212 & 0.201 & 0 & 0.018 & 0.011 \\ 1.552 & 0.770 & 0 & 0.382 & 0.007 \end{pmatrix}$$

is required to determine the covariance matrix by means of Eq. (V–6). The efficiencies at 100, 200 and 300 keV are 0.0210(6), 0.0221(12) and 0.0155(5) respectively, with the correlation matrix

$$\boldsymbol{R}_e = \begin{pmatrix} 1.00 & -0.16 & 0.21 \\ -0.16 & 1.00 & 0.80 \\ 0.21 & 0.80 & 1.00 \end{pmatrix}$$

If the covariances between the fitted parameters are neglected, all the standard deviations are overestimated as 0.0210(29), 0.0221(18) and 0.0155(14) for the efficiency at 100, 200 and 300 keV, respectively.

V–7. LIMITATIONS OF THE LSM

V–7.1. Bias in non-linear fit

The LSM in the non-linear case is only asymptotically unbiased (i.e. the bias in results goes to zero as the number of data points increases towards infinity or their variance tends to zero), which means that the fitted parameters in practical non-linear cases can be biased. The bias can be removed in some cases by direct evaluation of the expected value, but this is not a normal procedure since sometimes this term depends on the true value of the measured quantity. Thus, bias is a possibility that must be carefully investigated in non-linear fits.

V–7.2. Uncertainty in the independent variable

Only the y variables were assumed to be subject to uncertainties in the presentation of the LSM given above. However, the x variables are also subject to statistical fluctuation in many cases. Although there is no general solution to this problem, a relatively simple variance propagation accompanied by an iterative procedure is recommended. A first fit can be achieved by considering only the uncertainties of the variables y; using the results obtained in this first fit, effective y uncertainties can be calculated. If $y = y(x)$ is a function of x and the experimental value x_i has a standard deviation σ_{xi}, the effective variances of y_i that account for the uncertainties in both variables x_i and y_i are given by

$$\sigma_i'^2 = \sigma_i^2 + \frac{\partial y_i}{\partial x_i}\sigma_{xi}^2 \qquad \text{(V–38)}$$

where the derivatives must be evaluated at the observed values.

However, an important limitation of this approximation occurs when the standard deviation of the independent variable is not smaller than the dispersion of the variable. This limitation can be re-stated: if x_1, x_2 …... x_n are n independent variables, unbiased parameter estimates can be obtained when, for all or many x_i,

$$\sigma_{xi}^2 << \left\langle x^2 \right\rangle - \left\langle x \right\rangle^2 \qquad \text{(V–39)}$$

where

$$\left\langle x^2 \right\rangle = \frac{1}{n}\sum x_i^{\,2}$$
$$\left\langle x \right\rangle = \frac{1}{n}\sum x_i \qquad \text{(V–40)}$$

V–8. DETERMINATION OF COVARIANCES BETWEEN γ RAY INTENSITIES IN SPECTROSCOPIC MEASUREMENTS

The calculation of the γ ray intensity covariances in γ ray spectroscopy is outlined below. Even if the example developed in this section is relatively simple, the procedure contains all the necessary elements for the calculation of the covariance matrix of a real case.

V–8.1. Data description

Consider the decay scheme depicted in Fig. V–2. The observed peak-area is $A_i' \pm s_i'$ for each gamma ray γ_i that changes to $A_i \pm s_i$ after correcting for sum, pile-up and any other secondary detection effect. Although the corrections introduce some statistical dependences between the different values, the covariances arising from these adjustments can usually be neglected. Therefore, the covariance matrix of the net peak areas can be approximated by the diagonal matrix:

$$\mathbf{V}_A = \begin{vmatrix} s_1^{\,2} & & & & \\ & \ddots & & \mathbf{0} & \\ & & s_i^{\,2} & & \\ & \mathbf{0} & & \ddots & \\ & & & & s_m^{\,2} \end{vmatrix}$$

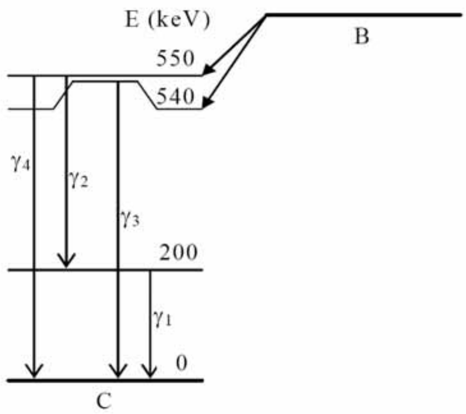

FIG. V–2. Example of a decay scheme.

where m is the number of γ ray transitions. However, if there are unresolved doublets, the covariance between the corresponding peak areas must not be neglected and should be placed in the appropriate row and column of $\mathbf{V}_A$.

