International Atomic Energy Agency

INDC(NDS)-437
Distr. NG+G

I N D C INTERNATIONAL NUCLEAR DATA COMMITTEE

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

Summary Report of the Third Research Co-ordination Meeting

IAEA, Vienna, Austria

21 - 24 October 2002

Prepared by

M. Herman and A. L. Nichols

IAEA Nuclear Data Section
Vienna, Austria

December 2002

Reproduced by the IAEA in Austria
December 2002

INDC(NDS)-437
Distr. NG+G

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

Summary Report of the Third Research Co-ordination Meeting

IAEA, Vienna, Austria

21 - 24 October 2002

Prepared by

M. Herman and A. L. Nichols

IAEA Nuclear Data Section
Vienna, Austria

Abstract

The Third Research Co-ordination Meeting to Update X- and γ-ray Decay Data Standards for Detector Calibration and Other Applications was held at IAEA Headquarters, Vienna from 21 to 24 October 2002. A primary aim of this meeting was to review progress in the evaluation and recommendation of the specified decay data. CRP participants reviewed the status of their evaluations, as agreed at the previous meetings, and demonstrated that good progress had been made. Details of the content and presentational format of the recommended database were agreed, with an aim of completion by the end of 2002 and publication of the IAEA-TECDOC report in 2003.

December 2002

CONTENTS

Summary Report of the
Third Research Co-ordination Meeting on

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

IAEA, Vienna, Austria
21 - 24 October 2002

BACKGROUND

An IAEA Consultants' Meeting in May 1998[1)] recommended the establishment of a Co-ordinated Research Project to Update X- and Gamma-ray Decay Data for Detector Calibration (ie., re-evaluate and update the recommended decay data in IAEA-TECDOC-619[2)]), and extend the database for use in agreed applications. Hence, an IAEA programme began, with the first Co-ordinated Research Meeting[3)] (RCM) at IAEA Headquarters, Vienna in December 1998, and the second RCM at PTB Braunschweig in May 2000[4)]. The primary objective of the CRP is to improve detector efficiency calibrations as used in most critical non-energy applications, including safeguards, material analysis, environmental monitoring, nuclear medicine, waste management, dosimetry, and basic photon spectroscopy. Three types of decay data (half-lives, energies and emission probabilities) are being compiled and evaluated. Consideration is also being 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 are strictly applied to determine the recommended half-lives and emission probabilities for all prominent X- and γ rays emitted by each selected radionuclide. Both the overall recommendations and conclusions of the final RCM, held at the IAEA Headquarters in October 2002, are given below.

WORK STATUS

J.M. Los Arcos was unable to attend, and his apologies were received. He will be kept informed of RCM decisions and CRP developments.

Radionuclidic decay data

The status of each individual evaluation for the radionuclides selected as X- and γ-ray standards is summarised in Table 1. Thirty radionuclide evaluations had been completed, reviewed and submitted in their original form to NDS before the meeting. Further discussion revealed that a further 26 evaluations have been completed and reviewed, while the remaining 6 are well advanced (see Table 1: 'x' denotes that decay-data evaluations have been completed). The originally agreed layout of the recommended data was found to be too detailed and inappropriate for inclusion in the final TECDOC. In particular, only the strongest X- and γ-ray emissions with accurately known probabilities should be retained and quoted as suitable for detector calibration. Evaluators agreed to select and list the most suitable electromagnetic transitions from their respective evaluations, and organise the data accord to a common template agreed and reproduced in Appendix 3.

X-ray decay data for ^{55}Fe were judged to be best calculated using well established theory, and will be submitted by M-M. Bé. Half-lives for 59 of 64 of the specified radionuclides have been evaluated by M.J. Woods (64 includes 'pairings' (^{106}Ru-^{106}Rh and ^{166}Ho-^{166m}Ho), but not daughters of ^{226}Ra and ^{228}Th decay chains). As much as 70% of the original data were

Table 1: Status of Decay Data Evaluations.

Radionuclide	Evaluation	Status
^{22}Na	INEEL	x
^{24}Na	INEEL	x
^{40}K	INEEL	x
^{46}Sc	INEEL	x
^{51}Cr	INEEL/PTB	x
^{54}Mn	INEEL/PTB	x
^{56}Mn	AEA	x
^{55}Fe	LNHB	x
^{59}Fe	LNHB	x
^{56}Co	NPL	x
^{57}Co	KRI	x
^{58}Co	LNHB	x
^{60}Co	INEEL	x
^{64}Cu	INEEL	x
^{65}Zn	INEEL	x
^{66}Ga	CIEMAT/UNED	
^{67}Ga	KRI	x
^{68}Ga	PTB	x
^{75}Se	LBL/PTB	x
^{85}Kr	NPL	x
^{85}Sr	PTB	x
^{88}Y	PTB	x
^{93m}Nb	KRI	x
^{94}Nb	NPL	x
^{95}Nb	INEEL	x
^{99}Mo	LNHB/ KRI	x
^{99m}Tc	LNHB	x
^{103}Ru	NPL	
^{106}Ru-^{106}Rh	NPL	
^{110m}Ag	INEEL	x
^{109}Cd	PTB	x
^{111}In	KRI	x
^{113}Sn	INEEL	x
^{125}Sb	CIEMAT/UNED	x
^{123m}Te	LNHB	x
^{123}I	LNHB	x
^{125}I	PTB	
^{129}I	KRI	x
^{131}I	LNHB	x
^{134}Cs	USP	x
^{137}Cs	INEEL	x
^{133}Ba	KRI	x
^{139}Ce	PTB	x
^{141}Ce	PTB	x
^{144}Ce	PTB	x
^{153}Sm	INEEL	x
^{152}Eu	USP	x
^{154}Eu	KRI	
^{155}Eu	KRI	x
^{166m}Ho-^{166}Ho	PTB	x/x
^{170}Tm	KRI	x

Radionuclide	Evaluation	Status
^{169}Yb	PTB/LNHB	x
^{192}Ir	LBL/INEEL/USP	x
^{198}Au	PTB	x
^{203}Hg	AEA	x
^{201}Tl	PTB	x
^{207}Bi	LNHB	x
^{226}Ra (and daughters)	INEEL	x
^{228}Th (and daughters)	AEA	x
^{234m}Pa	AEA	
^{241}Am	KRI	x
^{243}Am	CIEMAT/UNED	

AEA - AEA Technology, UK
CIEMAT - Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas, Spain
INEEL - Idaho National Engineering and Environmental Laboratory, USA
KRI - V.G. Khlopin Radium Institute, Russian Federation
LBL - Lawrence Berkeley Laboratory, USA
LNHB - Laboratoire National Henri Becquerel, France
NPL - National Physical Laboratory, UK
PTB - Physikalisch Technische Bundesanstalt, Germany
UNED - Universidad Nacional de Educacion a Distancia, Spain
USP - University of Sao Paulo, Brazil

regarded as discrepant. After careful review, these discrepancies were reduced to 16%, which is still unsatisfactory and indicates that more accurate measurements are badly needed.

Calibration by coincidence method (Hlaváč)

Fourteen radionuclides from the CRP list of X- and gamma-ray standards were judged to be of primary interest for detector calibration via the coincidence method: ^{24}Na, ^{46}Sc, ^{60}Co, ^{66}Ga, ^{75}Se, ^{88}Y, ^{94}Nb, ^{111}In, ^{123m}Te, ^{133}Ba, ^{134}Cs, ^{152}Eu, ^{154}Eu and ^{207}Bi, along with the 11.4 and 4.4 MeV cascade from the ^{11}B(p, γ)^{12}C* reaction. These nuclides cover the energy range from 80 to 2700 keV (and 80 to 11400 keV with the nuclear reaction included). Available data on angular correlations for the radionuclides have already been evaluated, and were reported during the RCM at Braunschweig. Recently, correlation coefficients for the ^{11}B(p, γ)^{12}C* reaction have also been estimated - they are rather weak which makes ^{11}B(p, γ)^{12}C* reaction suitable for detector calibration. Geometrical factors account for the solid angle correction in several simple geometries, and were calculated. At 90^{o} these factors are generally below 5%, although there are several cases for which the correction amounts to 15%. At 120^{o} and 54^{o} the same factors are below 1%. These results complete the set of data required for detector calibration by coincidence method.

