Practical Gamma-ray Spectrometry 2nd Edition

Gordon R. Gilmore Nuclear Training Services Ltd Warrington, UK



Practical Gamma-ray Spectrometry

Practical Gamma-ray Spectrometry 2nd Edition

Gordon R. Gilmore Nuclear Training Services Ltd Warrington, UK



Copyright © 2008 John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk Visit our Home Page on www.wiley.com

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1T 4LP, UK, without the permission in writing of the Publisher. Requests to the Publisher should be addressed to the Permissions Department, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, or emailed to permreq@wiley.co.uk, or faxed to (+44) 1243 770620.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The Publisher is not associated with any product or vendor mentioned in this book.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

The Publisher, and the Author make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of fitness for a particular purpose. The advice and strategies contained herein may not be suitable for every situation. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. The fact that an organization or Website is referred to in this work as a citation and/or a potential source of further information does not mean that the author or the publisher endorses the information the organization or Website may provide or recommendations it may make. Further, readers should be aware that Internet Websites listed in this work may have changed or disappeared between when this work was written and when it is read. No warranty may be created or extended by any promotional statements for this work. Neither the Publisher nor the Author shall be liable for any damages arising herefrom.

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Ltd, 6045 Freemont Blvd, Mississauga, Ontaria, L5R 4J3, Canada

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Library of Congress Cataloging in Publication Data

Gilmore, Gordon.
Practical gamma-ray spectrometry. — 2nd ed./Gordon Gilmore.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-86196-7 (cloth : alk. paper)
I. Gamma ray spectrometry—Handbooks, manuals, etc. I. Title.
QC793.5.G327G55 2008
537.5'352—dc22

2007046837

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 978-0-470-86196-7

Typeset in 9/11pt Times by Integra Software Services Pvt. Ltd, Pondicherry, India Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire

Dedication

To my friends and family who, I suspect, never really believed I would get this finished, and to the publishers who patiently tolerated many delays before I did so

Contents

c

1

Pr	eface	to the	Second Edition	XV			1.9.2	A source of generic	
Pr	eface	to the	First Edition	xvii				information	20
	cjucc					Prac	ctical Po	ints	22
In	ternet	t Resou	rces within the Book	xix		Furt	her Rea	ding	23
1	Rad	ioactiv	e Decay and the Origin of		2	Inte	eraction	s of Gamma Radiation with	
-	Gan	nma ar	nd X-Radiation	1		Ma	tter		25
	1.1	Introd	uction	1		2.1	Introdu	uction	25
	1.2	Beta I	Decav	2		2.2	Mecha	nisms of Interaction	25
		1.2.1	β^{-} or negatron decay	3			2.2.1	Photoelectric absorption	27
		1.2.2	β^+ or positron decay	5			2.2.2	Compton scattering	28
		1.2.3	Electron capture (EC)	6			2.2.3	Pair production	29
		1.2.4	Multiple stable isotopes	7		2.3	Total 4	Attenuation Coefficients	29
	1.3	Alpha	Decay	7		2.4	Interac	ctions within the Detector	30
	1.4	Spont	aneous Fission (SF)	8			2.4.1	The very large detector	30
	1.5	Minor	· Decay Modes	8			2.4.2	The very small detector	31
	1.6	Gamn	na Emission	8			2.4.3	The 'real' detector	32
		1.6.1	The electromagnetic spectrum	9			2.4.4	Summary	32
		1.6.2	Some properties of nuclear			2.5	Interac	ctions within the Shielding	33
			transitions	9			2.5.1	Photoelectric interactions	33
		1.6.3	Lifetimes of nuclear energy				2.5.2	Compton scattering	34
			levels	10			2.5.3	Pair production	35
		1.6.4	Width of nuclear energy levels	10		2.6	Brems	strahlung	35
		1.6.5	Internal conversion	11		2.7	Attenu	ation of Gamma Radiation	36
		1.6.6	Abundance, vield and			2.8	The D	esign of Detector Shielding	36
			emission probability	11		Prac	ctical Po	ints	38
		1.6.7	Ambiguity in assignment of			Furt	her Rea	ding	38
			nuclide identity	11					
	1.7	Other	Sources of Photons	12	3	Sen	nicondu	ctor Detectors for Gamma-Ray	
		1.7.1	Annihilation radiation	12		Spe	ctromet	try	39
		1.7.2	Bremsstrahlung	13		3.1	Introdu	uction	39
		1.7.3	Prompt gammas	13		3.2	Semic	onductors and Gamma-Ray	
		1.7.4	X-rays	13			Detect	ion	40
	1.8	The M	Athematics of Decay and				3.2.1	The band structure of solids	40
		Grow	th of Radioactivity	15			3.2.2	Mobility of holes	40
		1.8.1	The decay equation	15			3.2.3	Creation of charge carriers by	
		1.8.2	Growth of activity in reactors	16				gamma radiation	41
		1.8.3	Growth of activity from decay				3.2.4	Suitable semiconductors for	
			of a parent	17				gamma-ray detectors	41
	1.9	The C	Chart of the Nuclides	19			3.2.5	Newer semiconductor materials	42
		1.9.1	A source of nuclear data	19		3.3	The N	ature of Semiconductors	43

