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IAEA-NSDD Network: Recent Relevant CRPs and other activities (Evaluation of Decay Data: Relevant IAEA Coordinated Research Projects)

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Evaluation of Decay Data: Relevant IAEA Coordinated Research Projects

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Summary

Specific IAEA Coordinated Research Projects (CRPs) have been directed towards the generation of recommended high-quality decay data for a number of important applications. Decay-scheme data for specific radionuclides have required study and evaluation through an agreed set of procedures. The role of the IAEA Nuclear Data Section in creating these dedicated data files is described, and both the objectives and resulting decay data from these most relevant CRPs are also reviewed.

1. Introduction

Two primary aims of the IAEA Nuclear Data Section (NDS) are to develop and disseminate atomic and nuclear data in forms appropriate for a wide range of applications, as requested by IAEA Member States [1]. Hence, NDS staff prepare and maintain a significant number of databases, including atomic and molecular data for fusion energy and plasma research that are accessible through a separate server [2]. NDS staff are also involved in various forms of technology transfer activity to assist scientists of developing countries in their use of these atomic and nuclear databases.

Data development within the NDS is conducted mainly through Coordinated Research Projects (CRPs). Usually these projects result in the production of a new (or significant upgrades of an existing) database; typically 5-12 scientific groups from different countries work together under IAEA contracts or agreements over a period of normally 3 to 5 years, maintaining contact throughout the course of the CRP. Examples of recent CRPs sponsored and organised by the NDS are listed in Table 1 (duration and participant numbers are subject to change).

Following a brief description of the IAEA-NDS and how to gain access to their facilities and databases, the contents of this paper focus on those CRPs devoted over recent years to improving the recommended decay data used in both energy- and non-energy-based applications. Specific decay-data requirements were identified by users and consultants, and a suitable evaluation procedure was adopted to achieve the desired objectives.

Table 1: Recent IAEA-NDS Coordinated Research Projects (CRPs).

Short Title	Duration	No. of Participants
RIPL-II: Input Parameters for Modelling Nuclear Reactions	1998-2001	13
Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications	**1998-2003**	13
Prompt Gamma Activation Analysis	1999-2003	10
Atomic and Molecular Data for Fusion Plasma Diagnostics	2001-05	12
Molecular Processes in Edge Plasmas	2001-05	11
Neutron Cross-Section Standards	2002-06	14
Tritium Inventory in Fusion Machines	2002-07	12
Nuclear Data for Th-U Fuel Cycle	2002-07	11
RIPL-III: Parameters for Nuclear Reaction Applications – Non-energy Applications	2003-07	12
Cross Sections for Production of Therapeutic Radionuclides	2003-07	8
Atomic and Molecular Data for Plasma Modelling	2004-08	14
Atomic Data for Heavy Element Impurities in Fusion Reactors	2005-10	12
Updated Decay Data Library for Actinides	**2005-09**	9
Reference Database for Ion Beam Analysis	2005-09	9
Reference Database for Neutron Activation Analysis	2005-09	8
Charged-Particle Interactions in Medical Therapy Applications	2007-10	13
Data for Surface Composition Dynamics Relevant to Erosion Processes	2007-12	10
Minor Actinide Neutron Reaction Data	2007-11	12
Nuclear Data for Fusion Materials Testing Facilities	2008-12 (?)	10 (?)

1.1 Nuclear data

Nuclear data are commonly categorized in terms of two main groups:

- **Nuclear reaction data:** Encompasses cross sections, angular and energy distributions of secondary particles, resonance parameters and related quantities. These libraries are complete for neutron-induced reactions up to 20 MeV. While coverage of higher neutron energies and photonuclear and charged-particle induced reactions is less comprehensive, these gaps are being filled as a consequence of the increased compilation efforts of the various data centres.
- **Nuclear structure and decay data:** Atomic masses, half-lives, decay schemes, nuclear level properties, and energies and intensities of emitted particles and γ rays are included in these data. The major database is ENSDF, while related bibliographic information is contained in NSR. There are many other nuclear structure and decay data libraries, mostly derived from or related to ENSDF and including the *Table of Isotopes* [3], *Isotope Explorer* [4] and NUBASE [5].

This information can also be classified on the basis of bibliographic detail, experimental data and evaluated data. All data are available on the internet (http://www-nds.iaea.org).

- **Bibliographic data:** References with some description of the contents, but no numerical data. Examples are CINDA (Computer Index of Neutron Data) and NSR (Nuclear Science References).
- **Experimental data:** Results of individual measurements as reported by the authors. The most important example of a compiled library of experimental nuclear reaction data is EXFOR/CSISRS.
- **Evaluated data:** Recommended values are based on all available data from experiments and/or theory, derived from a critical analysis of the experimental data and their uncertainties, inter- and extrapolation, and/or nuclear model calculations. The resulting libraries are assembled in strictly defined formats such as ENDF-6 (internationally-accepted format of nuclear data for applications) or ENSDF (format of the Evaluated Nuclear Structure Data File).

1.2 International nuclear data networks

Two international networks are coordinated by the IAEA to collect, compile, evaluate and distribute nuclear data (Table 2):

- Network of Nuclear Reaction Data Centres (NRDC) [6],
- Network of Nuclear Structure and Decay Data Evaluators (NSDD) [7].

The centres participating in these nuclear data networks are involved in the various stages of data preparation between measurement and application (i.e., compilation, review, evaluation, processing and distribution).

Table 2: Nuclear data networks.

Network of Nuclear Reaction Data Centres	Network of Nuclear Structure and Decay Data Evaluators
IAEA Nuclear Data Section, Vienna, Austria	**IAEA Nuclear Data Section,** Vienna, Austria
OECD, NEA Data Bank, Paris, France	**US National Nuclear Data Center,** Brookhaven, USA (maintains Master database)
US National Nuclear Data Center, Brookhaven National Laboratory, USA	**18 data evaluation centres (mid-2008):** Australia, Bulgaria, Canada, France, PRChina (2), IAEA, India (2), Japan, Kuwait, Russian Federation and USA (6)
Russian Nuclear Data Centre, IPPE, Obninsk, Russian Federation	**Data dissemination centres:** USA and IAEA
9 co-operating specialised centres: PRChina, Hungary, Japan (2), Republic of Korea, Russian Federation (3) and Ukraine	

1.2.1 Network of Nuclear Reaction Data Centres (NRDC)

Specialized data centres cooperate with the major centres in the various functions of the NRDC (particularly data compilation and evaluation). This sharing of the compilation of nuclear reaction cross-section data on a worldwide basis is normally defined on the basis of their geographical location and data expertise, and is coordinated by the IAEA Nuclear Data Section.

1.2.2 Network of Nuclear Structure and Decay Data Evaluators

Nuclear structure and decay data are compiled and evaluated by means of a collaborative programme organised through the International Network of Nuclear Structure and Decay Data Evaluators (NSDD) and established in 1974 under the auspices of the International Atomic Energy Agency (IAEA). This network began at a time when the workload was heavily reliant on USA input. A more equitable involvement of other national laboratories and universities was envisaged, and partially achieved. Network contacts, affiliations and their mass chain responsibilities are listed in Table 3. The total NSDD evaluation effort is equivalent to about 9 full-time equivalent scientists per annum (FTE), albeit approximately 12 FTE are required to maintain the desired currency and quality of ENSDF.

Table 3: International Network of Nuclear Structure and Decay Data Evaluators (2008).

Country/affiliation	Contact and co-workers	Assigned mass chains
Argentina		
CNEA, Buenos Aires	G.V. Marti	(178, 191, 193)
Australia		
ANU, Canberra	T. Kibédi	172-175
Bulgaria		
University of Sofia	D.L. Balabanski S.P. Lalkovski	(112, 200)
Canada		
McMaster University, Hamilton	B. Singh J.A. Cameron	1, 31-44, 64, 89, 98, 100, 149, 151, 164, 188, 190, 194
China		
CNDC, CIAE, Beijing	Ge Zhigang Huang Xiaolong	51-56, 62, 63, 195-198
Jilin University, Changchun	Huo Junde	
France		
CEA Bruyères-le-Châtel	J. Blachot	101, 104, 107-109, 111, 113-117
India		
IIT, Roorkee	A.K. Jain	218-229
Manipal University	M. Gupta	(260-294)
Japan		
JAEA, Ibaraki-ken	J. Katakura T. Tamura	120-129
Kuwait		
University of Kuwait	A.R. Farhan	74-80
Russian Federation		
PNPI, St. Petersburg	I.A. Mitropolsky A. Rodionov Yu. Khazov	130-135
United Kingdom		
University of Oxford	N.J. Stone	-
United States of America		
NNDC, BNL	J.K. Tuli E. Browne-Moreno T.W. Burrows D.J.A. De Frenne P. Obložinský C.W. Reich A.A. Sonzogni	45-50, 57, 58, 60, 61, 65-73, 82, 84-88, 94-97, 99, 102, 103, 105, 106, 110, 112, 118, 119, 136-148, 150, 152-163, 165, 230-240, >249
LBNL, Berkeley	C.M. Baglin M.S. Basunia R.B. Firestone S.-C. Wu	21-30, 59, 81, 83, 90-93, 166-171, 180-187, 189, 191-193, 210-217
ORNL, Oak Ridge	M.S. Smith M.J. Martin	241-249
TUNL, Duke University, Durham	J.H. Kelley D.R. Tilley H.R. Weller	2-20
ANL	F.G. Kondev	176-179, 199-209
Texas A&M	N. Nica	(140, 147, 252)
IAEA		
Vienna, Austria	D.H Abriola A.L. Nichols	(94, 96)

( ) denotes partially shared responsibility.

The organisers of the International Network of Nuclear Structure and Decay Data Evaluators have become aware of an increasing problem in maintaining and updating ENSDF evaluations with the necessary regularity. Evidence of a shortfall in effort has been detected over the previous ten years as evaluators in Europe have retired without any obvious replacements. While some progress has been made in recruitment through the commitment of nuclear physics institutes in India and elsewhere for this essential work, these welcome additions are not fully commensurate with the losses experienced in Europe, a region of the world that might have been expected to ensure some re-generation of expertise in this vital area of research and development.

1.3 Access to IAEA-NDS data libraries

The IAEA Nuclear Data Section holds a total of about 100 nuclear data libraries, constituting enormous scientific and economic value. All libraries and the related documentation are available free of charge to scientists in IAEA Member States. An overview is given in the document *Index of Nuclear Data Libraries Available from the* IAEA *Nuclear Data Section* [8], and brief descriptions of the contents and format of most libraries are published in the IAEA-NDS-report series [9].

The main method of distributing numerical nuclear data in the early 21st century is via the internet, and therefore the IAEA Nuclear Data Section offers a variety of such electronic services. At the same time, conventional mail services have been maintained for the convenience of users with their varying needs and technical infrastructures (i.e., sending customized retrievals or complete libraries as hardcopy and CD-ROM, as well as by e-mail). Users are also kept up to date with information on new data libraries and other developments through the *IAEA Nuclear Data Newsletter* [10].

- **Worldwide Web (WWW)**: The web page of IAEA Nuclear Data Services can be found at the web addresses *http://www-nds.iaea.org* (IAEA Vienna, Austria), *hhtp://www-nds.indcentre.org.in* (BARC, India), and *http://www-nds.ipen.br* (IPEN, Brazil). This page contains interactive access to the major databases as well as an overview of all nuclear data libraries and databases available from the IAEA *(IAEA Nuclear Data Guide)*, access to various reports, documents and manuals, nuclear data utility programs, and the *IAEA Nuclear Data Newsletter*.

- Hardcopy documents published by NDS include handbooks, research and meeting reports (INDC report series), data library documents (IAEA-NDS report series), and the *IAEA Nuclear Data Newsletter*. Most new reports are available electronically on the WWW in PDF format. NDS staff can be contacted by e-mail to request hardcopy documents, and other mail services and nuclear data related information [11].

1.4 Technology transfer

Technology transfer to developing countries is carried out in several ways by the NDS:

- Technical co-operation projects to provide online nuclear data services to countries with insufficient internet connections to the NDS through the installation of mirror servers in Brazil and India.

- Nuclear data workshops are organized on a regular basis, and are usually held at the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. Regular topics have included “Nuclear Reaction Data and Nuclear Reactors: Physics, Design

and Safety" and "Nuclear Data for Science and Technology" (varying from medical physics to materials analysis). More appropriately, over the previous 6 years a combination of IAEA and IAEA-ICTP workshops have been dedicated to "Nuclear Structure and Decay Data: Theory and Evaluation".