Nuclear reactions (Marcinkowski)

Evaluations of the γ-ray production cross sections from thermal neutron capture and resonance capture of protons on several isotopes were completed a year ago. Evaluations were also undertaken for the intensity ratios for pairs of γ rays from multi-gamma cascades following proton capture. A draft report of this work for the TECDOC was discussed in detail during the meeting, and some minor corrections will be made to the data. These modifications

include updating the γ-ray energies to the most recent measurements by Molnar, and removing certain reactions or γ rays with low intensities or too high an uncertainty. Also absolute data for γ-ray emission intensities from thermal neutron capture on Cr isotopes will be removed from the text, since relative intensities are known with much better accuracy. The $^{11}B(n,\gamma_0)$ reaction can also be used for detector calibration up to 100 MeV with an accuracy of the order of 6%.

Covariances (Helene)

As with many other physical quantities, decay data may be statistically correlated. However, currently available data do not generally allow for proper evaluations of the correlation coefficients. Although these coefficients have been shown to be negligible for the few cases in which they have been calculated, this observation arises from the nature of the specific decay schemes analysed and should not be taken as a normal characteristic of decay data. Rather, strong statistical correlations are expected to occur in many cases. As foreseen, lack of suitable information prevented the CRP from providing a consistent set of correlations for all radionuclides considered. However, the TECDOC will contain an outline of the methodology for calculating covariances, a few example studies, and a clear statement defining the information that needs to be provided by measurers so that covariances can be formulated.

Experiments – see also Appendix 4

The intensities of all high-energy γ-lines from the reactions: $^{35}Cl(n, \gamma)$ with 34 lines, $^{47,48}Ti(n, \gamma)$ with 19 lines and $^{51,52,53}Cr(n, \gamma)$ with 25 lines were re-measured with an accuracy of about 1%, based on the $^{14}N(n, \gamma)$ standard. Data for $^{35}Cl(n, \gamma)$ are absolute, while those for $^{48}Ti(n, \gamma)$ and $^{51,52,53}Cr(n, \gamma)$ are relative. Using similar techniques, data of comparable accuracy were obtained for the high-energy emitter radionuclides ^{56}Co, ^{66}Ga and ^{226}Ra.

Neutron capture on Cr isotopes is the most relevant for detector calibration because the useful energy range extends up nearly to the same energy as the $^{14}N(n, \gamma)$ reaction, while the lower limit reaches 560 keV compared to 1.6 MeV for $^{14}N(n, \gamma)$. This energy range provides a good overlap with the energy range covered by radioactive sources and permits easy normalization. In addition, the γ-ray spectrum from Cr neutron capture is simple when compared to that from the $^{35}Cl(n, \gamma)$ reaction, which facilitates calibration of low resolution detectors.

New measurements of γ-ray energies were performed for 19 emissions from $^{47,48}Ti(n, \gamma)$ and 25 emissions from $^{51,53,54}Cr(n, \gamma)$ reactions, using the $^{35}Cl(n, \gamma)$ standard. The energies of 30 emissions from the decay of ^{226}Ra and its daughters were also remeasured. These measurements provide very accurate data consistent with the CRP database. The new data will be considered by Marcinkowski when updating the high-energy γ-ray standards.

STRUCTURE OF TECDOC

Participants decided that for the convenience of users two documents should be prepared:

(i) TECDOC which contains a description of the CRP, full documentation of the evaluation procedures, and the recommended data, and

(ii) short summary with an introduction and concise tables of recommended half-lives and electromagnetic transitions.

In addition, the CRP database will be distributed on CD-ROMs and through the dedicated website.

The participants agreed on the following TECDOC structure:

PART 1. DATA STATUS AND ASSESSMENT

1.INTRODUCTION

2.OBJECTIVES OF THE CO-ORDINATED RESEARCH PROJECT

3.DATA EVALUATIONS

- 3.1. HALF-LIVES
- 3.2. X-RAY EMISSIONS
- 3.3. GAMMA-RAY EMISSION PROBABILITIES
- 3.4. HIGH-ENERGY GAMMA RAYS
- 3.5. COINCIDENCE METHOD
- 3.6. COVARIANCES AND STATISTICAL CORRELATIONS

4.CONCLUSIONS

REFERENCES

ANNEXES
- A: EVALUATION PROCEDURES
- B: HIGH-ENERGY GAMMA RAYS
- C: ANGULAR CORRELATION COEFFICIENTS
- D: COVARIANCE ANALYSES

PART 2. EVALUATED DECAY DATA

PART 3. RECOMMENDED DATA

- TABLE 1. HALF-LIVES OF RADIONUCLIDES
- TABLE 2. X-RAY STANDARDS: ENERGIES AND EMISSION PROBABILITIES
- TABLE 3. GAMMA-RAY STANDARDS: ENERGIES AND EMISSION PROBABILITIES

Part 3 will evolve into the short Summary document [(ii), above]

Following technical details were agreed for the TECDOC:

- list of symbols along with their explanation will be included at the beginning of Part 1
- table of unit conversions will be included at the beginning of Part 1 (eg., days $\rightarrow$ years)
- scientific notation in the form 1.05×10^{-6} will be used whenever appropriate
- uncertainties will correspond to the standard deviation at the 1σ confidence level
- uncertainties will be given within brackets (eg., 1.05 (2)); however separate columns for uncertainties (and no brackets) will be used for data distributed through the web site
- precision of the uncertainties will not be better than 10%
- measured and recommended energies will have the same number of digits
- correlation data (if available) will be included as comments to a particular radionuclide
- references will be typed with initials in front of an author name, followed by journal abbreviation, volume number (in bold), year of publication (within brackets), and page number (see template - Appendix 3)

- section with requests for new experiments will be added if deemed appropriate
- tables of half-lives will follow the style used in TECDOC-619

ACTIONS

Name	Action	Dead-line
All decay data evaluators	• Provide evaluations of decay data for their respective radionuclides using standard template • Produce brief, major comments on evaluations for Table 2 of the TECDOC	December 31, 2002
Bé	• Missing file: provide evaluation of decay data for 55-Fe using standard template • Provide description of the decay data evaluation procedure in computer-editable format (Word or LaTeX)	December 31, 2002
S. Woods (M J Woods)	• Missing files: provide evaluated decay data for 103-Ru and 106-Ru/106-Rh using standard template • Re-evaluate 56-Co decay data (to include most recent measurements)	December 31, 2002
Nichols	Missing file: provide evaluated decay data for 234m-Pa using standard template	December 31, 2002
Chechev	Missing file: provide evaluated decay data for 154-Eu using standard template	December 31, 2002
Los Arcos	Missing files: provide evaluated decay data for 66-Ga, 125-Sb and 243-Am using standard template	December 31, 2002
Vanin	• Provide section on covariances for main text of TECDOC • Provide paragraph on input data that are required from experimenters in order to enable construction of covariances (to be included in the main text of the TECDOC)	December 31, 2002
Marcinkowski	Provide revised section on high-energy calibration standards as agreed during the meeting	December 31, 2002
Hlaváč	Provide section on coincidence calibration method, and pertinent data	December 31, 2002
Woods	Provide table (in agreed format) of half-lives, and supporting information (to be included in the evaluation detail of each radionuclide)	December 31, 2002

REFERENCES

1. Report on the Consultants' Meeting on the Preparation of the Proposal for a Co-ordinated Research Project to Update X- and γ-ray Decay Data Standards for Detector Calibration, A. Nichols and M. Herman, INDC(NDS)-378, May 1998.
2. X-ray and Gamma-ray Standards for Detector Calibration, IAEA-TECDOC-619, IAEA Vienna, 1991.
3. Update of X- and γ-ray Decay Data Standards for Detector Calibration and Other Applications, Summary Report of First Research Co-ordination Meeting, 9-11 December 1998, M. Herman and A. Nichols, INDC(NDS)-403, July 1999.
4. Update of X- and γ-ray Decay Data Standards for Detector Calibration and Other Applications, Summary Report of Second Research Co-ordination Meeting, 10-12 May 2000, M. Herman and A. Nichols, INDC(NDS)-415, September 2000.