	3.4	The M	Ianufacture of Germanium	
		Detec	tors	45
		3.4.1	Introduction	45
		3.4.2	The manufacturing process	45
		3.4.3	Lithium-drifted detectors	47
		3.4.4	The detector configurations	
			available	47
		3.4.5	Absorption in detector caps	
			and dead layers	47
		3.4.6	Detectors for low-energy	
			measurements	49
		3.4.7	Well detectors	49
	3.5	Detect	tor Capacitance	49
		3.5.1	Microphonic noise	50
	3.6	Charg	e Collection in Detectors	50
		3.6.1	Charge collection time	50
		3.6.2	Shape of the detector pulse	51
		3.6.3	Timing signals from	
			germanium detectors	52
		3.6.4	Electric field variations across	
			the detector	52
		3.6.5	Removing weak field regions	
			from detectors	53
		3.6.6	Trapping of charge carriers	53
		3.6.7	Radiation damage	54
	3.7	Packa	ging of Detectors	55
		3.7.1	Construction of the detector	
			mounting	55
		3.7.2	Exotic detectors	57
		3.7.3	Loss of coolant	58
		3.7.4	Demountable detectors	58
		3.7.5	Customer repairable detectors	58
		3.7.6	Electrical cooling of detectors	59
	Prac	tical Po	ints	59
	Furt	her Rea	ding	59
4	Elec	tronics	s for Gamma-Ray Spectrometry	61
	4.1	The G	eneral Electronic System	61
		4.1.1	Introduction	61
		4.1.2	Electronic noise and its	
			implications for spectrum	
			resolution	62
		4.1.3	Pulse shapes in	
			gamma spectrometry systems	63
		4.1.4	Impedance - inputs and outputs	64
		4.1.5	The impedance of cabling	64
		4.1.6	Impedance matching	65
	4.2	Detect	tor Bias Supplies	66
	4.3	Pream	plifiers	66
		4.3.1	Resistive feedback	
			preamplifiers	67
		4.3.2	Reset preamplifiers	69

	4.3.3	The noise contribution of	
		preamplifiers	69
	4.3.4	The rise time of	
		preamplifiers	70
4.4	Ampli	ifiers and Pulse Processors	70
	4.4.1	The functions of the	
		amplifier	70
	4.4.2	Pulse shaping	71
	4.4.3	The optimum pulse shape	72
	4.4.4	The optimum pulse shaping	
		time constant	73
	4.4.5	The gated integrator	
		amplifier	74
	4.4.6	Pole-zero cancellation	75
	4.4.7	Baseline shift	76
	4.4.8	Pile-up rejection	77
	4.4.9	Amplifier gain and overview	78
4.5	Resol	ution Enhancement	80
	4.5.1	New semiconductor	
		materials	80
4.6	Multio	channel Analysers and their	
	Analo	gue-to-Digital Converters	81
	4.6.1	Introduction	81
	4.6.2	Pulse range selection	82
	4.6.3	The ADC input gate	83
	4.6.4	The ADC	84
	4.6.5	MCA conversion time and	
		dead time	86
	4.6.6	Choosing an ADC	87
	4.6.7	Linearity in MCAs	88
	4.6.8	Optimum spectrum size	89
	4.6.9	MCA terms and definitions	89
	4.6.10) Arrangement of the MCA	
		function	91
	4.6.11	Simple MCA analysis	
		functions	91
4.7	Live 7	Fime Correction and Loss-Free	
	Count	ting	92
	4.7.1	Live time clock correction	92
	4.7.2	The Gedcke–Hale method	92
	4.7.3	Use of a pulser	92
	4.7.4	Loss-free counting (LFC)	93
	4.7.5	MCA throughput	94
4.8	Spect	rum Stabilization	94
	4.8.1	Analogue stabilization	95
	4.8.2	Digital stabilization	95
4.9	Coinc	idence and Anticoincidence	
	Gatin	g	96
4.10	Multi	plexing and Multiscaling	96
4.11	Digita	l Pulse Processing Systems	97
Prac	tical Pc	bints	98
Furt	her Rea	lding	99