2. Coordinated Research Project: Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications (STI/PUB/1287, May 2007; *http://www-pub.iaea.org/MTCD/publications/PDF/P1287_Volume_1+2.pdf*)

The question of γ-ray detector efficiency calibration arose during the CRP on Transactinium Decay Data (Section 3.1) when the importance of reputable reference standards became apparent. A strong recommendation was made to prepare an internationally-accepted file of X- and γ-ray decay data of nuclides used to calibrate detector efficiencies. Furthermore, the International Nuclear Data Committee (INDC) proposed a preparative meeting with experts associated with the International Committee for Radionuclide Metrology (ICRM) to pursue this aim. An IAEA Consultants' Meeting was held at the Centre d' Etudes Nucléaires de Grenoble in May 1985 to discuss the quality of all relevant data and define a suitable programme to resolve the various issues [12]. As a consequence of these discussions, a CRP on "X-ray and Gamma-ray Standards for Detector Calibration" was established in 1986 by the IAEA Nuclear Data Section. Participants in the programme were specialists in γ-ray spectroscopy, and the related areas of standards and data evaluation. Their objective was to produce a recommended set of decay parameters for selected radionuclides judged as the most important for the efficiency calibration of equipment used to detect and quantify X- and γ-ray emissions. 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 depends invariably upon the accuracy of the efficiency versus energy calibration curve, and hence upon 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. Participants were given the task of establishing a data file that would be internationally accepted. Valuable contributions were also provided by multinational intercomparison projects organised by the International Committee for Radionuclide Metrology (ICRM) and the Bureau International des Poids et Mesures (BIPM).

A set of recommended half-life and emission probability data was prepared by participants of the IAEA Coordinated Research Project on "X-ray and Gamma-ray Standards for Detector Calibration". The results from this work represented a significant improvement in the quality of specific decay parameters required for the efficiency calibration of X- and γ-ray detectors. Data inadequacies were highlighted, several of the identified inconsistencies remain unresolved, and further efforts are required to address these uncertainties. Accomplishments of this CRP included:

- assessment of the existing relevant data during 1986/87,
- coordination of measurements within the existing project and extensive cooperation among the participating research groups,
- performance of a large number of measurements stimulated by the CRP, and
- preparation of an IAEA-TECDOC report which consolidated most of the data needed for γ-ray detector efficiency calibration [13].

The resulting data were internationally accepted as a significant contribution to the improved quality of X- and γ-ray spectrometry. However, the recommended database that

evolved from this CRP has now been superseded by the results of a new IAEA initiative that began in 1998 to update calibrant decay data.

2.1. X-ray and gamma-ray decay data revisited (1998-2003)

A strong recommendation was formulated at the 1997 biennial meeting of the International Nuclear Data Committee for the IAEA-NDS to re-visit and place further emphasis on the development of improved decay data for standards applications. This recommendation arose as a consequence of the publication of relevant measured data beyond 1990 that were not included in the original CRP. Many such studies had been catalysed by the demands of this earlier CRP, and new efforts were required to incorporate the new data and extend the existing database to encompass the related needs of a number of important applications such as environmental monitoring and nuclear medicine. High-quality decay data are essential in the efficiency calibration of X- and γ-ray detectors that are used to quantify radionuclidic content by determining the intensities of any resulting X- and γ rays. A Consultants' Meeting was held at IAEA Headquarters in 1997 to assess the current needs, and identify the most suitable radionuclides [14]. The expert participants at this meeting advised the establishment of a new Coordinated Research Project entitled "Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications".

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

2.2 Main issues

2.2.1 Update of 1991 database

IAEA-TECDOC-619 contains recommended decay data for 36 radionuclides, extending up to γ-ray energy of 3.6 MeV [13]. 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 had also been published for at least 29 of the original 36 radionuclides. Most of the γ-ray energies were taken from Ref. [15], while original references were cited when such data were not available from this source. Only average X-ray energies and their emission probabilities were 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. However, X-ray energies were not evaluated, but taken from Schönfeld and Rodloff [16] and Browne and Firestone [17].

2.2.2 Additional radionuclides

A comprehensive list of 62 radionuclides and two heavy element decay chains was originally 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 were re-evaluated in an international exercise led by laboratories involved in the Decay Data Evaluation Project (DDEP) [18] and affiliated to the International Committee for Radionuclide Metrology (ICRM), with the IAEA-CRP providing impetus and the necessary coordination to achieve the desired objectives.

2.2.3 Extension of the energy range

New nuclear techniques suffer from a lack of high-energy calibration standards (for example, radiotherapy). Hence, 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. Various options were explored in order to provide energy and intensity calibration γ-lines above 10 MeV.

2.2.4 Other features

Angular correlation coefficients were evaluated for a few appropriate radionuclides of relevance to the γ-γ coincidence method of calibration. 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. A limited number of nuclides were evaluated in this manner. One conclusion arising from this exercise was the need to establish rules for the documentation of experiments that would enable the evaluators to estimate input covariances from the published decay data.

2.3 Specific radionuclides as standards

A recommended list of 62 nuclides evolved from the meetings of the IAEA CRP (Table 4), including specific parent-daughter combinations and two heavy-element decay chains. A primary standard is a nuclide for which γ-ray emission probabilities 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 the intensities of weak beta branches. Secondary standards are nuclides for which the recommended γ-ray intensities depend on prior measurements of the γ-ray intensities. When relative intensities had been measured, these parameters were evaluated as well as the normalisation 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 or derived from the database.

2.4 High-energy gamma rays

The radioactive sources discussed above permit the precise determination of the efficiency of a germanium detector up to about 2.7 MeV with either a ^{24}Na or ^{228}Th source, or to 3.45 MeV with a ^{56}Co source. Some sources of radiation can be used to extend the efficiency calibration to above 10 MeV, and were also considered. Except for one radioactive nuclide (^{66}Ga), these sources of radiation are based on nuclear reactions. While other reactions could be used, only thermal neutron capture and (p, γ) reactions were considered. Gamma rays emitted from the following nuclear reactions were considered for adoption as calibration standards:

^{14}N(n, γ)^{15}N*

Table 4: Selected radionuclides and applications.

Nuclide	X/γ-Ray Standard	Dosimetry Standard	Medical Applications	Environmental Monitoring	Waste Management	Safeguards
^{22}Na	P	-	x	-	-	-
^{24}Na	P	-	-	-	-	-
^{40}K	S	-	-	x	-	-
^{46}Sc	P	-	-	-	-	-
^{51}Cr	S	-	x	-	-	-
^{54}Mn	P	-	-	x	x	-
^{56}Mn	P	-	x	-	-	-
^{55}Fe	S	-	x	-	x	-
^{59}Fe	S	-	x	-	-	-
^{56}Co	S	-	-	-	-	-
^{57}Co	P (122 keV)	-	x	-	-	x
^{58}Co	P	-	-	x	-	-
^{60}Co	P	-	x	x	x	x
^{64}Cu	-	-	x	-	-	-
^{65}Zn	S	-	-	x	x	-
^{66}Ga	S	-	x	-	-	-
^{67}Ga	S	-	x	-	-	-
^{68}Ga	-	-	x	-	-	-
^{75}Se	S	-	x	-	-	-
^{85}Kr	-	-	-	x	-	-
^{85}Sr	P	-	x	x	-	-
^{88}Y	P (1836 keV) S (898 keV)	-	-	-	-	-
^{93m}Nb	-	x	-	-	-	-
^{94}Nb	P	-	-	-	-	-
^{95}Nb	P	-	-	x	-	x
^{99}Mo–^{99m}Tc	P (140.5 keV)	-	x	-	-	-
^{99m}Tc	P (140.5 keV)	-	x	-	-	-
^{103}Ru	-	-	x	x	-	x
^{106}Ru–^{106}Rh	S	-	x	x	-	x
^{110m}Ag (^{110}Ag)	S	-	-	x	x	-
^{109}Cd	S	-	-	x	-	-
^{111}In	P	-	x	-	-	-
^{113}Sn	P	-	-	-	-	-
^{125}Sb	-	-	-	x	-	x
^{123m}Te	-	-	x	-	x	-
^{123}I	P	-	x	-	-	-
^{125}I	S	x	x	-	-	-
^{129}I	S	-	-	x	x	-
^{131}I	S	x	x	x	-	x
^{134}Cs	S	-	-	x	-	x

Table 4: Selected radionuclides and applications (cont.).

Nuclide	X/γ-Ray Standard	Dosimetry Standard	Medical Application	Environmental Monitoring	Waste Management	Safeguards
^{137}Cs	P	x	-	x	x	x
^{133}Ba	S	-	x	-	-	-
^{139}Ce	P	-	-	x	-	-
^{141}Ce	S	-	-	x	-	x
^{144}Ce–^{144}Pr	S	-	x	x	-	x
^{153}Sm	-	-	x	-	-	x
^{152}Eu	S	-	-	x	x	x
^{154}Eu	S	-	-	x	x	x
^{155}Eu	S	-	-	x	x	x
^{166m}Ho–^{166}Ho	S	-	x	-	-	x
^{170}Tm	S	-	-	-	-	-
^{169}Yb	S	-	x	-	-	-
^{192}Ir	S	x	x	-	-	-
^{198}Au	P	-	-	-	-	-
^{203}Hg	P	-	-	-	-	-
^{201}Tl	-	-	x	-	-	-
^{207}Bi	P (569.7 keV)	-	x	-	-	-
^{226}Ra decay chain	S	x	-	x	x	x
^{228}Th decay chain	P	-	-	x	-	x
^{234m}Pa	-	-	-	x	x	-
^{241}Am	P	-	-	x	x	x
^{243}Am	-	-	-	-	x	x

P primary efficiency calibration standard.
S secondary efficiency calibration standard.

^{35}Cl(n, γ)^{36}Cl*

^{48}Ti(n, γ)^{49}Ti*

$^{50, 52, 53}$Cr(n, γ)$^{51, 53, 54}$Cr*

^{11}B(p, γ)^{12}C*

^{14}N(p, γ)^{15}O*

^{23}Na(p, γ)^{24}Mg*

^{27}Al(p, γ)^{28}Si*

The cross sections, and the energies and transition probabilities of their most prominent high-energy γ rays have been evaluated.

The high-energy γ-ray data were sometimes taken from a single reference, and were not subjected to the detailed evaluation of the other data. Furthermore, the data were of somewhat uneven quality. While some of the measurements had been undertaken with metrological goals in mind, other measurements were less well defined.

2.4.1 ^{66}Ga

^{66}Ga is the only radionuclide that has been used 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. New relative intensities have been determined to good accuracy for twenty-one gamma rays emitted by ^{66}Ga [19], and in good agreement with the equivalent measurements of Raman *et al.* [20]. Both the evaluated relative intensities and absolute emission probabilities of the main gamma rays are listed in Table 5. However, two limitations are immediately apparent: a half-life of 9.3 hours means that this radionuclide can only be used by gamma-ray spectroscopists with access to an appropriate production facility, and the uncertainties in the recommended emission probabilities above 3 MeV are of the order of 8% and rather large.

2.4.2 Thermal neutron capture reactions

Efficiency calibrations can be derived using γ rays from the thermal neutron capture reaction on selected target materials. Of the many thermal neutron capture reactions that could have been assessed, only a few were considered by the CRP. ^{14}N(n, γ)^{15}N reaction was judged to be of particular interest: as shown in Table 6, there are twelve suitable gamma rays ranging from 3 to 11 MeV that have uncertainties of ~ 1%, although the uncertainties in the emission probabilities of higher-energy gamma rays at 9149 and 10829 keV are 4.1% and 1.5%, respectively. The ^{35}Cl(n, γ)^{36}Cl reaction was also assessed, with twenty-four strong gamma rays ranging from 0.517 to 8.58 MeV of which ten are above 5 MeV.

Some ratios of γ-ray emission probabilities are given in Table 7. The adoption of these reactions depends on the availability of a neutron source, and the usefulness of any particular reaction depends on the reaction cross section, a suitable sample, and the lack of any interference from background radiation (including the production of the same reaction outside the target).

2.4.3 Proton capture reactions

Proton capture reactions can be used to provide γ rays to calibrate germanium detectors. Although there are some experimental difficulties, these reactions have the advantage that simple γ-ray spectra are often produced when the proton energy is chosen to coincide with a resonance. Some useful proton resonances and the related γ-ray emission probability ratios are listed in Table 8.

2.5 Recommended X-ray and gamma-ray decay data standards, 2007

A new set of recommended half-life and emission probability data has been prepared by participants in the IAEA-CRP to Update X- and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications. The results from 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. Examples of the data as presented to the reader of the technical report are given in Appendix A.

Table 5: Absolute emission probabilities per decay and relative probabilities of twenty-one gamma rays from the decay of ^{66}Ga.

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)	0.1593(6)
1039.220(3)	0.37(3)	1.000(3)
1333.112(5)	0.0117(9)	0.03175(13)
1418.754(5)	0.0061(5)	0.01657(8)
1508.158(7)	0.0055(4)	0.01497(7)
1898.823(8)	0.0039(3)	0.01051(8)
1918.329(5)	0.0199(16)	0.05368(23)
2189.616(6)	0.053(4)	0.1442(6)
2422.525(7)	0.0188(15)	0.05085(24)
2751.835(5)	0.227(18)	0.6135(26)
3228.800(6)	0.0151(12)	0.04082(22)
3380.850(6)	0.0146(12)	0.03960(23)
3422.040(8)	0.0086(7)	0.02314(16)
3432.309(7)	0.00288(24)	0.00777(10)
3766.850(9)	0.00149(13)	0.00403(15)
3791.004(8)	0.0109(9)	0.02941(24)
4085.853(9)	0.0127(10)	0.03445(20)
4295.187(10)	0.038(3)	0.1030(8)
4461.202(9)	0.0084(7)	0.0226(3)
4806.007(9)	0.0186(15)	0.0503(3)

[a] uncertainties of $P_{\gamma i}$ are relative to the uncertainty of $P_{\gamma 1039keV}$.