APPENDIX 1

International Atomic Energy Agency

Third Research Co-ordination Meeting on

Update of X- and Gamma-ray Decay Data Standards for Detector Calibration

IAEA Headquarters

Vienna, Austria

21 - 24 October 2002

AGENDA

Monday, 21 October

09:30 – 10:00	Opening (M. Herman, A. Nichols)
10:00 – 12:30	Review of the CRP status (roundtable discussion)
	Lunch
14:00 – 18:00	Outline and contents of the TECDOC
18:30	Reception (floor A-23)

Tuesday, 22 October

09:00 – 18:00	Review of the draft TECDOC

Wednesday, 23 October

09:00 – 18:00	Review of the draft TECDOC (cont.)
19:30	Conference dinner

Thursday, 24 October

09:00 – 16:00	Agree on actions and prepare minutes of the meeting

APPENDIX 2

International Atomic Energy Agency

Third Research Co-ordination Meeting on

Update of X- and Gamma-ray Decay Data Standards for Detector Calibration

IAEA Headquarters

Vienna, Austria

21 - 24 October 2002

LIST OF PARTICIPANTS

BRAZIL
Vito R. Vanin
Instituto de Física da
Universidade de São Paulo
Caixa Postal 66318
05315-970 São Paulo
Tel.: +55-11-3091-6853
Fax: +55-11-3091-6640
E-mail: vanin@if.usp.br

FRANCE
Marie-Martine Bé
Laboratoire National Henri Becquerel
Commissariat à l'Energie Atomique
F-91191 Gif-sur-Yvette Cedex
Tel.: +33-1-69084641
Fax: +33-1-69082619
E-mail: mmbe@cea.fr

GERMANY
Rainer Dersch
Lab. 6.11
Physikalisch Technische Bundesanstalt
Bundesallee 100
D-38116 Braunschweig
Tel.: +49-531-592-6313
Fax: +49-531-592-6305
E-mail: rainer.dersch@ptb.de

HUNGARY
Gabor L. Molnar
Department of Nuclear Research
Institute of Isotope and Surface Chemistry
Chemical Research Center
P.O. Box 77
H-1525 Budapest
Tel.: +36-1-392-2539
Fax: +36-1-392-2584
E-mail: molnar@iki.kfki.hu

POLAND
Andrzej Marcinkowski
Department of Nuclear Reactions
The Andrzej Soltan Institute for
Nuclear Studies
ul. Hoza 69
PL-00681 Warszawa
Tel.: +48-22-6213829
Fax: +48-22-6123829
E-mail: andrzej.marcinkowski@fuw.edu.pl

RUSSIA
Valery P. Chechev
V.G. Khlopin Radium Institute
2nd Murinski Ave. 28
194021 St. Petersburg
Tel.: +7-812-247-5641
Fax: +7-812-247-8095
E-mail: chechev@atom.nw.ru

SLOVAKIA

Stanislav Hlaváč
Department of Nuclear Physics
Institute of Physics
Slovak Academy of Sciences
Dubravska Cesta 9
SK-84228 Bratislava
Tel.: +421-2-69201900
E-mail: hlavac@savba.sk

SPAIN

José Maria Los Arcos*
Metrologia de Radiaciones Ionizantes
Centro de Investigaciones Energéticas
Medioambientales y Tecnológicas
Avenida Complutense 22
E-28040 Madrid
Tel: +34-91-346-6288
Fax: +34-91-346-6442
E-mail: jm.losarcos@ciemat.es

UNITED STATES OF AMERICA

Richard G. Helmer
Idaho National Engineering and
Environmental Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-2114
Tel.: +1-208-526-4157
Fax: +1-208-526-9267
E-mail: helmerr@pcif.net

UNITED KINGDOM

Michael J. Woods
Centre for Ionising Radiation Metrology
Module 6
National Physical Laboratory
Queens Road
Teddington, Middlesex TW11 0LW
Tel.: +44-20-8943-6425
Fax: +44-20-8614-0480
E-mail: michael.woods@npl.co.uk

*) unable to attend

IAEA

Michal Herman (Scientific Secretary)
Nuclear Data Section
Wagramer Strasse 5
A-1400 Vienna
Tel.: +43-1-2600-21713
Fax: +43-1-26007
E-mail: herman@iaeand.iaea.or.at

Alan L. Nichols
Nuclear Data Section
Wagramer Strasse 5
A-1400 Vienna
Tel.: +43-1-2600-21709
Fax: +43-1-26007
E-mail: a.nichols@iaea.org

DATA EVALUATION TEMPLATE

BEWARE – FOR USE AS TEMPLATE ONLY: some of the listed data are fictitious

^{207}Bi

Decay scheme evaluated by M.-M. Bé (BNM-CEA/LNHB, France) – March 1998.

Half-life evaluated by M. J. Woods (NPL, UK) – December 2002.

Recommended data:

Half-life

$T_{1/2}$ = 11936 (413) d

Selected gamma-rays

E_γ (keV)	P_γ per decay
569.698 (2)	0.9776 (3)
1063.656 (3)	0.7458 (49)
1770.228 (9)	0.0687 (3)

Selected X-rays

Origin		E_X (keV)	P_X per decay
Pb	L	9.58 – 16.84	0.332 (14)
Pb	Kα_2	73.7042	0.2169 (24)
Pb	Kα_1	75.9694	0.365 (4)
Pb	Kβ_1'	85.45 – 87.47	0.1246 (23)
Pb	Kβ_2'	89.238 – 90.911	0.0376 (10)
Po	L	9.18 – 15.84	0.332 (14)
Po	Kα_2	72.8042	0.2169 (24)
Po	Kα_1	74.9694	0.365 (4)
Po	Kβ_1'	84.45 – 85.47	0.1246 (23)
Po	Kβ_2'	87.238 – 87.911	0.0376 (10)

Input data:

Half-life

Half-life (d)	Reference
11523 (19)	Unterweger et al [H1]
11944 (292)[a]	Lin and Harbottle [H2]
13405 (511)	Yanokura et al [H3]
13880 (1461)	Rupnik [H4]
11936 (413)	

[a] footnote style

Comments

References – half-life

[H1] M.P. Unterweger, D.D. Hoppes, F.J. Schima, Nucl. Instrum. Meth. Phys. Res. **A312** (1992) 349.

[H2] W.-J. Lin, G. Harbottle, J. Radioanal. Nucl. Chem. **153** (1991) 51.

[H3] M. Yanokura, H. Kudo, H. Nakahara, K. Miyano, S. Ohya, O. Nitoh, Nucl. Phys. **A229** (1978) 92.

[H4] T. Rupnik, Phys. Rev. **C6** (1972) 1433.

Gamma rays: measured relative emission probabilities

Eγ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]
569.7	100	100	100	100	100	100
1063.7	78.4(24)	74.0(20)	78.7(40)	75.6(5)	77.70(45)	75.5(23)
1770.2	7.07(35)		7.5(4) [a]			6.95(20)

Eγ (keV) [1]	[8]	[9]	[10]	[11]	[12]	Evaluated [13]
569.7	100	100	100	100	100	100
1063.7	75.79(25)	76.5(5)	76.584(367)	76.4(5)	77.7(14)	76.29(50)
1770.2	7.026(29)		7.023(68)		7.11(13)	7.028(26)

[a] rejected value

Evaluated emission probabilities are the weighted averages calculated according to the Limitation of Relative Statistical Weights Method; no value has a relative weight greater than 50%.

Absolute emission probabilities were calculated from $\Sigma P_{\gamma+ce}(569+897) = 1.0$, giving a normalization factor of 0.9776(3).

References - radiations

[1] R.G. Helmer, C. van der Leun, Nucl. Instrum. Meth. Phys. Res. **A450** (2000) 35.

[2] D.P. Donnelly, H.W. Baer, J.J. Reidy, M.L. Wiedenbeck, Nucl. Instrum. Meth. **57** (1967) 219.

[3] G. Hedin, A. Bäcklin, Arkiv Fys. **38** (1969) 593.

[4] P. V. Rao, R.E. Wood, J.M. Palms, R.W. Fink, Phys. Rev. **178** (1969) 1997.