5	Stat	istics of	f Counting	101
	5.1	Introd	uction	101
		5.1.1	Statistical statements	101
	5.2	Count	ing Distributions	102
		5.2.1	The binomial distribution	102
		5.2.2	The Poisson and Gaussian	
			distributions	104
	5.3	Sampl	ing Statistics	104
		5.3.1	Confidence limits	105
		5.3.2	Combining the results from	
			different measurements	107
		5.3.3	Propagation of uncertainty	108
	5.4	Peak A	Area Measurement	108
		5.4.1	Simple peak integration	109
		5.4.2	Peaked-background	
			correction	111
	5.5	Optim	izing Counting Conditions	111
		5.5.1	Optimum background width	111
		5.5.2	Optimum spectrum size	112
		5.5.3	Optimum counting time	113
	5.6	Count	ing Decision Limits	114
		5.6.1	Critical limit (L_c)	114
		5.6.2	Upper limit $(L_{\rm H})$	116
		5.6.3	Confidence limits	117
		5.6.4	Detection limit $(L_{\rm p})$	117
		5.6.5	Determination limit (L_0)	118
		5.6.6	Other calculation options	118
		5.6.7	Minimum detectable activity	110
		0.017	(MDA)	119
		568	Uncertainty of the $(L_{\rm H})$ and	11)
		5.0.0	MDA	120
		5.6.9	An example by way of	120
		0.017	summary	120
	57	Specia	of Counting Situations	121
	5.7	5 7 1	Non-Poisson counting	121
		572	Low numbers of counts	121
		573	Non-Poisson statistics due to	121
		01110	pile-up rejection and loss-free	
			counting	122
	5.8	Uncer	tainty Budgets	123
	0.0	5.8.1	Introduction	123
		582	Accuracy and precision	124
		583	Types of uncertainty	124
		584	Types of distribution	124
		585	Uncertainty on sample	121
		5.0.5	preparation	124
		586	Counting uncertainties	125
		587	Calibration uncertainties	125
		588	An example of an uncertainty	120
		5.0.0	hudget	126
	Drag	tical Po	inte	120
	Furt	her Rea	ding	120
	run	nei Kea	uing	120

Reso	olution:	Origins and Control	131
6.1	Introdu	ction	131
6.2	Charge	Production $-\omega_{\rm P}$	133
	6.2.1	Germanium versus silicon	133
	6.2.2	Germanium versus sodium	
		iodide	134
	6.2.3	Temperature dependence of	
		resolution	134
63	Charge	Collection $-\omega_{\alpha}$	134
0.5	631	Mathematical form of w	135
64	Flectro	nic Noise $-\omega$	136
0.7	6 4 1	\mathbf{D}_{E}	126
	64.1	Paraner noise	120
	0.4.2	Elister asis	137
	0.4.3	Flicker hoise	137
	6.4.4	Total electronic noise and	
		shaping time	137
6.5	Resolvi	ng the Peak Width Calibration	138
Prac	tical Poir	nts	141
Furtl	her Read	ing	141
Refe	rences		141
Spec	ctromete	er Calibration	143
7.1	Introdu	ction	143
7.2	Referen	ce Data for Calibration	143
7.3	Sources	s for Calibration	144
7.4	Energy	Calibration	144
	7.4.1	Errors in peak energy	
		determination	146
7.5	Peak W	idth Calibration	147
	7.5.1	Factors affecting peak width	147
	752	Algorithms for peak width	117
	7.0.2	estimation	147
	753	Estimation of the neak height	149
	7.5.5	Anomalous neak widths	1/0
76	T.J. 4	Anomalous peak withins	150
7.0	7.6.1	Which officionay?	150
	7.0.1	Full an annual officiarian	150
	7.0.2	Full-energy peak enficiency	131
	1.0.3	Are efficiency calibration	150
		curves necessary?	152
	7.6.4	The effect of	
		source-to-detector distance	152
	7.6.5	Calibration errors due to	
		difference in sample geometry	153
	7.6.6	An empirical correction for	
		sample height	154
	7.6.7	Effect of source density on	
		efficiency	155
	7.6.8	Efficiency loss due to	
		random summing (pile-up)	158
	7.6.9	True coincidence summing	159
	7.6.10	Corrections for radioactive	
		decay	159
		-	