Table 6: 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. [21, 22].

$E_{\gamma i}$ (keV)	$P_{\gamma i}$(abs)				$\sigma_{\gamma i}$ (mb)
	Kennett *et al.* [21] (1986)	Jurney *et al.* [22] (1997)	UWM[a]	LWM[b] recommended	
1678.293(25)	0.0723(18)	0.0796(9)[c]	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] unweighted mean values.
[b] least squares weighted mean values.
[c] uncertainty adjusted to (18) based on chi-squared test.

Table 7: 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)	[20, 23-25]
	5902.69	2676.31	0.698(12)	[20, 23-25]
	6110.80	1951.1278[a]	1.037(11)	[20, 23-25]
	6110.80	517.07006	0.866(10)	[20, 23-25]
	6619.57	1959.343	0.612(9)	[20, 23-25]
	6977.79	1601.068	0.603(10)	[20, 23-25]
	7790.28	788.4230	0.493(6)	[20, 23-25]
$^{48}Ti(n, \gamma)^{49}Ti$	4881.32	1498.63	0.981(10)	[26]
	6418.38	341.69	0.906(9)	[26]
	6555.83	1585.95	0.487(6)	[26]
	6760.06	1381.72	0.518(5)	[26]
$^{52}Cr(n, \gamma)^{53}Cr$	5618.13	2321.09	0.980(8)	[27]
$^{53}Cr(n, \gamma)^{54}Cr$	6644.47	2239.16	0.907(8)	[27]
	7098.84	1784.69	0.750(8)	[27]
	8882.88	835.03	0.562(7)	[27]

[a] subsequent emission of three γ rays in cascade.

Table 8: 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. [3].

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]	[28]
	1388	12790	4438.03	1.000(<1)[a]	[28]
	2626	13920	4438.03	1.000(<1)[a]	[28]
$^{14}N(p, \gamma)^{15}O$	278	5182(1)	2373(1)	1.000(38)	[29]
		6174.9(1)	1380.1(17)	1.000(7)	[29]
		6791.4(17)	763.4(17)	1.000(37)	[29]
	1058	5239.9(3)	3042.8(6)	1.028(12)	[29]
$^{23}Na(p, \gamma)^{24}Mg$	1318	11588	1368.633	0.960(2)	[28]
	1417	8925.55	2754.028	0.9850(11)	[28]
$^{27}Al(p, \gamma)^{28}Si$	767	7706	2838.67(5)	0.981(2)	[28]
	992	10762.9	1778.969(12)	0.806(10)	[28]
	1317	6580	4500	1.017(6)	[28]

[a] another 1-2% uncertainty arises from the angular distribution, even when applied at $\theta = 55°$.

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). Complete decay-data listings are not necessarily included in the final technical document; however, the user is referred to relevant parallel publications by laboratories involved in the DDEP [30-33], and web pages located through:

http://www.nucleide.org/DDEP_WG/DDEPdata.htm

The accomplishments of the CRP include:

- re-evaluations of all existing relevant data from the 1986-90 programme;
- extension of the recommended database to satisfy the needs of a number of important applications;
- specific measurements were undertaken, particularly with respect to high-energy γ-ray emissions;
- preparation of an IAEA technical report which summarizes the recommended decay data for X- and γ-ray detector efficiency calibration and other applications [34].

As before, one important expectation is that the resulting set of data will be internationally accepted as a significant contribution to improving the quality of both X- and γ-ray spectroscopy.

3. Coordinated Research Project: Updated Decay Data Library for Actinides

Transactinium nuclides are important in the nuclear fuel cycles of both thermal and fast reactors, and have found increasing application in other fields. The IAEA convened an Advisory Group Meeting on Transactinium Isotope Nuclear Data (TND) at the Kernforschungszentrum Karlsruhe in 1975 [35]. Users and measurers were brought together to review the status and requirements of the nuclear data for transactinium nuclides relevant to fission reactor research and technology. One of the areas specifically addressed at this meeting was the status of the decay data for these nuclides; participants recommended that the IAEA implement a Coordinated Research Project to review, measure and evaluate the required transactinium decay data.

The accuracies requested for many of the data were quite high, especially the γ-ray emission probabilities that presented challenging experimental problems. Nevertheless, during the seven years of the CRP, some of these problems were solved, and a considerable amount of data was produced with the required accuracy (at least for the prominent transitions of most interest to the user). The work of the CRP not only helped improve the existing capabilities of the participating laboratories, but also encouraged the development of such capabilities at other laboratories. Together with the systematic production of highly accurately measured decay data, this interaction between laboratories represented one of the more significant long-term effects of the work.

3.1 Recommended transactinium decay data (1985-86)

The CRP highlighted a significant number of data requirements and succeeded in satisfying many of them. Improvements were subsequently been made in the quality of specific decay data for the transactinium nuclides, although several of the identified decay data needs remained unsatisfied. Specific goals were accomplished:

(a) Evaluated the accuracy requirements for decay data requested by users at the Advisory Group Meetings, and grouped them into three general categories:

(i) those satisfied by available data;

(ii) those which lie beyond the capabilities of measurement techniques (of 1985/6);

(iii) those not satisfied, but are achievable with existing experimental capabilities.

(b) Assessed the status of the existing data in the light of these requirements, and maintained an awareness of new measurements.

(c) Identified and coordinated the measurement expertise in order to acquire the required data.

(d) Prepared a report that presented a critical evaluation of the data and summarized their status [36].

The CRP participants concluded that, despite the large body of accurate decay data produced by the laboratories up to 1985/86, much remained to be done. A number of the accuracy requirements were not met. The outstanding transactinium decay data requirements have indeed encouraged others to become involved in producing highly accurate data, and plans were initiated in 2005 by IAEA-NDS staff to establish a new CRP to re-evaluate these data and update the recommended database.

3.2 Updated Decay Data Library for Actinides (2005-2009)

The previous CRP on actinide decay data addressed the preparation of a database directly, and provided the catalyst for a series of new measurements that continued well into the 1990s. All of this new work and earlier data needed to be re-compiled and evaluated to produce an updated set of recommended decay data to replace the existing IAEA database (of 1985/86). Furthermore, the International Nuclear Data Committee (INDC) in their advice to the Nuclear Data Section on nuclear data issues for 2002 and 2004 had noted the need for further improvements to the actinide decay data files for a wide range of applications. Thus, an appropriate CRP began in late 2005, with the following aims:

- promotion of actinide decay data research and development;
- evaluation of actinide decay data - proposed actinides and associated decay chains include: ^{226}Ra and daughters, ^{232}Th and daughters, ^{231}Th, ^{231}Pa, ^{233}Pa, $^{232\text{-}237}$U, ^{239}U, ^{237}Np, ^{239}Np, $^{238\text{-}242}$Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{242}Cm, ^{244}Cm and ^{252}Cf;
- assembly of recommended decay data files for the agreed set of actinides, and all recommended data to be added to the NDS home page.

Scientists from several research laboratories in eight countries are involved in the agreed work programme to quantify with greater accuracy the complete decay scheme data for approximately 40 actinides and 45 of their daughters (Table 9). Specific measurements have also been carried out using sources prepared and stored at Argonne National Laboratory, USA. Individual participants have completed and are undertaking comprehensive evaluations by means of the well-defined methodology adopted for the Decay Data Evaluation Project [18]. Two Research Coordination Meetings have taken place at IAEA Headquarter in Vienna [37, 38]. Participants discussed and selected specific nuclides for evaluation, and agreed the procedures to be adopted. Progress was reviewed at the second Research Coordinated Meeting, and recommendations for new measurements and evaluations to address existing deficiencies in the data were also discussed. Examples of the recommended decay data and their origins from within the technical literature are

given in Appendix B. Further details of some of these decay data evaluations can be found in the studies of Chechev [39], Chechev and Kuzmenko [40], and Chisté *et al*. [41].

Although the decay scheme evaluations will continue for a further one or two years, a number of anomalies have already been observed during the course of the initial studies (Table 10). Most of the inadequacies could be addressed through well-defined measurement programmes as outlined below, although source availability will prove problematic for some of the proposed studies. The most significant issues are identified with the conflicting α and γ decay data for ^{224,226}Ra, the comprehensive lack of uncertainties in the ^{233}Th decay data, and the inadequate nature of the decay schemes derived for ^{236,236m}Np and ^{242,244,244m}Am.

The actinide decay data of importance in the proposed database include half-lives, branching fractions, and α-particle and γ-ray energies and emission probabilities – their definition to good accuracy provides the means of monitoring the presence and transport of these actinides in nuclear facilities, as well as assisting in the detection of any clandestine activities. Most of the remaining CRP activities will focus on the comprehensive evaluation of the decay scheme data for the agreed set of actinides and their natural decay products. Recommended data files are available on the DDEP-LNHB Web site located at *http://www.nucleide.org/DDEP_WG/DDEPdata.htm*, and in ENSDF (Evaluated Nuclear Structure Data File) and ENDF-6 formats for their inclusion within specialized nuclear applications libraries.

4. Concluding Remarks

The survival and maintenance of the quality of ENSDF depends on the recruitment of new data evaluators to replace the ageing nuclear physicists undertaking this important work. Unless new blood can be introduced soon, there is a serious danger that the current loose confederation of dedicated participants will fade away and as a consequence the core nuclear physics databases will become hopelessly outdated. An urgent need has arisen for younger scientists to join the NSDD evaluation network and to contribute to the nuclear data activities. There can be no doubt that the assistance of the worldwide nuclear physics research community is urgently required to ensure the survival of ENSDF at the necessary level of credibility, reliability and quality. Anyone with the necessary expertise, supportive infrastructure and personal interest in undertaking mass chain evaluations for ENSDF should contact Jagdish Tuli at NNDC, Brookhaven National Laboratory, USA.

Decay-data studies undertaken under the auspices of the International Atomic Energy Agency are strongly linked to the needs of Member States, and are therefore applications oriented. All resulting nuclear data are brought together on the IAEA-NDS web site located at http://www-nds.iaea.org/.

Specific inadequacies in our knowledge of important decay-data parameters have been identified through IAEA-sponsored Advisory Group Meetings and Consultants' Meetings. Therefore, at various periods of time over the previous 30 years, staff within the IAEA Nuclear Data Section have been encouraged by Member States to organise Coordinated Research Projects (CRPs) to resolve difficulties and uncertainties identified with:

- decay data of the transactinium nuclides (1977-85);
- X-ray and γ-ray standards for detector calibration (1986-90);
- update of X-ray and γ-ray decay data standards for detector calibration and other applications (1998-2003);
- updated decay data library of actinides (2005-09).

Table 9: Actinide and decay chain data - radionuclides selected for extensive re-evaluation.

Responsible evaluator	Actinides	Natural decay products
M.-M. Bé	^{234,238}U, ^{243}Am, ^{252}Cf	^{210}Tl, ^{210,214}Pb, ^{210,214}Bi, ^{210,214,218}Po, ^{218}At, ^{218,222}Rn, ^{226}Ra
V.P. Chechev	^{233}Th, ^{233}Pa, ^{237,239}U, ^{236,236m,237,238,239}Np, ^{238,239,240,241,242}Pu, ^{241}Am, ^{242,244}Cm	^{227}Ac
Huang Xiaolong	^{231}Th, ^{235}U	^{213}Bi, ^{213}Po, ^{217}At, ^{217}Rn, ^{221,223}Fr, ^{225}Ra, ^{225}Ac
F.G. Kondev	^{243,245,246}Cm	^{206}Hg, ^{206,207,209}Tl, ^{209,211}Pb
A. Luca	^{234}Th, ^{236}U	^{228}Ra
G. Mukherjee	^{229}Th, ^{233}U	-
A.L. Nichols	^{228}Th, ^{242,242m,244,244m}Am	^{208}Tl, ^{212}Pb, ^{212,215}Bi, ^{212,216}Po, ^{211,219}At, ^{219,220}Rn, ^{224}Ra
A.K. Pearce	^{232}Th, ^{231}Pa, ^{232}U	^{223}Ra, ^{228}Ac
Unallocated, April 2007	-	^{211}Bi, ^{211,215}Po, ^{215}At

Table 10: Some anomalies and inadequacies in the evaluated actinide decay data.

Radionuclide	Comments
^{224}Ra	Discrepancy between related measurements of absolute emission probability of 240.99-keV γ ray and the α-particle emission probabilities to the ground and first excited states of ^{220}Rn.
^{226}Ra	Modest discrepancy between related measurements of absolute emission probability of 186.21-keV γ ray and the α-particle emission probabilities to the ground and first excited states of ^{222}Rn.
^{233}Th	Measured γ-ray emission probabilities are reported without uncertainties.
^{233}Pa	Precise measurements of low-energy γ rays and LX-rays would assist greatly in resolving difficulties in decay scheme evaluation.
^{237}U	Half-life measurements merited to fortify earlier experimental studies.
^{239}U	Large numbers of observed γ rays are unplaced in decay scheme.
^{236}Np, ^{236}Np^{m}	Inadequate experimental data.
^{242}Am	Half-life studies merited to fortify the three existing measurements; γ-ray studies would also be beneficial.
^{244}Am	Half-life studies required to fortify only one known measurement; γ-ray studies would also be beneficial.
^{244}Am^{m}	Half-life measurements are required to quantify the value and uncertainty with much greater confidence; γ-ray studies would also be extremely beneficial (only one known decay data measurement).
^{242}Cm	Accurate measurements of 44-, 102-, 157- and 210-keV γ-ray emission probabilities merited.