[5] D.C. Robinson, J.M. Freeman, Nucl. Phys. **A181** (1972) 645.

[6] J.B. Willett, G.T. Emery, Annal. Phys. 78 (1973) 496.

[7] L.J. Jardine, Phys. Rev. **C11** (1975) 1385.

[8 Y. Yoshikawa, Y. Iwata, T. Kaku, T. Katoh, J.Z. Ruan, T. Kojima, Y. Kawada, Nucl. Instrum. Meth. **174** (1980) 109.

[9] K. Debertin, U. Schötzig, IAEA-CRP GS/55 (1989).

[10] F.J. Schima, IAEA-CRP GS/59 (1989).

[11] R.G. Helmer, Int. J. Appl. Radiat. Isot. **41** (1990)791.

[12] W.J. Lin, G. Harbottle, J. Radioanal. Nucl. Chem. Letters **153** (1991) 51.

[13] M.-M. Bé, E. Browne, V. Chechev, R.G. Helmer, E. Schönfeld, Table de Radionucléides – Comments, ISBN 2 7272 0211 3, CEA/Saclay – DIMRI/LNHB, F-91191 Gif-sur-Yvette Cedex, France (2000).

[14] M.-M. Bé, E. Browne, V. Chechev, R. Helmer, E. Schönfeld, Table de Radionucléides, Volume 5, ISBN 2 7272 0200 8, CEA/Saclay – DIMRI/LNHB, F-91191 Gif-sur-Yvette Cedex, France (1999).

Detailed tables and comments can be found in references [13] and [14] or on:

http://www.bnm.fr/bnm-lnhb/NucData.htm

Appendix 4

Precise determination of γ-ray intensities for high-energy calibration standards

G. L. Molnár, Zs. Révay and T. Belgya

Institute of Isotope and Surface Chemistry,

Chemical Research Center, Budapest, H-1525, Hungary

Abstract

In the framework of the IAEA Co-ordinated Research Project on the update of X- and γ-ray standards, relative intensities were measured for six high-energy γ-ray standards using the ^{14}N(n,γ) capture γ-rays as efficiency standard. The new values are accurate to one percent or better. The strong γ rays from neutron capture on ^{35}Cl, ^{48}Ti and ^{51,53,54}Cr can be used for detector efficiency calibration up to 9.7 MeV energy. Relative intensities were also obtained for the high-energy γ-ray emitter radionuclides ^{226}Ra, ^{56}Co and ^{66}Ga, which are applicable up to 4.8 MeV.

Introduction

Accurate efficiency calibration of germanium γ-ray detectors for neutron capture studies has long been problematic due to the lack of suitable standards. The ^{14}N(n,γ) reaction, providing gamma rays from 1768 to 10829 keV, is the only generally accepted efficiency standard for high energies. The emission probabilities have been determined in two independent measurements by a fit to the simple decay scheme, and they are accurate to nearly one percent [Ke86,Ju97]. This standard is practical, however, only for high flux facilities, in that the capture cross-section is as small as 80 mb. Therefore, other alternatives have long been thought.

The high isotopic abundance and thermal neutron capture cross-section, as well as the evenly distributed strong γ-rays have made the ^{35}Cl(n,γ) reaction the most popular alternative to nitrogen. Its further advantage is the availability of precise crystal spectrometer data [Kr82], enabling the simultaneous use of this reaction for energy calibrations. An accurate measurement of the emission probabilities for γ-rays between 517 and 8579 keV exists [Co96], and the results have recently been confirmed for 17 γ-rays [Ra00]. Nevertheless, it was desirable to extend the number of useful γ-rays and improve the accuracy level toward the 1% margin.

The doublet character of many strong chlorine γ-rays poses a problem for detectors with lower energy resolution, which may be the case in practical applications. Hence other candidates have to be considered. Titanium is frequently used as a standard for in-beam neutron flux measurements and detector efficiency calibrations in PGAA laboratories. The dominating reaction for natural titanium is the ^{48}Ti(n,γ) reaction, which has sufficiently high cross-section and isotopic abundance. A number of strong gamma rays are available from 342 keV to 6760 keV, several of which are cascades with one-to-one intensity ratio. Unfortunately, only one high-quality measurement exists [Ru83], and even in that work the data accuracy is limited.

Another important candidate is chromium. Thermal neutron capture in the three main target isotopes (^{50}Cr, ^{52}Cr and ^{53}Cr) provides four pairs of strong cascades of low- and high- energy γ-rays with intensity ratio mostly close to unity. In addition, two ground-state transitions of

7939 and 9719 keV energy can be used to extend the energy range to the practical limit. The spectrum is sufficiently simple, and small metallic targets can be used to imitate a point source. Although several (n,γ) experiments have been performed on enriched chromium targets, very few have been done on natural targets. The most complete natural target experiments were performed by Loper and Thomas Ref. [Lo72], but the uncertainties of their intensity data are rather large.

The neutron capture reactions can also be used for obtaining accurate intensity values for the three most important high-energy emitter radionuclides, ^{226}Ra ($T_{1/2}$=1500 a), ^{56}Co ($T_{1/2}$=77 d), and ^{66}Ga ($T_{1/2}$=19.5 h) suitable up to 2.5, 3.5 and 4.8 MeV energy, respectively.

Experiments and results

The measurements were carried out at the PGAA facility of Budapest Research Reactor {Mo97,Be02] using the neutron capture γ rays [Ju97] from the ^{14}N(n,γ) reaction for detector efficiency calibration, as described in Refs [Mo02b] and [Mo02].

Chlorine capture

The capture γ-rays from the ^{35}Cl(n,γ)^{36}Cl reaction were remeasured at the Budapest PGAA facility, first at the thermal guide [Be97] and later at the new cold neutron guide [Be02]. Thin polyvinyl chloride (PVC) targets were used to avoid high count rates and absorption problems.

The new relative intensities for 34 intense gamma rays between 292–8579 keV are accurate to better than 2%, while the best 28 cases are accurate to at least 1%. These results are listed in *Table 1* where the best available energy data [Kr82,Ke85], adjusted to the 1998 values of the fundamental constants [Mo99], are also included for completeness. Absolute transition probabilities per capture were also obtained by normalising to the sum of the 50 ground state transitions. The new absolute intensity data agree well with previous results of comparable precision, as shown in *Table 2* [Mo02a].

Titanium capture

The measurements were performed using natural titanium targets. On the thermal beam, a metal foil of 0.4 mm thickness was measured. The experiment was repeated on the new cold beam a year later, using 0.25 mm thick samples of 6 and 133 mm diameter.

The averaged results for 19 intense γ-rays are shown in *Table 3*. While most of them come from the ^{48}Ti(n,γ) reaction, the 983.5 and 1553.8 keV lines originate from captures in ^{47}Ti and ^{49}Ti, respectively. The three strong cascades with intensity ratio close to unity are especially useful for controlling the slope of the efficiency curve. Data of nearly comparable precision have been published [Ru83] for ^{48}Ti only. However, the ratios of the present intensities to literature values imply calibration inconsistencies for the low- and high-energy lines, measured separately in the work by Ruyl and Endt [Ru83]. The gamma-ray energies have also been remeasured, using the chlorine capture gamma rays of *Table 1* for calibration.

Chromium capture

For the chromium capture measurements a thin natural chromium metal target was used. The 25 strong γ-rays from the neutron capture in three different isotopes cover the energy range from 564 to 9720 keV. The new relative intensities [Be02a] are listed in *Table 4*. Most of them are accurate to 1% or better. In five cases the fitted full-energy peak areas were corrected for an escape contribution of a higher energy transition. These corrections are less than 0.6% in all cases, but in non-Compton-suppressed spectra they will be much larger. A background correction of 3.5% was applied for the 5269.1 keV transition, due to the

contribution of nitrogen in the air. The gamma-ray energies have also been remeasured, using the chlorine capture gamma rays of *Table 1* for calibration.

Unfortunately, no other measurements of comparable accuracy exist in the literature; hence a meaningful comparison is not possible. However, we can provide a comparison of the relative intensities for the individual isotopes using the data obtained from ENSDF by normalising the intensities to the ENSDF value of the lowest energy transition in each nucleus. As can be seen from the table, the precision of the present intensities is usually an order pf magnitude better than that of the ENSDF data, thus the uncertainties of the ratios are dominated by the ENSDF uncertainties. Despite the large uncertainty, two z-score values exceed the 3-sigma limit.