		7.6.11	Electronic timing problems	160
	7.7	Mathen	natical Efficiency Calibration	160
		7.7.1	ISOCS	161
		7.7.2	LabSOCS	162
		773	Other programs	162
	Practi	cal Point	e e e e e e e e e e e e e e e e e e e	162
	Furth	ar Daadir	5	163
	runn	ei Keauii	ig	105
8	True	Coincid	ence Summing	165
	8.1	Introdu	ction	165
	8.2	The Or	igin of Summing	166
	8.3	Summi	ng and Solid Angle	166
	8.4	Spectra	l Evidence of Summing	167
	8.5	Validity	y of Close Geometry	
		Calibra	tions	168
		8.5.1	Efficiency calibration using	
			QCYK mixed nuclide	
			sources	168
	8.6	Summa	ry	171
	8.7	Summi	ng in Environmental	
		Measur	ements	171
	8.8	Achiev	ing Valid	
		Close (Geometry Efficiency	
		Calibra	tions	172
	89	TCS G	eometry and Composition	174
	8 10	$\Delta chiev$	ing 'Summing_free'	1/7
	0.10	mansur	aments	175
			Using the fintemolative fit?	175
		8.10.1	Using the interpolative in	175
		0 10 0	to correct for TCS	1/5
		8.10.2	Comparative activity	1.7.5
			measurements	175
		8.10.3	Using correction	
			factors derived from	
			efficiency calibration curves	176
		8.10.4	Correction of results using	
			'bodged' nuclear data	176
	8.11	Mathen	natical Summing Corrections	176
	8.12	Softwar	re for Correction of TCS	178
		8.12.1	GESPECOR	179
		8.12.2	Calibrations using	
			summing nuclides	179
		8.12.3	TCS correction in spectrum	
		011210	analysis programs	179
	Practi	cal Point	s s	180
	Furth	ar Daadir	a	180
	rutu	u Reauli	ιŏ	100
9	Com	puter An	alysis of Gamma-Ray	
	Spect	ra		183
	9.1	Introdu	ction	183
	9.2	Method	ls of Locating Peaks	
		in the S	Spectrum	185
		9.2.1	Using regions-of-interest	185

	9.2.2	Locating peaks using	
		channel differences	185
	9.2.3	Derivative peak searches	185
	9.2.4	Peak searches using	
		correlation methods	186
	9.2.5	Checking the acceptability	
		of peaks	187
9.3	Library	Directed Peak Searches	187
9.4	Energy	Calibration	188
9.5	Estimat	ion of the Peak Centroid	189
9.6	Peak W	idth Calibration	189
9.7	Determ	ination of the Peak Limits	191
	9.7.1	Using the width calibration	192
	9.7.2	Individual peak width	
		estimation	192
	9.7.3	Limits determined by a	
		moving average minimum	192
9.8	Measur	ements of Peak Area	192
9.9	Full En	ergy Peak Efficiency	
	Calibra	tion	193
9.10	Multipl	et Peak Resolution	
	by Dec	onvolution	195
9.11	Peak St	tripping as a Means	
	of Avo	iding Deconvolution	196
9.12	The An	alvsis of the Sample Spectrum	197
	9.12.1	Peak location and	
		measurement	198
	9.12.2	Corrections to the peak	
	,	area for peaked	
		background	198
	9.12.3	Upper limits and	
		minimum detectable	
		activity	198
	9.12.4	Comparative activity	
		estimations	199
	9.12.5	Activity estimations using	
		efficiency curves	199
	9.12.6	Corrections independent	
		of the spectrometer	199
9.13	Nuclide	e Identification	200
	9.13.1	Simple use of look-up	
		tables	200
	9.13.2	Taking into account other	
		peaks	200
9.14	The Fir	nal Report	200
9.15	Setting	Up Nuclide and Gamma-Ray	
	Librarie	es s	201
9.16	Buying	Spectrum Analysis Software	202
9.17	The Sp	ectrum Analysis Programs	
	Referre	d to in the Text	202
Practi	cal Point	S	202
Furth	er Readir	ng	203
		-	

10	Scintil	lation Spe	ctrometry	205
	10.1	Introduct	ion	205
	10.2	The Scin	tillation Process	205
	10.3	Scintillat	ion Activators	206
	10.4	Life time	of Excited States	206
	10.5	Temperat	ture Variation of the	
		Scintillat	or Response	207
	10.6	Scintillat	or Detector Materials	207
		10.6.1	Sodium iodide – NaI(Tl)	207
		10.6.2	Bismuth germanate –	
			BGO	208
		10.6.3	Caesium iodide -	
			CsI(Tl) and CsI(Na)	209
		10.6.4	Undoped caesium	
			iodide – CsI	209
		10.6.5	Barium fluoride – BaF_2	209
		10.6.6	Caesium fluoride – CsF	210
		10.6.7	Lanthanum halides –	
			$LaCl_3(Ce)$ and $LaBr_3(Ce)$	210
		10.6.8	Other new scintillators	210
	10.7	Photomu	ltiplier Tubes	211
	10.8	The Phot	ocathode	211
	10.9	The Dyn	ode Electron Multiplier	212
	10.10	Chain		212
	10.10	Photodio	de Scintillation	212
	10.11	Construct	tion of the Complete	212
	10.11	Detector	tion of the Complete	212
			Detector shares	215
		10.11.1	Optical coupling of the	215
		10.11.2	scintillator to the	
			photomultiplier	213
	10.12	The Reso	photomultiplier	215
	10.12	Systems	sentimeter	214
		10.12.1	Statistical uncertainties	211
		1011211	in the detection process	215
		10.12.2	Factors associated with	
			the scintillator crystal	215
		10.12.3	The variation of	
			resolution with	
			gamma-ray energy	216
	10.13	Electroni	cs for Scintillation	
		Systems		216
		10.13.1	High-voltage supply	216
		10.13.2	Preamplifiers	217
		10.13.3	Amplifiers	217
		10.13.4	Multi-channel analysers	
			and spectrum analysis	217
	10.14	Comparis	son of Sodium Iodide and	
		Germaniu	im Detectors	218
	Practic	al Points		219
	Further	r Reading		219