New measurements have been performed and in-depth evaluations undertaken in order to formulate recommended decay data for the relevant radionuclides, as specified at the various Consultants' Meetings.

A comprehensive form of in-depth evaluation methodology has been developed in conjunction with the Decay Data Evaluation Programme (DDEP). The various agreed evaluation procedures have been applied to all relevant decay data for each individual radionuclide, representing a high degree of analysis. Such detail is extremely labour intensive, and the limited amount of expertise worldwide prevents general application to the full range of mass chain evaluations.

Much has been achieved to resolve a wide range of specific difficulties and discrepancies, and a number of extremely useful applications-based decay-data files have been assembled by the IAEA Nuclear Data Section to ensure that the most up-to-date values are adopted by users in Member States. Further work is merited, including the need to measure specific actinide decay data in order to address observed problems and discrepancies. One further intention will be to maintain strong technical links between the relatively modest number of experts to be found working within the DDEP and involved in IAEA-CRPs dedicated to the evaluation and recommendation of decay data.

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APPENDIX A

X-RAY AND γ-RAY DECAY DATA STANDARDS FOR DETECTOR CALIBRATION AND OTHER APPLICATIONS

RECOMMENDED EXAMPLE DATA

Recommended radionuclide half-lives

Nuclide	Half-life (days) 1 year = 365.2422 days	
	value	uncertainty
11-Na-22	950.57	± 0.23
11-Na-24	0.62329	± 0.00006
19-K-40	(4.563	± 0.013) 10^{+11}
21-Sc-46	83.79	± 0.04
24-Cr-51	27.7009	± 0.0020
25-Mn-54	312.29	± 0.26
25-Mn-56	0.107449	± 0.000019
26-Fe-55	1002.7	± 2.3
26-Fe-59	44.494	± 0.013
27-Co-56	77.236	± 0.026
27-Co-57	271.80	± 0.05
27-Co-58	70.86	± 0.06
27-Co-60	1925.23	± 0.27
29-Cu-64	0.52929	± 0.00018
30-Zn-65	243.86	± 0.20
31-Ga-66	0.3889	± 0.0034
31-Ga-67	3.2616	± 0.0004
31-Ga-68	0.04703	± 0.00007
34-Se-75	119.778	± 0.029
36-Kr-85	3927	± 8
38-Sr-85	64.851	± 0.005
39-Y-88	106.625	± 0.024
41-Nb-93m	(5.73	± 0.22) 10^{+3}
41-Nb-94	(7.3	± 0.9) 10^{+6}
41-Nb-95	34.985	± 0.012
42-Mo-99	2.7478	± 0.0007
43-Tc-99m	0.250281	± 0.000022
44-Ru-103	39.247	± 0.013
44-Ru-106	371.8	± 1.8
45-Rh-106	0.000348	± 0.000004
47-Ag-110m	249.85	± 0.10
48-Cd-109	461.4	± 1.2
49-In-111	2.8049	± 0.0006
50-Sn-113	115.09	± 0.04
51-Sb-125	1007.48	± 0.21
52-Te-123m	119.45	± 0.25

Recommended radionuclide half-lives

Nuclide	Half-life (days) 1 year = 365.2422 days	
	value	uncertainty
53-I-123	0.55098	± 0.00009
53-I-125	59.402	± 0.014
53-I-129	(5.89	± 0.23) 10^{+9}
53-I-131	8.0228	± 0.0024
55-Cs-134	753.5	± 1.0
55-Cs-137	(1.099	± 0.004) 10^{+4}
56-Ba-133	3848.7	± 1.2
58-Ce-139	137.642	± 0.020
58-Ce-141	32.503	± 0.014
58-Ce-144	285.1	± 0.6
62-Sm-153	1.938	± 0.010
63-Eu-152	4941	± 7
63-Eu-154	3138.1	± 1.4
63-Eu-155	1736	± 6
67-Ho-166	1.1165	± 0.0013
67-Ho-166m	(4.4	± 0.7) 10^{+5}
69-Tm-170	127.8	± 0.8
70-Yb-169	32.016	± 0.006
77-Ir-192	73.822	± 0.009
79-Au-198	2.6950	± 0.0007
80-Hg-203	46.594	± 0.012
81-Tl-201	3.0422	± 0.0017
83-Bi-207	(1.18	± 0.03) 10^{+4}
88-Ra-226	(5.862	± 0.022) 10^{+5}
90-Th-228	698.60	± 0.23
91-Pa-234m	0.000805	± 0.000011
95-Am-241	(1.5785	± 0.0023) 10^{+5}
95-Am-243	(2.692	± 0.008) 10^{+6}

Data uncertainties are defined as standard deviations corresponding to the 1σ confidence level.

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
11-Na-22	511	-	1.798	± 0.002	annihilation radiation
11-Na-22	1274.537	± 0.003	0.99940	± 0.00014	
11-Na-24	1368.626	± 0.005	0.999935	± 0.000005	
11-Na-24	2754.007	± 0.011	0.99872	± 0.00008	
19-K-40	1460.822	± 0.006	0.1066	± 0.0013	
21-Sc-46	889.271	± 0.002	0.999833	± 0.000005	
21-Sc-46	1120.537	± 0.003	0.99986	+0.00004 -0.00036	
24-Cr-51	320.0835	± 0.0004	0.0987	± 0.0005	
25-Mn-54	834.838	± 0.005	0.999746	± 0.000011	
25-Mn-56	846.7638	± 0.0019	0.9885	± 0.0003	
25-Mn-56	1810.726	± 0.004	0.269	± 0.004	
25-Mn-56	2113.092	± 0.006	0.142	± 0.003	
25-Mn-56	2523.06	± 0.05	0.0102	± 0.0002	
26-Fe-59	142.651	± 0.002	0.00972	± 0.00015	
26-Fe-59	192.349	± 0.005	0.0292	± 0.0003	
26-Fe-59	1099.245	± 0.003	0.5659	± 0.0021	
26-Fe-59	1291.590	± 0.006	0.4321	± 0.0025	
27-Co-56	846.7638	± 0.0019	0.999399	± 0.000023	
27-Co-56	977.363	± 0.004	0.01422	± 0.00007	
27-Co-56	1037.833	± 0.0024	0.1403	± 0.0005	
27-Co-56	1175.088	± 0.0022	0.02249	± 0.00009	
27-Co-56	1238.2736	± 0.0022	0.6641	± 0.0016	
27-Co-56	1360.196	± 0.004	0.04280	± 0.00013	
27-Co-56	1771.327	± 0.003	0.1545	± 0.0004	
27-Co-56	2015.176	± 0.005	0.03017	± 0.00014	
27-Co-56	2034.752	± 0.005	0.07741	± 0.00013	
27-Co-56	2598.438	± 0.004	0.1696	± 0.0004	
27-Co-56	3009.559	± 0.004	0.01038	± 0.00019	
27-Co-56	3201.93	± 0.011	0.03203	± 0.00013	
27-Co-56	3253.402	± 0.005	0.0787	± 0.0003	
27-Co-56	3272.978	± 0.006	0.01855	± 0.00009	
27-Co-56	3451.119	± 0.004	0.00942	± 0.00006	
27-Co-57	14.41295	± 0.00031	0.0915	± 0.0017	
27-Co-57	122.06065	± 0.00012	0.8551	± 0.0006	
27-Co-57	136.4736	± 0.00029	0.1071	± 0.0015	
27-Co-58	511		0.300	± 0.004	annihilation radiation
27-Co-58	810.759	± 0.002	0.9945	± 0.0001	
27-Co-60	1173.228	± 0.003	0.9985	± 0.0003	
27-Co-60	1332.492	± 0.004	0.999826	± 0.000006	
29-Cu-64	511		0.3572	± 0.0028	annihilation radiation
29-Cu-64	1345.77	± 0.16	0.00475	± 0.00010	
30-Zn-65	511		0.0284	± 0.0004	annihilation radiation

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
30-Zn-65	1115.539	± 0.002	0.5060	± 0.0022	
31-Ga-66	833.5324	± 0.0021	0.059	± 0.005	
31-Ga-66	1039.220	± 0.003	0.37	± 0.03	
31-Ga-66	1333.112	± 0.005	0.0117	± 0.0009	
31-Ga-66	1418.754	± 0.005	0.0061	± 0.0005	
31-Ga-66	1508.158	± 0.007	0.0055	± 0.0004	
31-Ga-66	1898.823	± 0.008	0.0039	± 0.0003	
31-Ga-66	1918.329	± 0.005	0.0199	± 0.0016	
31-Ga-66	2189.616	± 0.006	0.053	± 0.004	
31-Ga-66	2422.525	± 0.007	0.0188	± 0.0015	
31-Ga-66	2751.835	± 0.005	0.227	± 0.018	
31-Ga-66	3228.800	± 0.006	0.0151	± 0.0012	
31-Ga-66	3380.850	± 0.006	0.0146	± 0.0012	
31-Ga-66	3422.040	± 0.008	0.0086	± 0.0007	
31-Ga-66	3791.004	± 0.008	0.0109	± 0.0009	
31-Ga-66	4085.853	± 0.009	0.0127	± 0.0010	
31-Ga-66	4295.187	± 0.010	0.038	± 0.003	
31-Ga-66	4461.202	± 0.009	0.0084	± 0.0007	
31-Ga-66	4806.007	± 0.009	0.0186	± 0.0015	
31-Ga-67	91.265	± 0.005	0.0307	± 0.0011	
31-Ga-67	93.310	± 0.005	0.378	± 0.009	
31-Ga-67	184.576	± 0.010	0.209	± 0.007	
31-Ga-67	208.950	± 0.010	0.0237	± 0.0008	
31-Ga-67	300.217	± 0.010	0.168	± 0.006	
31-Ga-67	393.527	± 0.010	0.0466	± 0.0016	
31-Ga-68	511		1.7828	± 0.0022	annihilation radiation
31-Ga-68	1077.34	± 0.05	0.0322	± 0.0003	
34-Se-75	66.0518	± 0.0008	0.01112	± 0.00012	
34-Se-75	96.7340	± 0.0009	0.0342	± 0.0003	
34-Se-75	121.1155	± 0.0011	0.172	± 0.003	
34-Se-75	136.0001	± 0.0006	0.582	± 0.007	
34-Se-75	198.6060	± 0.0012	0.0148	± 0.0004	
34-Se-75	264.6576	± 0.0009	0.589	± 0.003	
34-Se-75	279.5422	± 0.0010	0.2499	± 0.0013	
34-Se-75	303.9236	± 0.0010	0.01316	± 0.00008	
34-Se-75	400.6572	± 0.0008	0.1147	± 0.0009	
36-Kr-85	513.997	± 0.005	0.00435	± 0.00010	
38-Sr-85	514.0048	± 0.0022	0.985	± 0.004	
39-Y-88	898.036	± 0.004	0.9390	± 0.0023	
39-Y-88	1836.052	± 0.013	0.9938	± 0.0003	
41-Nb-93m	30.77	± 0.02	(5.59	± 0.16) 10^{-6}	
41-Nb-94	702.639	± 0.004	0.99815	± 0.00006	
41-Nb-94	871.114	± 0.003	0.99892	± 0.00003	
41-Nb-95	765.803	± 0.006	0.99808	± 0.00007	