^{226}Ra and its daughters

A standard point source from PTB Braunschweig was used for the experiments. Spectra were collected using the Compton suppressed spectrometer (with two different gains), and with a planar HPGe detector up to 2.2 MeV. For the efficiency calibration of the planar detector the present chlorine data were used instead of the nitrogen standard. Accuracies up to 0.3-0.4% were attained for relative efficiencies in the range of interest. Contribution of the natural background has been subtracted, although very small. No other corrections were necessary.

The γ-ray energies were obtained from measurements with four different combinations of standard sources[He00], the γ-rays of which (^{137}Cs-^{60}Co; ^{54}Mn-^{56}Co; ^{110m}Ag; planar: ^{57}Co-^{54}Mn) were used as internal calibration lines. The systematic uncertainty of the non-linearity curve (between 0.001-0.014 keV) was added back quadratically after averaging the results from the different runs.

Table 5 summarises the energy results for 30 strong γ-rays from the decay of ^{226}Ra and its daughters, and the relative intensities (with respect to the 609 keV ^{214}Bi line) for those 28 in equilibrium. The literature energies were adjusted to the most recent value of the gold standard [He00] whenever required. The intensities are compared with a very accurate recent measurement by Delgado et al. [De01], relying on their own ^{56}Co data. The agreement with the best available values is excellent for both energy and intensity, and even a slight improvement of precision is obtained in a number of cases.

^{56}Co decay

The decay γ-rays of ^{56}Co were measured using the same technique as for the capture γ-ray standards. The sources were produced by the ^{56}Fe(p.n)^{56}Co activation reaction. Spectra were collected with Compton suppression and without, to investigate the effect of Compton edges on certain γ-rays.

All the 46 γ-rays, listed in ENSDF, could be identified. In *Table 6* the relative intensities of 20 strong γ-rays are compared with evaluated values [Ba02], as well as with another recent measurement [Ra00] relying on the nitrogen standard. It should be stressed that only data obtained with measured (rather than extrapolated) efficiencies have been considered, as elaborated in Ref. [Ba02]. Again, the agreement is excellent and the uncertainties are further reduced in most cases.

Moreover, the obtained precise relative intensity values of 0.016(3) and 0.0103(6) for the respective 2657 keV and 3370 keV weak ground-state branches yield a new absolute emission probability of 0.99944(3) for the dominating 846.8 keV ground-state transition. This value is in good agreement with the previous number of 0.99933(7) [IA91], and can be used to convert the new relative intensities to emission probabilities.

^{66}Ga decay

The decay γ-rays of ^{66}Ga were measured [Ba02] in a similar way as the capture standards, except using the chlorine capture lines for efficiency calibration. New relative intensities with an accuracy of 1% or better could be obtained for 18 strong γ-rays from 834 to 4806 keV, as described along with an independent measurement at Lawrence Berkeley National Laboratory [Ba02]. The results are summarised in *Table 7*.

Above 2500 keV the new intensities systematically deviate from previous results [Ca71] relying on the assumption of a linear extrapolation of efficiency versus energy on a log-log scale . Recent similar results by Raman et al. [Ra00] also reaffirm the need for a global revision of all intensity data which have been obtained under this assumption. In particular, high-energy measurements relying on calibrations with ^{56}Co and ^{66}Ga data by Camp et al. [Ca71] should be ignored or corrected. To be able to perform the correction, an empirical function has been determined [Ba02] by which the data of Camp et al. [Ca71] should be multiplied:

$$f(E_\gamma) = 1.116(11) - 0.155(11)E_\gamma + 0.0397(22)E_\gamma^2$$

where E_γ is in MeV units and the numbers in brackets are the uncertainties in the least-significant digits. This formula gives very similar results to the one determined by McCallum and Coote [Mc75] using proton capture γ-ray pairs for efficiency calibration, and can be used for correcting both ^{56}Co and ^{66}Ga calibration data above about 2 MeV.

Conclusions

We conclude with a brief summary of the advantages of each high-energy calibration standard for which precise new γ-ray intensity data were obtained in the present work.

Neutron capture γ-ray standards

- ^{14}N(n, γ) up to 10.8 MeV – only previously accepted standard (used for calibration by us);
- ^{35}Cl(n, γ) up to 8.5 MeV – good cross section, precise energy data, other recent intensity data;
- ^{48}Ti(n, γ) up to 6.8 MeV – good cross section, precise energies are being measured at ILL Grenoble;
- ^{50,52,53}Cr(n,γ), up to 9.7 MeV – high upper energy limit, good cross section, simple spectrum;

Radioactive decay standards

- ^{66}Ga ($T_{1/2}$ = 19.5 h) up to 4.8 MeV – highest decay energy, precise energies available
- ^{56}Co ($T_{1/2}$ = 70 d) up to 3.5 MeV – easy to make, more practical half-life, precise energies available
- ^{226}Ra ($T_{1/2}$ = 1500 a) up to 2.5 MeV – longest half-life

References

[Ba02] C. M. Baglin, E. Browne, E. B. Norman, G. L. Molnár, T. Belgya, Zs. Révay and F. Szelecsényi, *Nucl. Instr. Meth.* ***A*** **481,** 365 (2002).

[Be02] T. Belgya, Zs. Révay, P. P. Ember, J. L. Weil, G. L. Molnár and S. M. Qaim, *Proc. 11th Int. Symp. on Capture Gamma-Ray Spectroscopy and Related Topics*, Pruhonice, Czech Republic, 2-6 September 2002, World Scientific, Singapore, in press.

[Be02a] T. Belgya and G. L. Molnár, *5th Int Topical Meeting on Industrial Radiation and Radioisotope Measurement Applications (IRRMA-V)*, Bologna, Italy, 9-14 June 2002, *Nucl. Instr. Meth. B*, to be published.

[Ca71] D. C. Camp and G. L. Meredith, *Nucl. Phys.* ***A*** **166,** 349 (1971).

[Co96] C. Coceva, A. Brusegan and C. van der Vorst, *Nucl. Instr. Meth.* ***A*** **378,** 511 (1996).

[De01] J. U. Delgado, J. Morel and M. Etcheverry, *Appl. Radiat. Isot.* **56,** 137 (2002).

[He79] R. G. Helmer, R. J. Gehrke and R. C. Greenwood, *Nucl. Instr. Meth.* **166,** 469 (1979).

[He00] R. G. Helmer and C. van der Leun, *Nucl. Inst. Meth. A* **450,** 35 (2000).

[IA91] X-ray and gamma-ray standards for detector calibration, IAEA-TECDOC-619, International Atomic Energy Agency, Vienna, 1991.

[Ju97] E. T. Jurney, J. W. Starner, J. E. Lynn and S. Raman, *Phys. Rev.* ***C*** **56,** 118 (1997).

[Ke81] T. J. Kennett, M. A. Islam and W. V. Prestwich, *Can. J. Phys.* **59** (1981) 93.

[Ke86] T. J. Kennett, W. V. Prestwich and J. S. Tsai, *Nucl. Instr. and Meth.* ***A*** **249** (1986) 366.

[Kr82] B. Krusche, K. P. Lieb, H. Daniel, T. von Egidy, G. Barreau, H. G. Börner, R. Brissot, C. Hofmeyr and R. Rascher, *Nucl. Phys.* ***A*** **386,** 245 (1982).

[Lo72] G. D. Loper and G. E. Thomas, *Nucl. Instr. Meth.* **105,** 453 (1972).

[Mc75] G. J. McCallum and G. E. Coote, *Nucl. Instr. Meth.* **124**, 309 (1975).

[Mo97] G. L. Molnár, T. Belgya, L. Dabolczi, B. Fazekas, Z. Révay, A. Veres, I. Bikit, Z. Kis and J. Ostor, *J. Radioanal. Nucl. Chem.* **215** (1997) 111.

[Mo99] P. J. Mohr and B. N. Taylor, J. Phys. Chem. Reference Data, **28**, No. 6 (1999); Rev. Mod. Phys. **72**, No. 2 (2000).