We will assume that the γ_i rays are observed by means of a detector whose efficiency was calibrated using Eq. (V–37), and therefore the parameters given in Table V–3 of Section V–6 may be used. The efficiency for each γ ray can be interpolated by Eq. (V–37) by using the appropriate energy to give a set of values ε_i whose covariance matrix can be calculated from Eq. (V–6) as shown in Section V–6.2:

$$\boldsymbol{V}_\varepsilon = \boldsymbol{D}\boldsymbol{V}_{ab}\boldsymbol{D}^t$$

where $\mathbf{V}_{ab}$ is the covariance matrix of the fitted efficiency parameters (Eq. (V–12)) and $\boldsymbol{D}$ is the matrix of derivatives with respect to the parameters (Eq. (V–7)). Using the γ ray energies deduced from Fig. V–2, we obtain

$$\boldsymbol{V}_\varepsilon = 10^{-7}\begin{vmatrix} 13.33 & 2.499 & 0.2423 & 0.2064 \\ 2.499 & 1.404 & 0.8362 & 0.8166 \\ 0.2423 & 0.8362 & 0.6927 & 0.6820 \\ 0.2064 & 0.8166 & 0.6820 & 0.6717 \end{vmatrix}$$

Table V–4 lists the peak areas and uncertainties needed to complete this example.

The γ ray intensities can be calculated by means of the expression:

$$I_i = \frac{A_i}{NF(A,\varepsilon,\tau)\varepsilon_i} \qquad \text{(V–41)}$$

TABLE V–4. PEAK AREAS AND STANDARD DEVIATIONS (σ) USED IN THE EXAMPLE

i	Energy (keV)	Net area (σ)
1	200	529841(923)
2	350	324767(744)
3	540	55873(403)
4	550	689661(1132)

We will disregard the internal conversion coefficients and assume no β feeding to the ground state for the sake of brevity. No generality is lost by ignoring the internal conversion coefficients and the ground state β feeding fraction, because they generate an additional set of parameters τ that affects the variance of the normalization factor (NF), but will not normally introduce any correlation with the γ ray intensities (at least when studying nuclides adopted for γ ray detector calibration when the main decay is via the γ rays).

V–8.2. Absolute gamma ray intensities

Considering that the sum of the intensities of the transitions to the ground state is 1, the normalization factor (NF) for this decay scheme is determined to be:

$$NF(A,\varepsilon) = \frac{A_1}{\varepsilon_1} + \frac{A_3}{\varepsilon_3} + \frac{A_4}{\varepsilon_4} \quad \text{(V–42)}$$

The determination of the emission intensities along with their covariances is a problem associated with a change of variables, with m functions (given by Eq. (V–41)) of $2m$ random variables: m net peak areas and m efficiencies. However, since the observed peak areas and the interpolated efficiencies are statistically independent, the matrix of the total uncertainties in the intensities can be given by the sum of the variance matrices from these two primary datasets:

$$\boldsymbol{V}_I = \boldsymbol{F}\boldsymbol{V}_A\boldsymbol{F}^t + \boldsymbol{G}\boldsymbol{V}_\varepsilon\boldsymbol{G}^t \quad \text{(V–43)}$$

where $\boldsymbol{F}$ and $\boldsymbol{G}$ are defined through

$$F_{iv} = \frac{\partial I_i}{\partial A_v} \text{ and } G_{iv} = \frac{\partial I_i}{\partial \varepsilon_v} \quad \text{(V–44)}$$

which avoid the use of larger matrices to accommodate all $2m$ random variables together.

Care must be taken when formulating the matrices $\boldsymbol{F}$ and $\boldsymbol{G}$ to ensure the correct dependence on the random variables. For example,

$$\frac{\partial I_2}{\partial A_2} = \frac{I_2}{A_2} \text{ and } \frac{\partial I_2}{\partial \varepsilon_2} = -\frac{I_2}{\varepsilon_2}$$

where the minus sign on the derivative with respect to the efficiency is extremely important, because this parameter will not be squared in the determination of the covariances. The other derivatives are more complicated:

$$\frac{\partial I_1}{\partial A_1} = \frac{I_1}{A_1} - \frac{I_1^2}{A_1} \text{ and } \frac{\partial I_1}{\partial \varepsilon_1} = -\frac{I_1}{\varepsilon_1} + \frac{I_1^2}{\varepsilon_1}$$

Most of the crossed derivatives are not null:

$$\frac{\partial I_2}{\partial A_1} = -\frac{I_1 I_2}{A_1}$$

The final results are given in Table V–5.