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
42-Mo-99/43-Tc-99m	40.58323	± 0.00017	0.01022	± 0.00027	
42-Mo-99/43-Tc-99m	140.511	± 0.001	0.896	± 0.017	
42-Mo-99/43-Tc-99m	181.094	± 0.002	0.0601	± 0.0011	
42-Mo-99/43-Tc-99m	366.421	± 0.015	0.01194	± 0.00023	
42-Mo-99/43-Tc-99m	739.500	± 0.017	0.1212	± 0.0015	
42-Mo-99/43-Tc-99m	777.921	± 0.020	0.0428	± 0.0008	
43-Tc-99m	140.511	± 0.001	0.885	± 0.002	
43-Tc-99m	142.683	± 0.001	0.00023	± 0.00002	
44-Ru-103	39.760	± 0.010	0.00071	± 0.00003	
44-Ru-103	53.275	± 0.010	0.00384	± 0.00006	
44-Ru-103	294.98	± 0.02	0.00289	± 0.00006	
44-Ru-103	443.80	± 0.02	0.00344	± 0.00003	
44-Ru-103	497.08	± 0.02	0.9131	± 0.0007	
44-Ru-103	557.04	± 0.02	0.00855	± 0.00005	
44-Ru-103	610.33	± 0.02	0.0578	± 0.0003	
44-Ru-106/45-Rh 106	511.8534	± 0.0023	0.2050	± 0.0021	
44-Ru-106/45-Rh-106	616.22	± 0.09	0.00724	± 0.00013	
44-Ru-106/45-Rh-106	621.93	± 0.06	0.0986	± 0.0011	
44-Ru-106/45-Rh-106	873.49	± 0.05	0.00435	± 0.00008	
44-Ru-106/45-Rh-106	1050.41	± 0.06	0.01488	± 0.00022	
44-Ru-106/45-Rh-106	1128.07	± 0.05	0.00399	± 0.00006	
47-Ag-110m	446.812	± 0.003	0.0365	± 0.0005	with ^{110}Ag
47-Ag-110m	620.3553	± 0.0017	0.0272	± 0.0008	with ^{110}Ag
47-Ag-110m	657.7600	± 0.0011	0.9438	± 0.0008	with ^{110}Ag
47-Ag-110m	677.6217	± 0.0012	0.1056	± 0.0006	with ^{110}Ag
47-Ag-110m	687.0091	± 0.0018	0.0645	± 0.0003	with ^{110}Ag
47-Ag-110m	706.6760	± 0.0015	0.1648	± 0.0008	with ^{110}Ag
47-Ag-110m	744.2755	± 0.0018	0.0471	± 0.0003	with ^{110}Ag
47-Ag-110m	763.9424	± 0.0017	0.2231	± 0.0009	with ^{110}Ag
47-Ag-110m	818.0244	± 0.0018	0.0733	± 0.0004	with ^{110}Ag
47-Ag-110m	884.6781	± 0.0013	0.740	± 0.012	with ^{110}Ag
47-Ag-110m	937.483	± 0.003	0.3451	± 0.0027	with ^{110}Ag
47-Ag-110m	1384.2931	± 0.0020	0.247	± 0.005	with ^{110}Ag
47-Ag-110m	1475.7792	± 0.0023	0.0403	± 0.0005	with ^{110}Ag
47-Ag-110m	1505.0280	± 0.0020	0.1316	± 0.0016	with ^{110}Ag
47-Ag-110m	1562.294	± 0.018	0.0121	± 0.0003	with ^{110}Ag
48-Cd-109	88.0336	± 0.0011	0.03626	± 0.00020	
49-In-111	171.28	± 0.03	0.9066	± 0.0025	
49-In-111	245.35	± 0.04	0.9409	± 0.0006	
50-Sn-113	255.134	± 0.010	0.0211	± 0.0008	
50-Sn-113	391.698	± 0.003	0.6494	± 0.0017	
51-Sb-125	176.314	± 0.002	0.0682	± 0.0007	
51-Sb-125	380.452	± 0.008	0.01520	± 0.00015	
51-Sb-125	427.874	± 0.004	0.2955	± 0.0024	

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
51-Sb-125	463.365	± 0.004	0.1048	± 0.0009	
51-Sb-125	600.597	± 0.002	0.1776	± 0.0018	
51-Sb-125	606.713	± 0.003	0.0502	± 0.0005	
51-Sb-125	635.950	± 0.003	0.1132	± 0.0010	
51-Sb-125	671.441	± 0.006	0.01783	± 0.00016	
52-Te-123m	158.97	± 0.05	0.8399	± 0.0008	
53-I-123	158.97	± 0.05	0.8325	± 0.0021	
53-I-123	528.96	± 0.05	0.0132	± 0.0008	
53-I-125	35.4919	± 0.0005	0.0667	± 0.0017	
53-I-129	39.578	± 0.004	0.0742	± 0.0008	
53-I-131	80.1850	± 0.0019	0.02607	± 0.00027	
53-I-131	284.305	± 0.005	0.0606	± 0.0006	
53-I-131	364.489	± 0.005	0.812	± 0.008	
53-I-131	636.989	± 0.004	0.0726	± 0.0008	
53-I-131	722.911	± 0.005	0.01796	± 0.00020	
55-Cs-134	563.243	± 0.003	0.0837	± 0.0003	
55-Cs-134	569.327	± 0.003	0.1538	± 0.0004	
55-Cs-134	604.720	± 0.003	0.97650	± 0.00018	
55-Cs-134	795.83	± 0.03	0.855	± 0.003	
55-Cs-134	801.945	± 0.004	0.0870	± 0.0003	
55-Cs-134	1365.186	± 0.004	0.03017	± 0.00012	
55-Cs-137	661.657	± 0.003	0.8499	± 0.0020	
56-Ba-133	53.1622	± 0.0006	0.0214	± 0.0003	
56-Ba-133	79.6142	± 0.0012	0.0265	± 0.0005	
56-Ba-133	80.9979	± 0.0011	0.329	± 0.003	
56-Ba-133	276.3989	± 0.0012	0.0716	± 0.0005	
56-Ba-133	302.8508	± 0.0005	0.1834	± 0.0013	
56-Ba-133	356.0129	± 0.0007	0.6205	± 0.0019	
56-Ba-133	383.8485	± 0.0012	0.0894	± 0.0006	
58-Ce-139	165.8575	± 0.0011	0.799	± 0.0004	
58-Ce-141	145.4433	± 0.0014	0.4829	± 0.0020	
58-Ce-144/59-Pr-144	33.568	± 0.010	0.00235	± 0.00012	^{144}Ce
58-Ce-144/59-Pr-144	40.98	± 0.10	0.0041	± 0.0025	^{144}Ce
58-Ce-144/59-Pr-144	80.12	± 0.05	0.0152	± 0.0010	^{144}Ce
58-Ce-144/59-Pr-144	133.515	± 0.004	0.1109	± 0.0016	^{144}Ce
58-Ce-144/59-Pr-144	696.505	± 0.004	0.01342	± 0.00014	^{144}Pr - per ^{144}Ce decay
58-Ce-144/59-Pr-144	1489.148	± 0.003	0.00296	± 0.00005	^{145}Pr - per ^{144}Ce decay
58-Ce-144/59-Pr-144	2185.645	± 0.005	0.00680	± 0.00018	^{146}Pr - per ^{144}Ce decay
62-Sm-153	69.67301	± 0.00018	0.0473	± 0.0003	
62-Sm-153	83.36716	± 0.00017	0.00192	± 0.00007	
62-Sm-153	89.48593	± 0.00021	0.00158	± 0.00015	
62-Sm-153	97.43095	± 0.00017	0.00772	± 0.00018	
62-Sm-153	103.1801	± 0.00013	0.293	± 0.003	
62-Sm-153	172.85295	± 0.00021	0.000737	± 0.000020	

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
63-Eu-152	121.7817	± 0.0003	0.2841	± 0.0013	ε
63-Eu-152	244.6974	± 0.0008	0.0755	± 0.0004	ε
63-Eu-152	344.2785	± 0.0012	0.2658	± 0.0012	β^-
63-Eu-152	411.1165	± 0.0012	0.02237	± 0.00010	β^-
63-Eu-152	443.965	± 0.003	0.03125	± 0.00014	ε
63-Eu-152	778.9045	± 0.0024	0.1296	± 0.0006	β^-
63-Eu-152	867.380	± 0.003	0.04241	± 0.00023	ε
63-Eu-152	964.072	± 0.018	0.1462	± 0.0006	ε
63-Eu-152	1085.837	± 0.010	0.1013	± 0.0006	ε
63-Eu-152	1089.737	± 0.005	0.01731	± 0.00010	β^-
63-Eu-152	1112.076	± 0.003	0.1340	± 0.0006	ε
63-Eu-152	1212.948	± 0.011	0.01415	± 0.00009	ε
63-Eu-152	1299.142	± 0.008	0.01632	± 0.00009	β^-
63-Eu-152	1408.013	± 0.003	0.2085	± 0.0009	ε
63-Eu-154	123.0706	± 0.0009	0.404	± 0.005	
63-Eu-154	247.9288	± 0.0007	0.0689	± 0.0007	
63-Eu-154	591.755	± 0.003	0.0495	± 0.0005	
63-Eu-154	692.4205	± 0.0018	0.0179	± 0.0003	
63-Eu-154	723.3014	± 0.0022	0.2005	± 0.0021	
63-Eu-154	756.8020	± 0.0023	0.0453	± 0.0005	
63-Eu-154	873.1834	± 0.0023	0.1217	± 0.0012	
63-Eu-154	996.262	± 0.006	0.1050	± 0.0010	
63-Eu-154	1004.725	± 0.007	0.1785	± 0.0017	
63-Eu-154	1246.121	± 0.004	0.00862	± 0.00008	
63-Eu-154	1274.429	± 0.004	0.349	± 0.003	
63-Eu-154	1596.4804	± 0.0028	0.01783	± 0.00017	
63-Eu-155	26.531	± 0.021	0.00316	± 0.00022	
63-Eu-155	45.2990	± 0.0010	0.0131	± 0.0005	
63-Eu-155	60.0086	± 0.0010	0.0122	± 0.0005	
63-Eu-155	86.0591	± 0.0010	0.00154	± 0.00017	
63-Eu-155	86.5479	± 0.0010	0.307	± 0.003	
63-Eu-155	105.3083	± 0.0010	0.211	± 0.006	
67-Ho-166	80.576	± 0.002	0.0655	± 0.0008	
67-Ho-166	1379.437	± 0.006	0.00933	± 0.00016	
67-Ho-166	1581.833	± 0.007	0.00186	± 0.00004	
67-Ho-166	1662.439	± 0.006	0.00118	± 0.00005	
67-Ho-166m	80.5725	± 0.0013	0.1266	± 0.0023	
67-Ho-166m	184.4107	± 0.0011	0.725	± 0.005	
67-Ho-166m	215.871	± 0.007	0.0266	± 0.0017	
67-Ho-166m	259.736	± 0.010	0.01078	± 0.00010	
67-Ho-166m	280.4630	± 0.0023	0.2954	± 0.0025	
67-Ho-166m	300.741	± 0.003	0.0373	± 0.0004	
67-Ho-166m	365.768	± 0.006	0.0246	± 0.0004	
67-Ho-166m	410.956	± 0.003	0.1135	± 0.0018	

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
67-Ho-166m	451.540	± 0.004	0.02915	± 0.00014	
67-Ho-166m	464.798	± 0.006	0.0125	± 0.0004	
67-Ho-166m	529.825	± 0.004	0.094	± 0.004	
67-Ho-166m	570.995	± 0.005	0.0543	± 0.0020	
67-Ho-166m	611.579	± 0.006	0.0131	± 0.0021	
67-Ho-166m	670.526	± 0.004	0.0534	± 0.0021	
67-Ho-166m	691.253	± 0.007	0.0132	± 0.0007	
67-Ho-166m	711.697	± 0.003	0.549	± 0.012	
67-Ho-166m	752.280	± 0.004	0.122	± 0.003	
67-Ho-166m	810.286	± 0.004	0.573	± 0.011	
67-Ho-166m	830.565	± 0.004	0.0972	± 0.0018	
67-Ho-166m	950.988	± 0.004	0.02744	± 0.00019	
69-Tm-170	78.59	± 0.02	3.4E-05	± 0.000003	
69-Tm-170	84.25474	± 0.00008	0.0248	± 0.0009	
70-Yb-169	63.12044	± 0.00004	0.4405	± 0.0024	
70-Yb-169	93.61447	± 0.00008	0.02571	± 0.00017	
70-Yb-169	109.77924	± 0.00004	0.1736	± 0.0009	
70-Yb-169	118.18940	± 0.00014	0.01870	± 0.00010	
70-Yb-169	130.52293	± 0.00006	0.1138	± 0.0005	
70-Yb-169	177.21307	± 0.00006	0.2232	± 0.0010	
70-Yb-169	197.95675	± 0.00007	0.3593	± 0.0012	
70-Yb-169	261.07712	± 0.00009	0.01687	± 0.00008	
70-Yb-169	307.73586	± 0.00010	0.10046	± 0.00045	
77-Ir-192	205.79430	± 0.00009	0.0334	± 0.0004	
77-Ir-192	295.95650	± 0.00015	0.2872	± 0.0014	
77-Ir-192	308.45507	± 0.00017	0.2968	± 0.0015	
77-Ir-192	316.50618	± 0.00017	0.8275	± 0.0021	
77-Ir-192	468.06885	± 0.00026	0.4781	± 0.0024	
77-Ir-192	484.5751	± 0.0004	0.03189	± 0.00024	
77-Ir-192	588.5810	± 0.0007	0.04517	± 0.00022	
77-Ir-192	604.41105	± 0.00025	0.0820	± 0.0004	
77-Ir-192	612.46215	± 0.00026	0.0534	± 0.0008	
79-Au-198	411.80205	± 0.00017	0.9554	± 0.0007	
79-Au-198	675.8836	± 0.0007	0.00806	± 0.00007	
79-Au-198	1087.6842	± 0.0007	0.00159	± 0.00003	
80-Hg-203	279.1952	± 0.0010	0.8148	± 0.0008	
81-Tl-201	135.312	± 0.034	0.02604	± 0.00022	
81-Tl-201	167.450	± 0.030	0.100	± 0.0010	
81-Tl-208	277.37	± 0.03	0.0237	± 0.0011	per ^{228}Th decay - ^{228}Th decay chain
81-Tl-208	583.187	± 0.002	0.3055	± 0.0017	per ^{228}Th decay - ^{228}Th decay chain
81-Tl-208	860.56	± 0.03	0.0448	± 0.0004	per ^{228}Th decay - ^{228}Th decay chain
81-Tl-208	2614.511	± 0.010	0.3585	± 0.0007	per ^{228}Th decay - ^{228}Th decay chain
82-Pb-212	115.183	± 0.005	0.00623	± 0.00022	^{228}Th decay chain
82-Pb-212	238.632	± 0.002	0.436	± 0.003	^{228}Th decay chain