[Mo00] G. L. Molnár. Zs. Révay and T. Belgya Consistency of neutron and proton capture intensity standards - new relative intensities for ^{56}Co, ^{66}Ga decay and ^{35}Cl(n, γ) reaction gamma rays, pp. 59-64 in Summary Report of the Second Research Co-ordination Meeting of the IAEA Co-ordinated Research Project on *Update of X- and Gamma-Ray Decay Data Standards for Detector Calibration*, 10–12 May 2000, Braunschweig, Germany, IAEA report INDC(NDS)-415, International Atomic Energy Agency, Vienna, 2000).

[Mo02] G. L. Molnár, Z. Révay and T. Belgya, *Nucl. Instr. Meth.* ***A*** **489**, 140 (2002).

[Mo02a] G. L. Molnár, Z. Révay and T. Belgya, *5th Int. Topical Meeting on Industrial Radiation and Radioisotope Measurement Applications (IRRMA-V)*, Bologna, Italy, 9-14 June 2002, *Nucl. Instr. Meth. B*, to be published.

[Mo02b] G. L. Molnár, Z. Révay and T. Belgya, New intensities for high energy gamma-ray standards, *Proc. 11th Int. Symp. on Capture Gamma-ray Spectroscopy and Related Topics (CGS11)*, Pruhonice near Prague, Czech Republic, 2-6 September 2002, World Scientific, Singapore, in press.

[Ra00] S. Raman, C. Yonezawa, H. Matsue, H. Iimura and N. Shinohara, *Nucl. Instr. Meth.* ***A*** **454,** 389 (2000).

[Ru83] J. F. A. G. Ruyl and P. M. Endt, *Nucl. Phys.* ***A*** **407** 60 (1983).

[Sp76] A. M. J. Spits and J. Kopecky, *Nucl. Phys.* ***A*** **264** 63 (1976).

[St78] M. L. Stelts and R. E. Chrien, *Nucl. Instr. Meth.* **155** (1978) 253.

[Ve97] L. Venturini and B. R. S. Pecequilo, *Appl.Radiat.Isot.* **48** (1997) 493.

[Zo77] V. Zobel, J. Eberth, U. Eberth and E. Eube, *Nucl. Instr. Meth.* **141,** 329 (1977).

Table 1. New intensities for the 34 strongest gamma rays from the $^{35}Cl(n, \gamma)^{36}Cl$ reaction in natural chlorine.

Energy[a]			Intensity				Recomm.
E_γ (keV)	dE_γ	Ref.	P_γ[d] per capture	dP_γ	$I\gamma$ (rel.)	dI_γ	for calibration
292.175	0.005	b)	0.00271	0.00004	1.002	0.011	
436.220	0.005	b)	0.00939	0.00011	3.48	0.03	*
517.07006	0.00023	c)	0.230	0.003	85.0	0. 6	*
632.434	0.007	b)	0.00338	0.00006	1.250	0.015	
786.2970	0.0004	c)	0.1038	0.0013	38.4	0.3	*
788.4230	0.0004	c)	0.1645	0.0021	60.7	0.6	*
936.915	0.010	b)	0.00523	0.00006	1.934	0.015	
1131.244	0.012	b)	0.01902	0.00020	7.03	0.04	
1164.8579	0.0005	c)	0.271	0.003	100.0	0.5	*
1327.400	0.014	b)	0.01220	0.00013	4.52	0.03	
1601.068	0.017	b)	0.0368	0.0004	13.58	0.11	*
1951.1278	0.0014	c)	0.1921	0.0021	71.0	0.5	*
1959.343	0.008	c)	0.1244	0.0014	46.0	0.4	*
2676.31	0.03	b)	0.01617	0.00019	5.98	0.04	*
2845.49	0.03	b)	0.01061	0.00012	3.92	0.03	
2863.82	0.03	b)	0.0552	0.0006	20.41	0.14	*
2975.25	0.04	b)	0.01143	0.00016	4.23	0.04	
3015.94	0.04	b)	0.00996	0.00012	3.68	0.03	
3061.83	0.04	b)	0.0342	0.0004	12.65	0.08	*
3116.02	0.08	b)	0.00903	0.00012	3.33	0.03	
3428.83	0.04	b)	0.00824	0.00011	3.05	0.03	
4082.70	0.06	b)	0.00798	0.00017	2.96	0.06	
4440.38	0.05	b)	0.01143	0.00015	4.23	0.04	*
4979.72	0.05	b)	0.0374	0.0005	13.84	0.13	*
5517.21	0.06	b)	0.01699	0.00021	6.29	0.05	*
5715.20	0.06	b)	0.0552	0.0007	20.42	0.22	*
5902.69	0.06	b)	0.01128	0.00016	4.18	0.05	
6110.80	0.06	b)	0.200	0.003	74.2	0.7	*
6619.57	0.07	b)	0.0768	0.0010	28.4	0.3	*
6627.78	0.07	b)	0.0445	0.0006	16.46	0.18	*
6977.79	0.07	b)	0.0225	0.0004	8.30	0.12	*
7413.92	0.08	b)	0.0999	0.0016	36.9	0.6	*
7790.28	0.08	b)	0.0807	0.0012	29.8	0.4	*
8578.53	0.09	b)	0.0268	0.0005	9.91	0.18	*

a) All originally published energies are reduced by 6.5 ppm according to the change of fundamental constants [Mo99].

b) Calculated energies from Table 2 of ref. [Kr82]; 10 ppm (calibration) and 2.6 ppm (wavelength to energy conversion) systematic uncertainty added quadratically.

c) From ref. [Ke85].

d) From ref. [Mo02a]; 0.9% systematic uncertainty added quadratically.

Table 2. Absolute emission probabilities for the 35 strongest capture γ-rays of ^{36}Cl [Mo02a].

E_γ (keV)	I_γ per 100 captures								
	Raman [Ra00]	Coceva [Co96]	Venturini [Ve97]	Krusche [Kr82]	Kennett [Ke81]	Stelts [St78]	Spits[a] [Sp76]	Loper [Lo72]	Present [Mo02a]
292.1				0.263(40)			0.26(3)		0.271(3)
436.2				1.05(16)			0.86(7)		0.939(6)
517.1	23.8(5)	24.3(1.4)		23.4(35)			22.7(9)		23.02(15)
632.4				0.319(48)			0.32(2)		0.338(5)
786.3	10.4(3)	10.52(35)		11.2(17)			9.6(5)		10.38(9)
788.4	16.4(4)	16.32(36)		16.9(25)			15.0(3)		16.45(15)
936.9				0.589(88)			0.50(15)		0.523(4)
1131.3		1.911(56)		1.91(29)			1.58(9)		1.901(10)
1164.9	27.2(5)	27.20(72)		27.7(42)			25.7(8)		27.06(12)
1327.4				1.27(19)			1.13(6)		1.220(7)
1601.1	3.84(6)	3.484(89)		3.48(35)	3.82(45)	3.62(18)	3.43(17)		3.675(22)
1951.1	20.2(4)	19.39(57)	20.1(6)	20.2(20)	20.39(76)	19.75(42)	18.7(4)	20.6(14)	19.21(12)
1959.3	13.0(3)	12.56(28)	13.5(4)	12.9(13)	13.41(58)	12.78(42)	12.1(4)	14.0(9)	12.44(9)
2034.5				0.748(75)	0.79		0.60(3)		0.725(14)
2676.3		1.572(38)	1.59(5)	1.91(19)	2.06(11)	1.90(6)	1.70(5)		1.617(12)
2845.5			1.09(3)	1.27(13)	1.22(7)	1.24(4)	1.17(4)		1.061(8)
2863.8	5.64(9)	5.77(11)	6.56(14)	6.55(66)	6.63(21)	6.34(16)	6.00(20)	6.8(5)	5.52(3)
2975.2		1.046(25)	1.19(3)	1.21(12)	1.09		1.14(6)		1.143(13)
3016.0			1.17(3)	1.131(58)	1.13(7)	1.26(6)	0.98(5)		0.997(8)