11	Choo	sing and	Setting up a Detector, and	
	Check	king its S	Specifications	221
	11.1	Introduc	ction	221
	11.2	Setting	up a Germanium Detector	
		System	-	222
		11.2.1	Installation – the detector	
			environment	222
		11.2.2	Liquid nitrogen supply	223
		11.2.3	Shielding	224
		11.2.4	Cabling	224
		11.2.5	Installing the detector	225
		11.2.6	Preparation for	
			powering-up	225
		11.2.7	Powering-up and initial	
			checks	226
		11.2.8	Switching off the system	228
	11.3	Optimiz	zing the Electronic	
		System		228
		11.3.1	General considerations	228
		11.3.2	DC level adjustment and	
			baseline noise	228
		11.3.3	Setting the conversion	
			gain and energy range	228
		11.3.4	Pole-zero (PZ) cancellation	230
		11.3.5	Incorporating a pulse	
			generator	231
		11.3.6	Baseline restoration	
			(BLR)	231
		11.3.7	Optimum time constant	231
	11.4	Checkir	ng the Manufacturer's	
		Specific	cation	232
		11.4.1	The Manufacturer's	
			Specification Sheet	232
		11.4.2	Detector resolution and	
			peak shape	233
		11.4.3	Detector efficiency	235
		11.4.4	Peak-to-Compton (P/C)	
			ratio	237
		11.4.5	Window thickness index	238
	_	11.4.6	Physical parameters	238
	Practi	cal Point	S	238
	Furthe	er Readin	g	238

12	Trou	bleshooting	239
	12.1	Fault-Finding	239
		12.1.1 Equipment required	239
		12.1.2 Fault-finding guide	240
	12.2	Preamplifier Test Point and	
		Leakage Current	243
		12.2.1 Resistive feedback (RI	F)
		preamplifiers	243

		12.2.2	Transistor reset and	
			pulsed optical reset	
			preamplifiers	244
	12.3	Thermal	Cycling of the Detector	244
		12.3.1	The origin of the	
			problem	244
		12.3.2	The thermal cycling	
			procedure	245
		12.3.3	Frosted detector	
			enclosure	246
	12.4	Ground	Loops, Pick-up and	
		Microph	onics	246
		12.4.1	Ground loops	246
		12.4.2	Electromagnetic pick-up	247
		12.4.3	Microphonics	249
	Practi	cal Points	1 I I I I I I I I I I I I I I I I I I I	250
	Furth	er Reading	2	250
			2	
13	Low	Count Rs	ate Systems	251
10	13.1	Introduc	tion	251
	13.2	Counting	with High Efficiency	253
	10.2	13.2.1	MDA: efficiency and	200
		10.2.1	resolution	253
		1322	MDA: efficiency	200
		10.2.2	background and counting	
			period	253
	13.3	The Effe	ect of Detector Shape	257
	10.0	13.3.1	Low energy measurements	257
		13.3.2	Well detectors	258
		13 3 3	Sample quantity and	-00
		10.0.0	geometry	259
	13.4	Low Ba	ckground Systems	262
	1011	13.4.1	The background spectrum	263
		13.4.2	Low background	200
			detectors	263
		13.4.3	Detector shielding	265
		13.4.4	The graded shield	265
		13.4.5	Airborne activity	266
		13.4.6	The effect of cosmic	
		101110	radiation	266
		13.4.7	Underground measurements	269
	13.5	Active F	Background Reduction	270
		13.5.1	Compton suppression	
			systems	270
		13.5.2	Veto guard detectors	273
	13.6	Ultra-Lo	w-Level Systems	273
	Practi	cal Points		276
	Furth	er Reading	3	276
	- 0101		2	270
14	Hiah	Count P	ate Systems	279
14	14 1	Introduc	tion	270
	14.2	Detector	Throughput	280
	- · · ·			200