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
82-Pb-212	300.09	± 0.01	0.0318	± 0.0013	^{228}Th decay chain
82-Pb-214	53.2275	± 0.0021	0.01066	± 0.00014	^{226}Ra decay chain
82-Pb-214	241.997	± 0.003	0.0719	± 0.0006	^{226}Ra decay chain
82-Pb-214	295.224	± 0.002	0.1828	± 0.0014	^{226}Ra decay chain
82-Pb-214	351.932	± 0.002	0.3534	± 0.0027	^{226}Ra decay chain
83-Bi-207	569.698	± 0.002	0.9776	± 0.0003	
83-Bi-207	1063.656	± 0.003	0.7458	± 0.0049	
83-Bi-207	1770.228	± 0.009	0.0687	± 0.0003	
83-Bi-212	727.33	± 0.01	0.0674	± 0.0012	^{228}Th decay chain
83-Bi-212	785.37	± 0.09	0.0111	± 0.0001	^{228}Th decay chain
83-Bi-212	1620.74	± 0.01	0.0151	± 0.0003	^{228}Th decay chain
83-Bi-214	609.316	± 0.003	0.4516	± 0.0033	^{226}Ra decay chain
83-Bi-214	665.453	± 0.022	0.01521	± 0.00011	^{226}Ra decay chain
83-Bi-214	768.367	± 0.011	0.04850	± 0.00038	^{226}Ra decay chain
83-Bi-214	806.185	± 0.011	0.01255	± 0.00011	^{226}Ra decay chain
83-Bi-214	934.061	± 0.012	0.03074	± 0.00025	^{226}Ra decay chain
83-Bi-214	1120.287	± 0.010	0.1478	± 0.0011	^{226}Ra decay chain
83-Bi-214	1155.19	± 0.02	0.01624	± 0.00014	^{226}Ra decay chain
83-Bi-214	1238.110	± 0.012	0.05785	± 0.00045	^{226}Ra decay chain
83-Bi-214	1280.96	± 0.02	0.01425	± 0.00012	^{226}Ra decay chain
83-Bi-214	1377.669	± 0.012	0.03954	± 0.00033	^{226}Ra decay chain
83-Bi-214	1401.516	± 0.014	0.01324	± 0.00011	^{226}Ra decay chain
83-Bi-214	1407.993	± 0.007	0.02369	± 0.00019	^{226}Ra decay chain
83-Bi-214	1509.217	± 0.008	0.02108	± 0.00021	^{226}Ra decay chain
83-Bi-214	1661.316	± 0.013	0.01037	± 0.00010	^{226}Ra decay chain
83-Bi-214	1729.640	± 0.012	0.02817	± 0.00023	^{226}Ra decay chain
83-Bi-214	1764.539	± 0.015	0.1517	± 0.0012	^{226}Ra decay chain
83-Bi-214	1847.420	± 0.025	0.02000	± 0.00018	^{226}Ra decay chain
83-Bi-214	2118.536	± 0.008	0.01148	± 0.00011	^{226}Ra decay chain
83-Bi-214	2204.071	± 0.021	0.0489	± 0.0010	^{226}Ra decay chain
83-Bi-214	2447.673	± 0.010	0.01536	± 0.00015	^{226}Ra decay chain
86-Rn-220	549.76	± 0.04	0.00115	± 0.00015	^{228}Th decay chain
88-Ra-224	240.986	± 0.006	0.0412	± 0.0004	^{228}Th decay chain
88-Ra-226	186.211	± 0.013	0.03533	± 0.00028	^{226}Ra decay chain
90-Th-228	84.373	± 0.003	0.0117	± 0.0005	^{228}Th decay chain
90-Th-228	131.612	± 0.004	0.00124	± 0.00006	^{228}Th decay chain
90-Th-228	215.985	± 0.004	0.00226	± 0.00020	^{228}Th decay chain
91-Pa-234m	258.24	± 0.07	0.00073	± 0.000009	daughter of ^{234}Th (^{238}U)
91-Pa-234m	742.814	± 0.022	0.00096	± 0.00003	daughter of ^{234}Th (^{238}U)
91-Pa-234m	766.358	± 0.020	0.00318	± 0.00005	daughter of ^{234}Th (^{238}U)
91-Pa-234m	786.272	± 0.022	0.00054	± 0.00001	daughter of ^{234}Th (^{238}U)
91-Pa-234m	1001.025	± 0.022	0.00832	± 0.00010	daughter of ^{234}Th (^{238}U)
95-Am-241	26.3446	± 0.0002	0.024	± 0.0003	
95-Am-241	33.1963	± 0.0003	0.00121	± 0.00003	

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
95-Am-241	59.5409	± 0.0001	0.3578	± 0.0009	
95-Am-243	43.53	± 0.02	0.0589	± 0.0010	
95-Am-243	74.66	± 0.02	0.672	± 0.012	

Data uncertainties are defined as standard deviations corresponding to the 1σ confidence level.

^{51}Cr

Half-life evaluated by M. J. Woods (NPL, UK), September 2003.
Decay scheme evaluated by E. Schönfeld (PTB, Germany) and R. G. Helmer (INEEL. 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]	Unterweger *et al* [H1]
27.71 (3)	Walz *et al* [H2]
27.704 (3)	Rutledge *et al* [H3]
27.690 (5)	Houtermans *et al* [H4]
27.72 (3)	Lagoutine *et al* [H5]
27.703 (8)	Tse *et al* [H6]
27.75 (1) [b]	Visser *et al* [H7]
28.1 (17) [b]	Araminowicz and Dresler [H8]
27.76 (15) [b]	Emery *et al* [H9]
27.80 (51) [b]	Bormann *et al* [H10]
27.7009 (20)	

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

References - half-life

[H1] M. P. Unterweger, D. D. Hoppes, F. J. Schima, Nucl. Instrum. Meth. Phys. Res. **A312** (1992) 349
[H2] K. F. Walz, K. Debertin, H. Schrader, Int. J. Appl. Radiat. Isot. **34** (1983) 1191.
[H3] A. R. Rutledge, L. V. Smith, J. S. Merritt, AECL-6692 (1980).
[H4] H. Houtermans, O. Milosevic, F. Reichel, Int. J. Appl. Radiat. Isot. **31** (1980) 153.
[H5] F. Lagoutine, J. Legrand, C. Bac, Int. J. Appl. Radiat. Isot. **26** (1975) 131.
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[H7] C. J. Visser, J. H. M. Karsten, F. J. Haasbroek, P. G. Marais, Agrochemophysica **5** (1973) 15.
[H8] J. Araminowicz, J. Dresler, INR-1464 (1973) 14.

[H9] J. F. Emery, S. A. Reynolds, E. I. Wyatt, G. I. Gleason, Nucl. Sci. Eng. **48** (1972) 319.
[H10] M. Bormann, A. Behrend, I. Riehle, O. Vogel, Nucl. Phys. **A115** (1968) 309.

Gamma ray: measured and evaluated 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 Relative Statistical Weights Method; no value has a relative weighting factor greater than 0.50.

References - radiations

[1] R. G. Helmer, C. van der Leun, Nucl. Instrum. Meth. Phys. Res. **A450** (2000) 35.
[2] M. E. Bunker, J. W. Starner, Phys. Rev. **97** (1955) 1272, and **99** (1955) 1906.
[3] S. G. Cohen, S. Ofer, Phys. Rev. **100** (1955) 856.
[4] J. S. Merritt, J. G. V. Taylor, AECL-1778 (1963) 31.
[5] K. C. Dhingra, U. C. Gupta, N. P. S. Sidhu, Current Sci., India **34** (1965) 504.
[6] J. Legrand, CEA-R-2813 (1965).
[7] C. Ribordy, O. Huber, Helv. Phys. Acta **43** (1970) 345.
[8] U. Schötzig, K. Debertin, K. F. Walz, Nucl. Instrum. Meth. **169** (1980) 43.
[9] S. A. Fisher, R. I. Hershberger, Nucl. Phys. **A423** (1984) 121.
[10] T. Barta, L. Szücs, A. Zsinka, Appl. Radiat. Isot. **42** (1991) 490.

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

^{203}Hg

Half-life evaluated by M. J. Woods (NPL, 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 rays

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)	Unterweger *et al* [H1]
46.612 (19)	Walz *et al* [H2]
46.60 (1)	Rutledge *et al* [H3]
46.582 (2) [a]	Houtermans *et al* [H4]
46.76 (8) [b]	Emery *et al* [H5]
47.00 (3) [b]	Lagoutine *et al* [H6]
46.594 (12)	

[a] uncertainty increased to (9) to ensure weighting factor not greater than 0.50.
[b] rejected as an outlier.

References - half-life

[H1] M. P. Unterweger, D. D. Hoppes, F. J. Schima, Nucl. Instrum. Meth. Phys. Res. **A312** (1992) 349.
[H2] K. F. Walz, K. Debertin, H. Schrader, Int. J. Appl. Radiat. Isot. **34** (1983) 1191.
[H3] A. R. Rutledge, L. V. Smith, J. S. Merritt, AECL-6692 (1980).
[H4] H. Houtermans, O. Milosevic, F. Reichel, Int. J. Appl. Radiat. Isot. **31** (1980) 153.
[H5] J. F. Emery, S. A. Reynolds, E. I. Wyatt, G. I. Gleason, Nucl. Sci. Eng. **48** (1972) 319.
[H6] F. Lagoutine, Y. L. Gallic, J. Legrand, Int. J. Appl. Radiat. Isot. **19** (1968) 475.

Gamma ray: energy and emission probability

Comments:

γ-ray energy of 279.1952 keV have been adopted from Ref. [1].
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 beta 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 ($5/2^- \rightarrow 3/2^+$).
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

[1] R. G. Helmer, C. van der Leun, Nucl. Instrum. Meth. Phys. Res. **A450** (2000) 35.
[2] H. H. Hansen, European Appl. Res. Rept., Nucl. Sci. Technol. **6**, No. 4 (1985) 777.
[3] J. G. V. Taylor, Can. J. Phys. **40** (1962) 383.
[4] C. J. Herrlander, R. L. Graham, Nucl. Phys. **58** (1964) 544.
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Detailed tables and comments can be found on:
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{226}Ra with Daughters

Half-life evaluated by M. J. Woods (NPL, UK), September 2003.
Decay scheme evaluated by R. G. Helmer (INEEL, 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_γ (keV)	P_γ 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]	Ramthun [H1]
585131 (3204)	Martin and Tuck [H2]
590609 (4135)	Sebaoun [H3]
592436 (4749)	Kohman *et al* [H4]
$5.862\ (22) \times 10^5$	

[a] uncertainty increased to (2250) to ensure weighting factor not greater than 0.50.

References - half-life

[H1] H. Ramthun, Nukleonik **8** (1966) 244.
[H2] G. R. Martin, D. G. Tuck, Int. J. Appl. Radiat. Isot. **5** (1959) 141.
[H3] W. Sebaoun, Ann. Phys., Paris **1** (1956) 680.
[H4] T. P. Kohman, D. P. Ames, J. Sedlet, Nat. Nucl. Energy Series **14** (1949) 1675.

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

APPENDIX B

UPDATED ACTINIDE DECAY DATA

EXAMPLE DATA

Health Warning: all decay data are subject to change (see Section 3.2)

$^{242}_{95}Am_{147}$

1 Decay Scheme

Am-242 decays by β^- emission to the first excited level and the ground state of Cm-242 (83.1%), and by electron capture decay to the first excited level and ground state of Pu-242 (16.9%).