TABLE V–5. ABSOLUTE EMISSION INTENSITIES AND CORRELATION MATRIX DETERMINED FOR THE EXAMPLE

id	Energy (keV)	$I = P_\gamma$	Correlation coefficient			
			1	2	3	4
1	200	0.200(9)	1	0.59	–0.85	–0.999
2	350	0.1993(12)	0.59	1	–0.50	–0.59
3	540	0.0499(7)	–0.85	–0.50	1	0.83
4	550	0.751(9)	–0.999	–0.59	0.83	1

Due to the nature of the decay scheme in which γ_1 and γ_4 are unique transitions de-exciting a level to the ground state, normalization induces a strong statistical correlation between their absolute intensities, as manifested by $\rho_{14} = -0.999$ in Table V–5.

The intensities (I_i) and the associated covariance matrix ($\boldsymbol{V_I}$) represent the properly reduced experimental data (Table V–5 lists the correlation matrix rather than the covariance matrix because correlations are quantities easier to interpret than covariances). This set of values summarizes and conveys all the statistical information obtained in the experiment in such a way that no other data are required for the calculation of any statistical quantity related to the decay scheme.

V–8.3. Relative gamma ray intensities

Sometimes only relative intensities are measured because either the decay scheme is not sufficiently well known to define an NF or the relative intensities are much more precise than the absolute emission probabilities. Under such circumstances the covariances of the NF with the intensities must be provided to allow further statistical calculations (such as the normalization of the decay scheme or changing the reference line of the relative intensities).

The NF for relative intensities is

$$NF_r\left(A,\varepsilon\right) = \frac{A_r}{I_r \varepsilon_r} \qquad \text{(V–45)}$$

where r identifies the reference transition (chosen as $r = 4$ with intensity $I_r = 100$).

Since the reference value has no uncertainty, the covariance matrix of the relative transition intensities has a dimension equal to $m - 1$ (i.e. one less than the number of γ ray transitions). However, the correct uncertainties in the relative photon fluxes $\phi_i = A_i/\varepsilon_i$, (of total number m) are impossible to retrieve with this smaller matrix. The best way to complete the set of variables is to add the NF (NF_r) to the set of relative intensities and rescale the NF to the reference value I_r as detailed below.

Considering I_{r1}, I_{r2}, I_{r3} and NF_r as the reduced data set representing the data obtained, the derivatives required to constitute matrices **F** and **G** are simpler:

$$\frac{\partial I_{ri}}{\partial A_j} = \frac{I_{ri}}{A_i}\delta_{ij} \quad i,j = 1,\ 2,\ 3$$

$$\frac{\partial I_{ri}}{\partial A_4} = -\frac{I_{ri}}{A_4} \quad i = 1,\ 2,\ 3$$

$$\frac{\partial NF_r}{\partial A_j} = \frac{NF_r}{A_r}\delta_{jr} \quad j = 1\ \ldots\ 4$$

where δ is the Kronecker delta, and generate similar results for the derivatives with respect to the efficiencies. The results are shown in Table V–6.

Even if the data in the table represent the experimental result, the absolute value of the NF is in most cases irrelevant and should be omitted from these results. This removal process can be accomplished by rescaling the covariance matrix and multiplying the column and the row corresponding to the NF by I_r/NF_r (i.e. the diagonal element is multiplied by the square of the NF). Since rescaling a covariance matrix does not affect the correlations, the final result will be almost identical to Table V–6 except for the last line, and is shown in Table V–7.

When restoring the original value for the relative photon fluxes, all the covariance terms must be taken into account. For example, when recalculating

TABLE V–6. RELATIVE γ RAY INTENSITIES AND NF DETERMINED FROM SAMPLE DATA

Variable	Energy (keV)	$100\ I_\gamma/I_4$	Correlation coefficient			
			I_{r1}	I_{r2}	I_{r3}	NF_r
I_{r1}	200	26.6(15)	1	0.95	0.04	–0.43
I_{r2}	350	26.5(4)	0.95	1	0.064	–0.32
I_{r3}	540	6.65(5)	0.04	0.064	1	–0.01
NF_r	-	$9.01(25) \times 10^5$	–0.43	–0.32	–0.01	1

TABLE V–7. RELATIVE γ RAY INTENSITIES DETERMINED FROM SAMPLE DATA

id	Energy (keV)	I_γ	Correlation coefficient			
			1	2	3	4
1	200	26.6(15)	1	0.95	0.04	–0.43
2	350	26.5(4)	0.95	1	0.064	–0.32
3	540	6.65(5)	0.04	0.064	1	–0.01
4	550	100.0(28)	–0.43	–0.32	–0.01	1