	14.3	Preamp	lifiers for High	
		Count I	Rate	281
		14.3.1	Energy rate saturation	281
		14.3.2	Energy resolution	283
		14.3.3	Dead time	283
	14.4	Amplifi	iers	283
		14.4.1	Time constants and pile-up	284
		14.4.2	The gated integrator	284
		14.4.3	Pole zero correction	285
		14.4.4	Amplifier stability – peak shift	285
		1445	Amplifier stability –	200
		111110	resolution	285
		14.4.6	Overload recovery	286
	14.5	Digital	Pulse Processing	286
	14.6	The AL	DC and MCA	288
	14.7	Dead T	imes and Throughput	288
		14.7.1	Extendable and	
			non-extendable dead time	289
		14.7.2	Gated integrators	290
		14.7.3	DSP systems	291
		14.7.4	Theory versus practice	291
	14.8	System	Checks	292
	Practi	cal Point	S	293
	Furth	er Readin	ıg	293
15	Fncu	rina Au	ality in Gamma-Ray	
10	Ensu	ring Qua		
10	Spect	trometry		295
10	Spect 15.1	trometry Introdu	ction	295 295
10	Spect 15.1 15.2	trometry Introdue Nuclear	ction : Data	295 295 296
ii ii	Spect 15.1 15.2 15.3	Trometry Introduc Nuclear Radion	ction : Data uclide Standards	295 295 296 296
i.	Spect 15.1 15.2 15.3 15.4	Introduce Introduce Nuclear Radionu Maintai	ction Data uclide Standards ning Confidence in the	295 295 296 296
i.	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclean Radion Maintai Equipm	ction Data uclide Standards ning Confidence in the tent	295 295 296 296 296
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radion Maintai Equipm 15.4.1	ction Data uclide Standards ning Confidence in the nent Setting up and	295 295 296 296 297
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclean Radionu Maintai Equipm 15.4.1	ction Data uclide Standards ning Confidence in the nent Setting up and maintenance procedures	295 295 296 296 297 297
	Spect 15.1 15.2 15.3 15.4	ing Qua rometry Introduc Nuclean Radionu Maintai Equipm 15.4.1 15.4.2	ction • Data uclide Standards ining Confidence in the tent Setting up and maintenance procedures Control charts	295 295 296 296 297 297 298
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclean Radionu Maintai Equipm 15.4.1 15.4.2 15.4.3	ction Data uclide Standards ning Confidence in the nent Setting up and maintenance procedures Control charts Setting up a control chart	295 296 296 297 297 297 298 299
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radione Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining	ction : Data uclide Standards ning Confidence in the tent Setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum	295 295 296 296 297 297 297 298 299
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radione Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi	ction : Data uclide Standards ning Confidence in the tent Setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum IS	295 295 296 296 297 297 298 299 301
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radion Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi 15.5.1	ction Data uclide Standards ning Confidence in the tent Setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum s Test spectra	295 296 296 297 297 297 298 299 301 301
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radion Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi 15.5.1 15.5.2	ction Data uclide Standards ning Confidence in the tent Setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum is Test spectra Computer-generated test	295 295 296 296 297 297 298 299 301 301
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radion Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi 15.5.1 15.5.2	ction Data uclide Standards ning Confidence in the tent Setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum s Test spectra Computer-generated test spectra	295 295 296 296 297 297 298 299 301 301 302
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radion Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi 15.5.1 15.5.2 15.5.3	ction Data uclide Standards ning Confidence in the ning Confidence in the ning Confidence procedures Control charts Setting up a control chart Control charts Setting up a control chart Confidence in the Spectrum S Test spectra Computer-generated test spectra Test spectra created by	295 295 296 296 297 297 297 298 299 301 301
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radion Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi 15.5.1 15.5.2 15.5.3	ction Data uclide Standards ining Confidence in the tent Setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum S Test spectra Computer-generated test spectra Test spectra created by counting Accounting	295 295 296 297 297 297 297 298 299 301 301 302 306
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radion Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi 15.5.1 15.5.2 15.5.3 15.5.4	ction • Data uclide Standards ining Confidence in the eent Setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum (s) Test spectra Computer-generated test spectra Test spectra created by counting Assessing	295 295 296 297 297 297 298 299 301 301 302 306
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radion Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi 15.5.1 15.5.2 15.5.3 15.5.4	ction Data uclide Standards ining Confidence in the ent Setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum S Test spectra Computer-generated test spectra Test spectra created by counting Assessing spectrum analysis	295 295 296 297 297 297 297 298 299 301 301 302 306
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radion Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi 15.5.1 15.5.2 15.5.3 15.5.4	ction Data uclide Standards ining Confidence in the ining Confidence in the ining Confidence in the setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum is Test spectra Computer-generated test spectra Test spectra created by counting Assessing spectrum analysis performance	295 295 296 297 297 297 297 298 299 301 301 302 306
	Spect 15.1 15.2 15.3 15.4	rometry Introduc Nuclear Radion Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi 15.5.1 15.5.2 15.5.3 15.5.4	ction Data uclide Standards ining Confidence in the ining Confidence in the ining Confidence in the setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum is Test spectra Computer-generated test spectra Test spectra created by counting Assessing spectrum analysis performance Intercomparison exercises Assessment of	295 295 296 297 297 297 297 298 299 301 301 302 306 307 310
	Spect 15.1 15.2 15.3 15.4	Introduction Introduction Introduction Nuclear Radion Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi 15.5.1 15.5.2 15.5.3 15.5.4 15.5.5 15.5.6	ction Data uclide Standards ning Confidence in the nent Setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum s Test spectra Computer-generated test spectra Test spectra created by counting Assessing spectrum analysis performance Intercomparison exercises Assessment of intercomparison exercises	295 295 296 297 297 297 298 299 301 301 302 306 307 310
	Spect 15.1 15.2 15.3 15.4	Introduction In	ction Data uclide Standards ining Confidence in the ining Confidence in the nent Setting up and maintenance procedures Control charts Setting up a control chart g Confidence in the Spectrum is Test spectra Computer-generated test spectra Test spectra created by counting Assessing spectrum analysis performance Intercomparison exercises Assessment of intercomparison exercises	295 295 296 297 297 297 298 299 301 301 302 306 307 310
	Spect 15.1 15.2 15.3 15.4 15.5	Ining Qua rometry Introduc Nuclear Radion Maintai Equipm 15.4.1 15.4.2 15.4.3 Gaining Analysi 15.5.1 15.5.2 15.5.3 15.5.4 15.5.5 15.5.6 Maintai	ction Data uclide Standards ning Confidence in the ning Confidence in the nent Setting up and maintenance procedures Control charts Setting up a control chart Confidence in the Spectrum S Test spectra Computer-generated test spectra Test spectra created by counting Assessing spectrum analysis performance Intercomparison exercises Assessment of intercomparison exercises ning Records tratice	295 295 296 297 297 297 297 298 299 301 301 302 306 307 310 311 311