2 Nuclear Data

$T_{½}(^{242}Am)$	:	16.01	(2)	h
$Q^-(^{242}Am)$	:	664.5	(4)	keV
$Q_{EC}(^{242}Am)$	:	751.3	(7)	keV

2.1 β^- Transitions

	Energy keV	Probability x 100	Nature	lg *ft*
$\beta^-_{0,1}$	622.4 (5)	45.8 (2)	1st forbidden non-unique	6.84
$\beta^-_{0,0}$	664.5 (4)	37.3 (1)	1st forbidden non-unique	7.03

2.2 Electron Capture Transitions

	Energy keV	Probability x 100	Nature	lg *ft*	P_K	P_L	P_M
$EC_{0,1}$	706.8 (7)	10.6 (1)	1st forbidden non-unique	7.26	0.7261 (23)	0.2016 (15)	0.0532 (10)
$EC_{0,0}$	751.3 (7)	6.3 (1)	1st forbidden non-unique	7.55	0.7303 (22)	0.1987 (15)	0.0522 (10)

2.3 Gamma Transitions and Internal Conversion Coefficients

	Energy keV	$P_{\gamma+ce}$ x 100	Multipolarity	α_K	α_L	α_{M+}	α_{total}
$\gamma_{1,0}$(Cm)	42.13 (5)	45.8 (2)	E2	-	836 (12)	319 (5)	1155 (17)
$\gamma_{1,0}$(Pu)	44.54 (2)	10.6 (1)	E2	-	544 (8)	204 (3)	748 (11)

3 Atomic Data

3.1 Pu

ω_K	:	0.971	(4)
ω_L	:	0.521	(20)
n_{KL}	:	0.790	(5)

3.1.1 X Radiations

		Energy keV	Relative probability
X_L			
	$L\ell$	12.124 }	
	$L\alpha$	14.087 - 14.282 }	
	$L\eta$	16.333 }	192.17
	$L\beta$	16.498 – 18.541 }	
	$L\gamma$	21.420 – 22.153 }	
X_K			
	$K\alpha_2$	99.525	63.17
	$K\alpha_1$	103.734	100
	$K\beta_3$	116.244 }	
	$K\beta_1$	117.228 }	36.65
	$K\beta_5$	117.918 }	
	$K\beta_2$	120.540 }	
	$K\beta_4$	120.969 }	12.81
	$KO_{2,3}$	121.543 }	

3.1.2 Auger Electrons

	Energy keV	Relative probability
Auger L	6.09 – 13.83	$4.7 \times 10^{+3}$
Auger K		
KLL	75.263 – 85.357	100
KLX	92.607 – 103.729	61.90
KXY	109.93 – 121.78	9.05

3.2 Cm

ω_K : 0.972 (4)
ω_L : 0.538 (23)
n_{KL} : 0.785 (5)

3.2.1 X Radiations

		Energy keV	Relative probability
X_L			
	$L\ell$	12.633	
	$L\alpha$	14.746 - 14.961	
	$L\eta$	17.314	
	$L\beta$	17.286 – 19.688	
	$L\gamma$	22.735 – 23.527	

3.2.2 Auger Electrons

	Energy keV	Relative probability
Auger L	6.19 – 14.46	

4 Electron Emissions

		Energy keV	Electrons per 100 disint.
e_{AL}	(Pu)	6.09 – 13.83	9.9 (5)
e_{AK}	(Pu)		
	KLL	75.263 – 85.357	0.21 (3)
	KLX	92.607 – 103.729	0.13 (2)
	KXY	109.93 – 121.78	0.019 (3)
e_{AL}	(Cm)	6.19 – 14.46	15.4 (9)
$ec_{1,0\ T}$	(Pu)	21.44 – 44.53	10.58 (10)
$ec_{1,0\ L}$	(Pu)	21.44 – 26.48	7.70 (7)
$ec_{1,0\ M+}$	(Pu)	38.61 – 44.53	2.88 (3)
$ec_{1,0\ T}$	(Cm)	17.60 – 42.11	45.76 (20)
$ec_{1,0\ L}$	(Cm)	17.60 – 23.16	33.12 (15)
$ec_{1,0\ M+}$	(Cm)	35.79 – 42.11	12.64 (5)
$\beta^-_{0,1}$			
	max:	622.4 (5)	45.8 (2)
	avg:	185.92 (14)	
$\beta^-_{0,0}$			
	max:	664.5 (4)	37.3 (1)
	avg:	200.17 (14)	

5 Photon Emissions

5.1 X-Ray Emissions

		Energy keV	Photons per 100 disint.
XL	(Pu)	12.124 – 22.153	10.8 (5)
$XK\alpha_2$	(Pu)	99.525	3.55 (4)
$XK\alpha_1$	(Pu)	103.734	5.62 (6)
$XK\beta_3$	(Pu)	116.244 }	
$XK\beta_1$	(Pu)	117.228 }	2.06 (4)
$XK\beta_5$	(Pu)	117.918 }	
$XK\beta_2$	(Pu)	120.540 }	
$XK\beta_4$	(Pu)	120.969 }	0.72 (2)
$XKO_{2,3}$	(Pu)	121.543 }	
XL	(Cm)	12.633 – 23.527	18.0 (9)

5.2 Gamma Emissions

	Energy keV	Photons per 100 disint.
$\gamma_{1,0}$(Cm)	42.13 (5)	0.040 (1)
$\gamma_{1,0}$(Pu)	44.54 (2)	0.014 (1)

6 Main Production Modes

Multiple neutron capture and β^- decay on U-238 in reactor fuel:
U-238(n,γ)U-239(β^-)Np-239(β^-)Pu-239(n,γ)Pu-240, etc.

Am-241(n,γ)Am-242

^{242}Am

Comments on evaluation of decay data

by A. L. Nichols

Evaluated: March 2007

Evaluation Procedure

Limitation of Relative Statistical Weight Method (LWM) was applied to average the decay data when appropriate.

Decay Scheme

A relatively simple decay scheme was constructed from the β^-/EC ratio and branching fraction measurements of Hoff *et al.* (1955Ho67, 1959Ho02), Baranov and Shlyagin (1955Ba31), Asaro *et al.* (1960As05), Gasteiger *et al.* (1969Ga17), Aleksandrov *et al.* (1969Al20) and Gabeskiriya (1972Ga35). There are no known well-defined gamma-ray spectroscopic studies.

Some confusion arose during the course of the 1950s as to the correct identity of the ground and metastable states of ^{242}Am. This problem was resolved in 1960 by Asaro *et al.* (1960As05) when the 16-hour half-life activity was shown to be the ground state. The possibile existence of an alpha branch has been extensively considered by Barnes *et al.* (1959Ba22) and Aleksandrov *et al.* (1969Al20). While Barnes *et al.* found such a branch (BF_α = 0.00476(14)), subsequent studies have shown no evidence for this particular decay mode, and Aleksandrov *et al.* were only able to set a limit of less than 10^{-7} of the total ^{242}Am decay.

Nuclear Data

^{242}Am needs to be better characterised for improved quantification of the production and decay heat contribution of ^{242}Cm.

Half-life

The recommended half-life of 16.01(2) hours has been adopted from three known sets of measurements (1953Ke38, 1969Al20, 1982Wi05). Five independent half-life measurements were individually reported by Aleksandrov *et al.* (1969Al20) from which a value of 16.07(14) hours was calculated (LWM). A limited data set of effectively three studies is rather unsatisfactory, and further measurements are required to determine the half-life with much greater confidence.

Half-life measurements.

Reference	Half-life (hours)
1953Ke38	16.01 ± 0.02
1969Al20	16.07 ± 0.14
1982Wi05	16.1 ± 0.1
Recommended value	16.01 ± 0.02

Gamma Rays

Energies

All gamma-ray transition energies were calculated from the structural details of the proposed decay scheme. The nuclear level energies of Akovali were adopted (2002Ak06), and used to determine the energies and associated uncertainties of the gamma-ray transitions that depopulate the first excited states of ^{242}Pu and ^{242}Cm.

Emission Probabilities

There are no known dedicated measurements of the gamma-ray emission probabilities. Under these unsatisfactory circumstances, the proposed gamma-ray decay data were derived from the tabulated P_{ce}/P_{β} data of Baranov and Shlyagin (1955Ba31) and the BF_{β} measurements (1959Ba22, 1959Ho02, 1969Al20, 1969Ga17, 1972Ga35). A BF_{β} of 0.831(3) was derived in terms of LWM, with the uncertainty extended to the minimum value measured (± 0.003); this parameter was adopted in preference to the equivalent LWM calculation for the β^-/EC ratio (i.e. 4.88(8) compared with a value of 4.92(9) calculated from the weighted mean BF_{β}).

β^-/EC ratio and BF_{β}.

Reference	BF_{β}	β^-/EC
1955Ba31	0.82	4.6
1955Ho67	0.81	4.2
1959Ba22	0.836 ± 0.008*	5.1 ± 0.2
1959Ho02	0.836 ± 0.003	5.1 ± 0.1*
1960As05	0.836*	5.1
1969Al20	0.82 ± 0.01*	4.6 ± 0.3
1969Ga17	0.828 ± 0.004	4.8 ± 0.1*
1972Ga35	0.827 ± 0.003*	4.78 ± 0.08
Recommended value	0.831 ± 0.003	[4.88 ± 0.08]

* Emphasis of the publication, and assumed to be the primary measurement.

Baranov and Shlyagin determined the conversion-electron emission intensities separately for both the electron-capture and beta decay processes, along with the β^- decay in equivalent units (1955Ba31) to furnish the following ratios:

P_{ce}(EC component)/$P_{\beta-}$ = 153.5/1200, and
P_{ce}(β^- component)/$P_{\beta-}$ = 661/1200.

Using these data and BF_{β} of 0.831(3):

$P_{ce}(\beta^-)$ = (661/1200) x $P_{\beta-}$ = 0.458(2) for the 42.13-keV gamma ray,
and P_{ce}(EC) = (153.5/1200) x $P_{\beta-}$ = 0.106(1) for the 44.54-keV gamma ray.

These values were then used in conjunction with the theoretical internal conversion coefficients to calculate the absolute gamma-ray emission probabilities. One problem involves the assignment of uncertainties to the $P_{ce}/P_{\beta-}$ values as determined by Baranov and Shlyagin. Both parameters are the ratios of two equivalent measurements, and therefore the resulting uncertainties were assumed to be minimal.

Quite remarkably, the resulting gamma-ray emission probabilities are in good agreement with the tabulated spetroscopic data of Vylov *et al.* (1980VyZZ) which are listed as 42.129(7) keV and 0.039(5)%, and 44.542(25) keV and 0.015(3)%. Accurate, high-resolution gamma-ray measurements are required to confirm the validity of the proposed decay scheme.

Gamma-ray emission: recommended energies, emission probabilities, multipolarities and theoretical internal conversion coefficients (frozen orbital approximation).

	E_γ (keV)	P_γ^{abs}	Multi	α_K	α_L	α_{M+}	α_{tot}	
$\gamma_{1,0}$ (Cm)	42.13(5)	0.040 ± 0.001	E2	-	836(12)	319(5)	1155(17)	β^-
$\gamma_{1,0}$ (Pu)	44.54(2)	0.014 ± 0.001	E2	-	544(8)	204(3)	748(11)	EC

Multipolarities and Internal Conversion Coefficients

The nuclear level scheme specified by Akovali has been used to define the multipolarities of the gamma transitions on the basis of known spins and parities (2002Ak06). Recommended internal conversion coefficients have been determined from the theoretical tabulations of Band *et al.* (2002Ba25, 2002Ra45) by means of the methodology of Kibedi *et al.* (2005KiZW).

Beta-particle Emissions

Energies and emission probabilities

Beta-particle energies were calculated from the nuclear level energies of Akovali (2002Ak06) and a Q_{β^-} value of 664.5 ± 0.4 keV taken from Audi *et al.* (2003Au03).

Assuming virtually full internal conversion of the 42.13-keV gamma transition, the beta-particle emission probabilities were calculated from BF_β of 0.831(3) and $P_{ce}(\beta^-)$ of 0.458(2):

Beta-particle Emission Probabilities per 100 Disintegrations of ^{242}Am.

	E_β (keV)	av. E_β (keV)	P_β	Transition type	log *ft*
$\beta^-_{0,1}$	622.4 ± 0.5	185.92 ± 0.14	45.8 ± 0.2	1st forbidden non-unique	6.84
$\beta^-_{0,0}$	664.5 ± 0.4	200.17 ± 0.14	37.3 ± 0.1	1st forbidden non-unique	7.03

EC Transitions

Energies and transition probabilities

EC transition energies were calculated from the nuclear level energies of Akovali (2002Ak06) and a Q_{EC} value of 751.3 ± 0.7 keV from Audi *et al.* (2003Au03).

Assuming virtually full internal conversion of the 44.54-keV gamma transition, the EC transition probabilities were calculated from BF_{EC} of 0.169(3) and P_{ce}(EC) of 0.106(1):

EC Transition Probabilities per 100 Disintegrations of ^{242}Am.

	E_{EC} (keV)	P_{EC}	Transition type	log *ft*	P_K	P_L	P_M
$EC_{0,1}$	706.8 ± 0.7	10.6 ± 0.1	1st forbidden non-unique	7.26	0.7261(23)	0.2016(15)	0.0532(10)
$EC_{0,0}$	751.3 ± 0.7	6.3 ± 0.1	1st forbidden non-unique	7.55	0.7303(22)	0.1987(15)	0.0522(10)

Atomic Data

The x-ray and Auger electron data have been calculated using the evaluated gamma-ray data, and the atomic data from 1996Sc06, 1998ScZM and 1999ScZX.

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$^{244}_{95}Am_{149}$

1 Decay Scheme

Am-244 decays by β^- emission to a single excited level of Cm-244 (9^{th} excited state).