E_γ (keV)	I_γ per 100 captures								
3061.8	3.45(6)	3.521(66)	3.66(8)	3.88(20)	4.01(14)	3.70(21)	3.50(20)	3.8(3)	3.422(22)
3116.0			0.970(23)	0.994(55)	1.05(6)	1.10(5)	0.94(6)		0.903(8)
3428.8			0.813(20)	0.895(46)	0.90(5)	0.99(4)	0.81(4)		0.824(8)
3981.0			1.031(22)	1.028(55)	1.04(5)	1.26(4)	0.92(6)		1.006(22)
4082.7			0.810(18)	0.785(41)	0.73		0.67(4)		0.798(15)
4440.4		1.047(23)	1.105(27)	1.09(6)	1.11(4)	1.23(4)	1.00(5)		1.143(11)
4979.8		3.616(96)	3.74(8)	3.60(18)	3.95(10)	3.82(5)	3.53(15)	3.7(3)	3.74(3)
5517.3		1.689(42)	1.70(4)	1.71(9)	1.75(5)	1.54(2)	1.59(8)	1.9(1)	1.699(14)
5715.2		5.31(15)	5.55(11)	5.60(28)	5.68(12)	5.65(5)	5.14(6)	5.4(4)	5.52(5)
5902.7		1.104(31)		1.132(57)	1.18(4)	1.16(3)	1.11(4)	1.1(1)	1.128(13)
6110.8	20.8(4)	20.58(65)	20.3(4)	20.2(10)	20.96(33)	20.91(53)	19.70(20)	19.8(13)	20.02(18)
6619.6	7.59(15)	7.83(16)	8.13(19)	7.80(39)	8.31(16)	8.37(16)	8.10(10)	8.2(6)	7.68(7)
6627.8	4.44(9)	4.69(11)	4.95(13)	4.83(24)	4.74(10)	4.68(14)	4.64(10)	5.1(3)	4.45(5)
6977.8	2.24(5)	2.290(64)	2.26(5)	2.32(12)	2.40(6)	2.46(3)	2.23(9)	2.4(2)	2.25(3)
7414.0	10.00(25)	10.52(24)	10.30(22)	10.4(5)	10.69(19)	10.77(21)	10.00(10)	10.7(7)	9.99(14)
7790.3	8.25(22)	8.31(19)	8.25(19)	8.48(42)	8.69(16)	8.90(8)	8.61(8)	8.7(10)	8.07(10)
8578.6	2.73(7)	2.739(57)	2.76(7)	2.78(14)	2.84(7)	2.95(3)	2.94(6)	2.9(5)	2.68(4)
ΣI_γ	180.0	197.3	121.5	211.5	130.6	126.4	198.9	115.1	203.8
χ^2/ν	1.5	2.7	6.5	0.9	9.2	18.5	5.6	1.7	

[a] Without their estimated 8% systematic uncertainty.

[b] Without the estimated 0.9% upper limit for normalisation uncertainty.

[b] Percentage correction for the interfering single escape (SE) peak.

Table 3. New energies and relative intensities for 19 strong γ-rays from the (n,γ) reaction on natural titanium.

Target nuclide	E_γ (keV)	dE_γ (keV)	I_γ (rel.)	dI_γ (rel.)	dI_γ (%)	I_γ-ratio to ENSDF	E_γ' (keV)	I_γ/ I_γ'
^{48}Ti	137.46	0.03	1.218	0.010	0.8	1.93(11)		
^{48}Ti	341.69	0.03	37.86	0.14	0.4	1.305(12)	1381.7	0.38
^{47}Ti	983.50	0.04	2.275	0.019	0.8			
^{48}Ti	1381.72[a)]	0.03	100.0 [b)]	0.4	0.4	1.000(25)		
^{48}Ti	1498.63	0.03	5.70	0.03	0.6	1.00(3)	1762.0	0.95
^{49}Ti	1553.79	0.04	1.882	0.023	1.2			
^{48}Ti	1585.95	0.03	11.78	0.06	0.5	0.99(3)		
^{48}Ti	1761.96	0.03	6.00	0.04	0.6	0.96(3)		
^{48}Ti	1793.47	0.03	2.928	0.024	0.8	0.97(3)		
^{48}Ti	2943.12	0.04	1.221	0.013	1.1	1.11(4)		
^{48}Ti	3026.76	0.04	2.674	0.024	0.9	1.10(3)		
^{48}Ti	3475.62	0.04	1.950	0.018	0.9	1.06(3)		
^{48}Ti	3733.75	0.05	1.612	0.018	1.1	1.05(3)		
^{48}Ti	3920.44	0.05	1.629	0.018	1.1	1.081(22)		
^{48}Ti	4881.32	0.05	5.59	0.05	0.8	1.060(15)	1498.7	0.98
^{48}Ti	4966.74	0.05	3.66	0.04	1.0	1.082(15)		
^{48}Ti	6418.38	0.07	34.3	0.3	1.0	0.963(14)	341.7	0.91
^{48}Ti	6555.83	0.07	5.74	0.07	1.2	0.964(15)	1585.9	0.49
^{48}Ti	6760.06 [a)]	0.07	51.8	0.5	1.0	0.956(13)	1381.7	0.52

[a)] Used for normalisation of intensities from Ref. [Mo02b].

[b)] Used for energy calibration.

Table 4. New energies and relative intensities for 25 selected strong γ rays from the natural chromium (n, γ) reactions.

Origin	E_γ (keV)	dE_γ	I_γ (rel.)	dI_γ
^{53}Cr	564.35	0.06	8.19	0.03
^{51}Cr	749.32	0.06	41.36	0.12
^{54}Cr	835.03	0.06	100.0[a)]	0.3
^{51}Cr	1150.06	0.05	1.524	0.008
^{54}Cr	1784.69[b)]	0.05	12.83	0.05
^{51}Cr	1899.25	0.05	6.19	0.03
^{54}Cr	2239.16	0.05	13.53	0.06
^{53}Cr	2321.09	0.05	9.68	0.04
^{51}Cr	2376.84	0.05	2.590	0.013
^{53}Cr	2670.20	0.05	2.007	0.012
^{53}Cr	3616.88	0.08	1.886	0.013
^{54}Cr	3719.77	0.06	4.672	0.024
^{53}Cr	4322.43	0.08	2.118	0.015
^{53}Cr	5268.92	0.12	3.32	0.03
^{53}Cr	5618.13	0.11	9.48	0.07
^{54}Cr	5998.63	0.11	5.69	0.05
^{51}Cr	6135.39	0.13	4.66	0.10
^{54}Cr	6644.47	0.14	12.29	0.10
^{54}Cr	7098.84	0.19	9.62	0.09
^{51}Cr	7361.99	0.17	6.43	0.06
^{53}Cr	7374.68	0.17	5.57	0.05
^{53}Cr	7938.65[b)]	0.18	29.4	0.3
^{51}Cr	8511.55	0.20	15.55	0.18
^{54}Cr	8882.88	0.22	56.1	0.7
^{54}Cr	9717.5	0.3	19.9	0.3

[a)] Used for normalisation of intensities from Ref. [Be02a].

[b)] Used for energy calibration.

Table 5. New energies and relative intensities for γ-rays of ^{226}Ra and its daughters [Mo02b].