Practical Points	313
Further Reading	313
Internet Sources of Information	314

16	Gam	ma Spect	trometry of Naturally	
	Occu	irring Radioactive Materials		
	(NOF	(M)		315
	16.1	Introduc	ction	315
	16.2	The NO	ORM Decay Series	315
		16.2.1	The uranium series $-\frac{238}{202}$	316
		16.2.2	The actinium series $-\frac{235}{10}$ U	316
		16.2.3	The thorium series $-$ ²³² Th	317
		16.2.4	Radon loss	317
		16.2.5	Natural disturbance of the	
		~	decay series	318
	16.3	Gamma	Spectrometry of the NORM	
		Nuclide	S	318
		16.3.1	Measurement of ⁷ Be	318
		16.3.2	Measurement of ⁴⁰ K	318
		16.3.3	Gamma spectrometry of	
			the uranium/thorium series	
			nuclides	318
		16.3.4	Allowance for natural	
			background	319
		16.3.5	Resolution of the 186 keV	
			peak	319
		16.3.6	Other spectral	
			interferences and summing	322
	16.4	Nuclear	Data of the NORM Nuclides	324
	16.5	Measure	asurement of Chemically dified NORM	
		Modifie		
		16.5.1	Measurement of separated	
		101011	uranium	325
		1652	Measurement of separated	525
		10.5.2	thorium	325
		1653	'Non-natural' thorium	326
		16.5.7	Measurement of gypsum	520
		10.5.4	a cautionary tale	327
		1655	Concrol observations	220
	Enath	10.J.J m Daadim		220
	Furino	er Readin	g	328
17	Appli	cations		329
	17.1	Gamma	Spectrometry and the CTBT	329
		17.1.1	Background	329
		17.1.2	The global verification	
			regime	329
		17.1.3	Nuclides released in a	

17.1.5	ruendes released in a	
	nuclear explosion	330
17.1.4	Measuring the	
	radionuclides	331
17.1.5	Current status	332

17.2	Gamma Spectrometry of Nuclear	
	Industry Wastes	333
	17.2.1 Measurement of	
	isotopically modified	222
	uranium	333
	transuranic nuclides	222
	17.2.3 Waste drum scanning	337
173	Safeguards	335
17.5	17.3.1 Enrichment meters	336
	17.3.2 Plutonium spectra	336
	17.3.3 Fresh and aged samples	338
	17.3.4 Absorption of gamma-rays	338
	17.3.5 Hand-held monitors	338
17.4	PINS – Portable Isotopic Neutron	
	Spectrometry	340
Furth	er Reading	340
Annondiv	A · Sources of Information	3/13
A 1	Introduction	343
A.2	Nuclear Data	343
	A.2.1 Recent developments in	
	the distribution of nuclear	
	data	344
	A.2.2 On line internet sources of	
	gamma-ray emission data	345
	A.2.3 Off-line sources of	
	gamma-ray emission data	346
	A.2.4 Nuclear data in print	346
A.3	Internet Sources of Other Nuclear	
	Data	347
A.4	Chemical Information	34/
A.5	Other Publications in print	348 249
A.0	Other Publications in print	548
Appendix	B: Gamma- and X-Ray Standards	
	for Detector Calibration	351
Annendix	C. X-Rays Routinely Found in	
rppenum	Gamma Spectra	359
	-	
Appendix	D: Gamma-Ray Energies in the	
	Detector Background and the	2(1
	Environment	301
Appendix	E: Chemical Names, Symbols and	
	Relative Atomic Masses of the	
	Elements	365
Glossarv		369
Indox		201
inuex		301