2 Nuclear Data

$T_{½}(^{244}Am)$: 10.1 (1) h

$Q^-(^{244}Am)$: 1427.3 (10) keV

2.1 β^- Transitions

	Energy keV	Probability x 100	Nature	lg *ft*
$\beta^-_{0,9}$	387.1 (10)	100	(1^{st} forbidden non-unique)	5.63

2.3 Gamma Transitions and Internal Conversion Coefficients

	Energy keV	$P_{\gamma+ce}$ x 100	Multipolarity	α_K	α_L	α_{M+}	α_{total}
$\gamma_{1,0}$(Cm)	42.965 (10)	100 (8)	E2	-	760 (11)	290 (4)	1050 (15)
$\gamma_{2,1}$(Cm)	99.383 (4)	100 (8)	E2	-	13.9 (2)	5.4 (1)	19.3 (3)
$\gamma_{3,2}$(Cm)	153.863 (2)	72 (2)	E2	0.174 (3)	1.90 (3)	0.74 (1)	2.81 (4)
$\gamma_{4,3}$(Cm)	205.575 (4)	0.66 (15)	E2	0.141 (2)	0.541 (8)	0.205 (3)	0.887 (13)
$\gamma_{9,4}$(Cm)	538.402 (16)	0.69 (14)	E2	0.0292 (4)	0.0149 (2)	0.0054 (1)	0.0495 (7)
$\gamma_{9,3}$(Cm)	743.977 (5)	71 (2)	54%M1 + 46%E2	0.059 (4)	0.0130 (7)	0.0050 (3)	0.077 (5)
$\gamma_{9,2}$(Cm)	897.840 (7)	28 (8)	E2	0.0122 (2)	0.00358 (5)	0.00124 (2)	0.0170 (3)

3 Atomic Data

3.1 Cm

ω_K	:	0.972	(4)
ω_L	:	0.538	(23)
n_{KL}	:	0.785	(5)

3.1.1 X Radiations

		Energy keV	Relative probability
X_L			
	Lℓ	12.633	}
	Lα	14.746 - 14.961	}
	Lη	17.314	} 2.9 x 10^{+3}
	Lβ	17.286 – 19.688	}
	Lγ	22.735 – 23.527	}
X_K			
	$K\alpha_2$	104.590	63.8
	$K\alpha_1$	109.271	100
	$K\beta_3$	122.304	}
	$K\beta_1$	123.403	} 37.4
	$K\beta_5$	124.124	}
	$K\beta_2$	126.889	}
	$K\beta_4$	127.352	} 13.0
	$KO_{2,3}$	127.970	}

3.1.2 Auger Electrons

	Energy keV	Relative probability
Auger L	6.19 – 14.46	7.0 x 10^{+4}
Auger K		
KLL	78.858 – 89.973	100
KLX	97.226 – 109.267	62
KXY	115.57 – 128.23	9.5

4 Electron Emissions

		Energy keV	Electrons per 100 disint.
e_{AL}	(Cm)	6.19 – 14.46	86 (6)
e_{AK}	(Cm)		
	KLL	78.858 – 89.973	0.124 (20)
	KLX	97.226 – 109.267	0.077 (13)
	KXY	115.57 – 128.23	0.0118 (20)
$ec_{1,0\ T}$	(Cm)	18.439 – 42.948	100 (8)
$ec_{1,0\ L}$	(Cm)	18.439 – 23.995	72 (6)
$ec_{1,0\ M+}$	(Cm)	36.628 – 42.948	28 (2)
$ec_{2,1\ T}$	(Cm)	74.857 – 99.366	95 (8)
$ec_{2,1\ L}$	(Cm)	74.857 – 80.413	68 (6)
$ec_{2,1\ M+}$	(Cm)	93.046 – 99.366	27 (2)
$ec_{3,2\ T}$	(Cm)	25.613 – 153.846	53.1 (15)
$ec_{3,2\ K}$	(Cm)	25.613 (2)	3.2 (1)
$ec_{3,2\ L}$	(Cm)	129.337 – 134.893	35.9 (10)
$ec_{3,2\ M+}$	(Cm)	147.526 – 153.846	14.0 (4)
$ec_{9,3\ T}$	(Cm)	615.721 – 743.954	5.08 (16)
$ec_{9,3\ K}$	(Cm)	615.721 (5)	3.89 (12)
$ec_{9,3\ L}$	(Cm)	719.445 – 725.001	0.86 (3)
$ec_{9,3\ M+}$	(Cm)	737.634 – 743.954	0.33 (1)
$\beta^-_{0,9}$			
	max:	387.1 (10)	100
	avg:	109.6 (3)	

5 Photon Emissions

5.1 X-Ray Emissions

		Energy keV	Photons per 100 disint.
XL	(Cm)	12.633 – 23.527	100 (6)
$XK\alpha_2$	(Cm)	104.590	2.20 (15)
$XK\alpha_1$	(Cm)	109.271	3.45 (23)
$XK\beta_3$	(Cm)	122.304 }	
$XK\beta_1$	(Cm)	123.403 }	1.29 (9)
$XK\beta_5$	(Cm)	124.124 }	
$XK\beta_2$	(Cm)	126.889 }	
$XK\beta_4$	(Cm)	127.352 }	0.45 (4)
$XKO_{2,3}$	(Cm)	127.970 }	

5.2 Gamma Emissions

	Energy keV	Photons per 100 disint.
$\gamma_{1,0}$(Cm)	42.965 (10)	0.096 (8)
$\gamma_{2,1}$(Cm)	99.383 (4)	5.0 (5)
$\gamma_{3,2}$(Cm)	153.863 (2)	19 (1)
$\gamma_{4,3}$(Cm)	205.575 (4)	0.35 (8)
$\gamma_{9,4}$(Cm)	538.402 (16)	0.66 (13)
$\gamma_{9,3}$(Cm)	743.977 (5)	66 (6)
$\gamma_{9,2}$(Cm)	897.840 (7)	28 (8)

6 Main Production Modes

Multiple neutron capture and β^- decay on U-238 in reactor fuel:
U-238(n,γ)U-239(β^-)Np-239(β^-)Pu-239(n,γ)Pu-240, etc.

Am-243(n,γ)Am-244

^{244}Am

Comments on evaluation of decay data

by A. L. Nichols

Evaluated: January 2007

Evaluation Procedure

Limitation of Relative Statistical Weight Method (LWM) was applied to average the decay data when appropriate (but see below).

Decay Scheme

A relatively simple decay scheme was constructed from the gamma-ray studies of 1962Va08, 1963Ha29, 1967Sc34 and 1984Ho02. Only the gamma-ray measurements of Hoff *et al*. provide any estimates of the uncertainties in the gamma-ray probabilities expressed in terms of their relative intensity per 100 neutron captures in a high-flux reactor (1984Ho02). All other studies contained no information with respect to their overall uncertainties. Thus, no weighted mean data could be derived, and the data of 1984Ho02 were adopted wholesale and re-adjusted when deemed necessary (expressed in terms of the 743.977-keV gamma-ray emission probability (100%)). Further measurements are merited to quantify the gamma-ray emission probabilities and decay scheme with greater certainty.

Nuclear Data

^{244}Am is an important actinide for high burn-up fuel within the reactor core, and needs to be better characterised for improved assessments of accelerator-driven systems (ADS) and ^{244}Cm decay heat contribution.

Half-life

The recommended half-life has been adopted from the single known measurement of Vandenbosch and Day (1962Va08). Further measurements are required to determine this half-life with much greater confidence.

Half-life measurement.

Reference	Half-life (hours)
1962Va08	10.1 ± 0.1

Gamma Rays

Energies

All gamma-ray transition energies were calculated from the structural details of the proposed decay scheme. The nuclear level energies of Akovali were adopted (2003Ak04), and used to determine the energies and associated uncertainties of the gamma-ray transitions between the various populated-depopulated levels. However, Akovali recommended the gamma-ray energies determined by Hoff *et al.* (1984Ho02) by means of two curved-crystal spectrometers – minor differences do occur between the calculated energies of the higher energy transitions (538.402(16), 743.977(5) and 897.840(7) keV) and those observed by Hoff *et al*.

Emission Probabilities

Relative emission probabilities and their uncertainties were determined from measurements of Hoff *et al*. (1984Ho02). These data were estimated to be in reasonably good agreement with the earlier measurements of Vandenbosch and Day, and Schuman (1962Va08, 1967Sc34), although these latter two sets of data possessed no uncertainties. Under these unsatisfactory circumstances, the data of Hoff *et al.* had to be adopted wholesale as the only suitable starting point in the attempted construction of a consistent decay scheme. Adjusted were made to the relative emission probabilities of the 99.383-, 153.863- and 205.575-keV gamma rays (adjusted from 7.0(12) to 7.5(13), 25(5) to 28.6(60), and 0.52(12) to 0.53(12), respectively) to conform with the expected population-depopulation balance for the 501.79-, 296.21- and 142.35-keV nuclear levels of ^{244}Cm. Furthermore, a relative emission probability had to be calculated for the 42.96-keV gamma ray for which there were no data at all (from a population-depopulation balance of the 42.96-keV nuclear level of ^{244}Cm (populated by the 99.38-keV gamma ray and depopulated by the 42.96-keV gamma ray)). Downward adjustments were made to the uncertainties of specific gamma-ray transitions and emissions through consideration of these and other data that are judged to be heavily correlated (99.383- and 153.863-keV gamma rays compared with 743.977-keV gamma ray and each other).

Measured relative gamma-ray emission probabilities.

	E_γ (keV)	P_γ^{rel}		
		1962Va08	**1967Sc34**	**1984Ho02**
$\gamma_{1,0}$ (Cm)	42.965(10)	-	-	-
$\gamma_{2,1}$ (Cm)	99.383(4)	-	-	0.23(4) → 7.0(12)
$\gamma_{3,2}$ (Cm)	153.863(2)	72 → 100	-	0.82(16) → 25(5)
$\gamma_{4,3}$ (Cm)	205.575(4)	0.4 → 0.6	-	0.017(4) → 0.52(12)
$\gamma_{9,4}$ (Cm)	538.402(16)	0.4 → 0.6	-	0.033(7) → 1.0(2)
$\gamma_{9,3}$ (Cm)	743.977(5)	72 → 100	66.2 → 100	3.3(9) → 100
$\gamma_{9,2}$ (Cm)	897.840(7)	28 → 39	27.6 → 42	1.4(4) → 42(12)

Gamma-ray emissions: recommended energies, relative emission probabilities, multipolarities and theoretical internal conversion coefficients (frozen orbital approximation).

E_γ (keV)	P_γ^{rel}	Multipolarity	α_K	α_L	α_{M+}	α_{tot}	
42.965(10)	0.145(12)*	E2	-	760(11)	290(4)	1050(15)	β^-
99.383(4)	7.5(13)§	E2	-	13.9(2)	5.4(1)	19.3(3)	β^-
153.863(2)	28.6(60)§	E2	0.174(3)	1.90(3)	0.74(1)	2.81(4)	β^-
205.575(4)	0.53(12)§	E2	0.141(2)	0.541(8)	0.205(3)	0.887(13)	β^-
538.402(16)	1.0(2)	E2	0.0292(4)	0.0149(2)	0.0054(1)	0.0495(7)	β^-
743.977(5)	100	M1 + E2 δ = – 0.92(8)	0.059(4)	0.0130(7)	0.0050(3)	0.077(5)	β^-
897.840(7)	42(12)	E2	0.0122(2)	0.00358(5)	0.00124(2)	0.0170(3)	β^-

* Determined from the calculated theoretical internal conversion coefficients and the transition probability of the 99.383-keV gamma ray feeding the 42.965-keV nuclear level of ^{244}Cm.

§ Adjusted to conform with respect to the expected population-depopulation balances for the 501.79-, 296.21- and 142.35-keV nuclear levels of ^{244}Cm.

A normalisation factor of 0.66(6) was calculated from the relative emission probabilities of the three gamma rays that depopulate the 1040.188-keV nuclear level:

$$\sum^{3} P_{\gamma}(1+\alpha_{tot}) \times F = 100\%$$

$$[P^{rel}(897.84\,keV)(1+\alpha_{tot}) + P^{rel}(743.97keV)(1+\alpha_{tot}) + P^{rel}(538.40keV)(1+\alpha_{tot})] \times F = 100$$

$$F = 100 / 151.4635 = 0.66 \pm 0.06$$

Multipolarities and Internal Conversion Coefficients

The nuclear level scheme specified by Akovali has been used to define the multipolarities of the gamma transitions on the basis of known spins and parities (2003Ak04). Hansen *et al.* undertook angular correlation measurements to confirm the assignment of the 1040.2-keV nuclear level as the only ^{244}Cm nuclear level populated directly by β^- decay (1963Ha29), in which the depopulating 743.977-keV gamma ray was defined as (46 ± 4)% quadrupole [E2] and (54 ± 4)% dipole [M1] to give a mixing ratio (δ) of – 0.92(8) for this transition. Recommended internal conversion coefficients have been determined from the theoretical tabulations of Band *et al.* (2002Ba25, 2002Ra45) by means of the methodology of Kibedi *et al.* (2005KiZW).

Beta-particle Emission

Energy and emission probability

The single beta-particle energy was calculated from the structural detail of the proposed decay scheme. A nuclear level energy of 1040.188(12) keV from Akovali (2003Ak04) and a Q_{β^-} value of 1427.3 ± 1.0 keV from Audi *et al.* (2003Au03) were used to determine the energy and uncertainty of the beta-particle transition. By definition, this single beta transition was assigned an emission probability of 100%.

Beta-particle Emission Probability per 100 Disintegrations of ^{244}Am.

	E_β (keV)	P_β	Transition type	log *ft*
$\beta^-_{0,9}$	387.1 ± 1.0	100	(1st forbidden non-unique)	5.63

Atomic Data

The x-ray and Auger electron data have been calculated using the evaluated gamma-ray data, and the atomic data from 1996Sc06, 1998ScZM and 1999ScZX.

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