$\phi_1 = \frac{A_1}{\varepsilon_1} = NF_r I_{r1}$, the relative variance is given by

$$\left(\frac{\sigma_{\phi_1}}{\phi_1}\right)^2 = \left(\frac{\sigma_{NF_r}}{NF_r}\right)^2 + \left(\frac{\sigma_{r1}}{I_{r1}}\right)^2 + 2\frac{\mathrm{cov}\left(I_{r1}, NF_r\right)}{I_{r1} NF_r}$$

$$= \left(\frac{\sigma_{NF_r}}{NF_r}\right)^2 + \left(\frac{\sigma_{r1}}{I_{r1}}\right)^2 + 2\frac{\sigma_{NF_r}}{NF_r}\frac{\sigma_{r1}}{I_{r1}}\rho\left(I_{r1}, NF_r\right)$$

or $\frac{\sigma_{\varphi_1}}{\varphi_1} = 5.1\%$

to be compared with the erroneous calculation that ignores the covariance term to give

$\left(\frac{2.8}{100}\right)^2 + \left(\frac{1.5}{26.6}\right)^2 = (6.3\%)^2$ and the calculation that does not include the precision in the NF to give

$\frac{1.5}{26.6} = 5.6\%$.

Although this approach is satisfactory for the correlation between γ ray intensities, the procedure omits the constraints imposed by the physical nature of the problem (i.e. nuclear decay). This subject is discussed in Ref. [V–7], which points to the possibility of determining the branching ratios and feeding fractions instead of the γ ray intensities, and improving the accuracy of the results.

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LIST OF PARTICIPANTS

Bé, M.-M.	Laboratoire National Henri Becquerel, Commissariat à l'Énergie Atomique, France
Chechev, V.P.	V.G. Khlopin Radium Institute, Russian Federation
Dersch, R.	Physikalisch-Technische Bundesanstalt, Germany
Helene, O.A.M.	Instituto de Física, Universidade de São Paulo, Brazil
Helmer, R.G.†	Idaho National Laboratory, United States of America
Herman, M.	International Atomic Energy Agency
Hlaváč, S.	Institute of Physics, Slovak Academy of Sciences, Slovakia
Marcinkowski, A.	The Andrzej Soltan Institute for Nuclear Studies, Poland
Molnár, G.L.†	Institute of Isotope and Surface Chemistry, Chemical Research Centre, Hungary
Nichols, A.L.	AEA Technology, United Kingdom; International Atomic Energy Agency
Schönfeld, E.	Physikalisch-Technische Bundesanstalt, Germany
Vanin, V.R.	Instituto de Física, Universidade de São Paulo, Brazil
Woods, M.J.	National Physical Laboratory, United Kingdom

All contributing authors listed at the beginning of the report were the main participants in the CRP. Various co-workers also played important roles in ensuring that the agreed decay-data evaluations were undertaken:

Baglin, C.M.	Lawrence Berkeley National Laboratory, United States of America
Browne, E.	Lawrence Berkeley National Laboratory, United States of America
Castro, R.M.	Instituto de Física, Universidade de São Paulo, Brazil
Chisté, V.	Laboratoire National Henri Becquerel, Commissariat à l'Énergie Atomique, France
Collins, S.M.	National Physical Laboratory, United Kingdom
Egorov, A.G.	V.G. Khlopin Radium Institute, Russian Federation
Kuzmenko, N.K.	V.G. Khlopin Radium Institute, Russian Federation
MacMahon, T.D.	National Physical Laboratory, United Kingdom
Mariański, B.	The Andrzej Soltan Institute for Nuclear Studies, Poland

† Deceased.

Morillon, C.	Laboratoire National Henri Becquerel, Commissariat à l'Énergie Atomique, France
Pascholati, P.R.	Instituto de Física, Universidade de São Paulo, Brazil
Sergeev, V.O.	Research Institute of Physics, St. Petersburg State University, Russian Federation
Woods, S.A.[†]	National Physical Laboratory, United Kingdom

[†] Deceased.

Various groups around the world are engaged in the compilation and evaluation of decay data for either all known or specific radionuclides. Many evaluators operate independently and recommend slightly different values for the same parameter. Even small deviations in the recommended data can have a significant impact on the definition of the decay characteristics of radionuclides used as standards in detector efficiency calibrations and various applications. High quality decay data are essential for the efficiency calibration of X and gamma ray detectors that are used to quantify the radionuclidic content of a sample by determining the intensities of any resulting X and gamma rays. A major objective of the IAEA nuclear data programme is to promote improvements in the quality of nuclear data used in science and technology. This report presents the results of a coordinated research project on X Ray and Gamma Ray Decay Data Standards for Detector Calibration and Other Applications. Recommended half-lives and X and gamma ray emission probabilities are listed in Volume 1 of this report for a carefully selected set of radionuclides and nuclear reactions that are suitable for detector efficiency calibration and other applications. The recommendations and report of this work are published in two parts, Recommended Decay Data, High Energy Gamma Ray Standards and Angular Correlation Coefficients (Volume 1); and Data Selection, Assessment and Evaluation Procedures (Volume 2).

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