Parent nuclide	E_γ (keV) Present	E_γ (keV) Previous[a]	z-score	I_γ (rel.) Present	I_γ (rel.) [De01]	z-score
^{210}Pb	46.549(5)	46.539(1)	1.9			
^{214}Pb	53.232(4)	53.2275(21)	1.0	2.384(20)	2.329(23)	1.8
^{226}Ra	186.205(4)	186.211(13)	-0.5	7.85(5)	7.81(3)	0.8
^{214}Pb	241.995(4)	241.997(3)	-0.4	15.98(6)	15.90(5)	1.2
^{214}Pb	295.219(5)	295.224(2)	-0.8	40.61(13)	40.36(12)	1.4
^{214}Pb	351.939(6)	351.932(2)	1.2	78.34(23)	78.16(23)	0.5
^{214}Bi	609.329(7)	609.316(4)[b]	1.5	100.0(3)	100.0(3)	0.0
^{214}Bi	665.444(10)	665.453(22)[c]	-0.4	3.386(21)	3.359(17)	1.0
^{214}Bi	768.362(7)	768.369(10)[b]	-0.6	10.77(3)	10.66(5)	1.8
^{214}Bi	806.181(10)	806.186(10)[b]	-0.4	2.777(14)	2.788(22)	-0.4
^{214}Bi	934.054(8)	934.080(18)[c]	-1.4	6.83(4)	6.78(3)	1.0
^{214}Bi	1120.301(8)	1120.309(10)[c]	-0.7	32.77(12)	32.7 (1)	0.4
^{214}Bi	1155.214(9)	1155.190(20)	1.1	3.595(17)	3.59(4)	0.0
^{214}Bi	1238.131(10)	1238.135(12)[c]	-0.2	12.80(4)	12.83(6)	-0.4
^{214}Bi	1280.981(12)	1280.960(20)	0.9	3.159(16)	3.15(3)	0.4
^{214}Bi	1377.671(12)	1377.697(25)[c]	-0.9	8.79(3)	8.69(4)	2.0
^{214}Bi	1385.310(14)	1385.31(3)	0.0	1.755(16)	1.744(17)	0.5
^{214}Bi	1401.516(13)	1401.50(4)	0.4	2.934(13)	2.924(20)	0.4
^{214}Bi	1407.989(12)	1407.997(8)[b]	-0.6	5.250(19)	5.23(3)	0.5
^{214}Bi	1509.198(14)	1509.220(9)[b]	-1.4	4.67(3)	4.61(6)	0.9
^{214}Bi	1583.200(17)	1583.22(4)	-0.5	1.556(13)		
^{214}Bi	1661.272(17)	1661.311(15)[b]	-1.7	2.299(14)	2.27(3)	0.8
^{214}Bi	1684.020(23)	1684.022(21)[b]	-0.1	1.556(13)		
^{214}Bi	1729.592(19)	1729.635(14)[b]	-1.8	6.25(3)	6.23(3)	0.4
^{214}Bi	1764.485(14)	1764.533(16)[b]	-2.3	33.63(9)	33.54(10)	0.7
^{214}Bi	1847.432(17)	1847.46(5)[c]	-0.5	4.42(3)	4.45(4)	-0.6
^{214}Bi	2118.483(25)	2118.539(9)[b]	-2.1	2.548(21)	2.536(20)	0.4
^{214}Bi	2204.051(23)	2204.078(14)[b]	-1.0	10.75(9)	10.74(5)	0.1
^{214}Bi	2293.37(3)	2293.334(22)[b]	1.1	0.677(10)	0.665(17)	0.6
^{214}Bi	2447.67(3)	2447.681(16)[b]	-0.4	3.41(4)	3.402(24)	0.2
χ^2/ν			1.2			0.8

[a] ENSDF unless otherwise noted.
[b] Ref. [He79], decreased by 5.6 ppm.
[c] Ref. [Zo77], increased by 30 ppm.

Table 6. Comparison of the new relative intensities for strong γ-rays from ^{56}Co decay with a recent evaluation and another new measurement [Mo02b].

E_γ (keV) Helmer [He00]	I_γ (rel.) Present [Mo02b]	dI_γ (%)	I_γ (rel.) Baglin [Ba02]	z- score	I_γ (rel.) Raman [Ra00]	z-score
846.7638(19)	100.0(2)	0.2	100.0(2)	0.0	100	0.0
977.363(4)	1.424(6)	0.4	1.425(9)	0.1		
1037.8333(24)	14.07(4)	0.3	14.09(5)	0.3	14.11(22)	0.2
1175.0878(22)	2.252(9)	0.4	2.255(14	0.2	2.25(4)	0.0
1238.2736(22)	66.20(11)	0.2	66.3(3)	0.2	66.6(10)	0.4
1360.196(4)	4.22(15)	0.4	4.274(15	2.4	4.23(7)	0.2
1771.327(3)	15.24(8)	0.5	15.52(5)	3.1	15.42(25)	0.7
1810.726(4)	0.641(5)	0.7	0.643(4)	0.4		
1963.703(11)	0.698(3)	0.5	0.715(6)	2.5		
2015.176(5)	2.976(14)	0.5	3.041(16	3.0	3.03(5)	1.1
2034.752(5)	7.69(3)	0.4	7.79(4)	2.0	7.84(12)	1.2
2113.092(6)	0.372(4)	1.0	0.378(9)	0.7		
2212.898(3)	0.388(4)	1.0	0.389(4)	0.2		
2598.438(4)	16.82(7)	0.4	17.02(6)	2.2	17.1(3)	1.0
3009.559(4)	1.033(11)	1.0	1.03(3)	-0.1		
3201.930(11)	3.196(17)	0.5	3.22(3)	0.7	3.16(6)	-0.5
3253.402(5)	7.85(4)	0.5	7.90(6)	0.6	7.81(16)	-0.3
3272.978(6)	1.854(12)	0.6	1.864(15	0.6	1.84(4)	-0.3
3451.119(4)	0.940(10)	1.1	0.945(11	0.3	0.93(3)	-0.2
3547.93(6)[a]	0.196(2)	1.0	0.195(3)	-0.3	0.19(1)	-0.6
Sum or χ^2/ν	248.10(4)		248.99(5)	2.2		0.4

[a] ENSDF

Table 7. New relative intensities for 21 strong gamma rays from ^{66}Ga decay [Ba02].

E_γ (keV) [He00]	I_γ (rel.) [Ca71]	I_γ (rel.) [Ra00]	I_γ (rel.) Berkeley	I_γ (rel.) Budapest	I_γ (rel.) Average
833.5324 (21)	15.92 (17)	16.02 (24)	15.94 (14)	15.92 (6)	15.93 (5)
1039.220 (3)	100.0	100.0 (16)	100.0 (9)	100.0 (3)	100.0 (3)
1333.112 (5)	3.25 (4)	3.17 (5)	3.20 (3)[a]	3.171 (13)	3.175 (12)
1418.754 (5)	1.70 (3)		1.640 (23)	1.659 (8)	1.657 (8)
1508.158 (7)	1.520 (24)		1.503 (23)	1.496 (7)	1.497 (7)
1898.823 (8)	1.09 (4)		1.062 (23)	1.050 (8)	1.051 (8)
1918.329 (5)	5.63 (8)	5.33 (8)	5.44 (6)	5.360 (23)[b]	5.368 (21)
2189.616 (6)	15.06 (18)	14.54 (21)	14.50 (13)	14.39 (6)	14.42 (5)
2422.525 (7)	5.16 (5)	5.12 (8)	5.15 (6)	5.072 (24)	5.085 (22)
2751.835 (5)	61.2 (6)	61.2 (8)	61.5 (6)	61.34 (26)	61.35 (23)
3228.800 (6)	3.96 (4)	4.06 (8)	4.07 (4)	4.087 (22)	4.082 (19)
3380.850 (6)	3.78 (4)	3.96 (8)	3.99 (4)	3.950 (23)	3.960 (19)
3422.040 (8)	2.18 (4)		2.29 (3)	2.321 (16)	2.314 (14)
3791.036 (8)[c]	2.68 (3)	2.96 (5)	2.96 (4)	2.929 (24)	2.941(19)
4085.853 (9)	3.07 (4)	3.38 (8)	3.42 (4)	3.455 (20)	3.445 (18)
4295.224 (10)[c]	9.17 (11)	10.24 (26)[d]	10.54 (15)[e]	10.25 (7)[f]	10.30 (8)[g]
4461.202 (9)	1.875 (22)		2.20 (4)	2.275 (23)	2.26 (3)
4806.007 (9)	3.82 (4)	4.93 (11)	5.00 (7)	5.04 (3)	5.03 (3)

[a] Corrected for 1.8% background contribution from ^{60}Co.

[b] Corrected for up to 4% contribution from ^{57}Ni for enriched sources.

[c] From fit to level scheme; not recommended for energy calibration.

[d] Corrected for ~4% contribution from single-escape peak from 4806-keV γ ray.

[e] Corrected for 16% contribution from single-escape peak from 4806-keV γ ray.

[f] Corrected for 6.1(4)% contribution from single-escape peak from 4806-keV γ ray.

[g] After correction for contribution from single-escape of the 4806 keV γ ray.