Preface to the Second Edition

During 2005, while this second edition was being prepared, I was totally unprepared to receive a telephone call that my co-author on the first edition, John Hemingway, was seriously ill after suffering a brainhaemorrhage. Only a few days later, on 5th September, he passed away. My original, and obvious, intent was to update the sections allocated to John and myself and publish this second edition as 'Gilmore and Hemingway'. That intent was frustrated by contractual difficulties with John's estate. It became necessary for me to rewrite those sections completely and remove John's name from the second edition. I deeply regret that that was necessary. It has deprived us all of John's often elegant prose and has meant that some topics that John had particular interest in introducing to the new edition have had to be omitted.

Earlier in that year, another reminder of the inexorable passage of time came with the death of someone whose name had been familiar to me throughout my career in gamma spectrometry. On 16th January, Richard Helmer passed away at the age of 70 years. His co-authored work, the justly famous *Gamma and X-Ray Spectrometry with Semiconductor Detectors*, was one of the books that introduced John and myself to the complexities of gamma spectrometry and one which we consistently recommended to others. His influence as an author and in many other roles, such as an evaluator of nuclear data, has left all of us in his debt, whether we all realize it or not.

On a lighter note, during the year 2005 the very title of this book was called into question. The radiochemical mailing list, RADCH-L, agonized, in general terms, over which is the correct term – 'spectrometry' or 'spectroscopy'. Of course, the suffix '-metry' means to measure and '-scopy' means to visualize – and so the discussion went on, to and fro. Eventually, the 1997 IUPAC 'Golden Book', *Compendium of Chemical Terminology*, was quoted: 'SPECTROMETRY is the measurement of such [electromagnetic] radiations as a means of obtaining information about the system and their components'. That seemed to be the 'clincher'. The prime objective of our activities is to measure gamma radiation, not just to create a spectrum, and so spectrometry' it is, performed by 'gamma spectrometrists'!

Before a second edition is approved, the publishers canvass the opinion of people in the field as to whether a new edition is justified and ask them for suggestions for inclusion. I have taken all of the suggestions offered seriously but, in the event, have had to disappoint some of the reviewers. For example, X-ray spectrometry is such a wide field with a different emphasis to gamma spectrometry and the space available within this new edition so limited, that merely exposing a little more of the 'iceberg' seemed pointless. In other cases, my ignorance of certain specific matters was sufficient to preclude inclusion. I can only offer my apologies to those who may feel let down.

Since the first edition (1995), there have been a number of significant advances in gamma spectrometry. Indeed, some of those advances were taking place while I was writing, meaning re-writes even to the update! In particular, I have included digital pulse processing and I have explained the changes in the way that nuclear data are being kept up to date. On statistics, I have introduced the matter of uncertainty budgets as being of increasing importance now that more laboratories seek accreditation. I have had to re-assess the ideas I espoused in the first edition on peak width and now have a much more comfortable mathematical justification for fitting peakwidth calibrations.

Throughout, I have tried to keep to the principles John and I declared in the Preface to the first edition – an emphasis on the practical application of gamma spectrometry at the expense of, if possible, the mathematics. That being the case, I have reproduced most of the Preface to the first edition below. The first edition was very well received. I can only hope that I have done enough to ensure that popular opinion is as supportive of this second edition.

Preface to the First Edition

This book was conceived during one of the Gamma Spectrometry courses then being run at the Universities' Research Reactor at Risley. At that time, we had been 'peddling' our home-spun wisdom for seven or eight years, and transforming the lecture notes into something more substantial for the benefit of course participants seemed an obvious development.

Our intention is to provide more of a workshop manual than an academic treatise. In this spirit, each chapter ends with a 'Practical Points' section. This is not a summary as such but a reminder of the more important practical features discussed within the chapter. We have attempted, not always successfully, it must be admitted, to keep the mathematics to a minimum. In most cases, equations are presented as *faites accomplis* and are not derived.

One practical process that can have a major influence on the reliability of the results obtained by users of gammaspectrometric equipment is that of *sampling*. It was after much discussion and with some regret that we decided to omit this topic. This is because it is peripheral to our main concern of describing the best use of instrumentation, because we suspect that another book would be necessary to do justice to the subject, and because we do not know much about it. What is clear is that an analyst must be aware that uncertainties introduced by taking disparate samples from an inhomogeneous mass can far outweigh uncertainties in the individual measurements themselves. This is a particular problem when sampling such a diverse and complex mass as the natural environment.

No previous knowledge of nuclear matters or instrumentation is assumed, and we hope the text can be used by complete beginners. There is even a list of names and symbols of the elements; while chemists may smile at this, in our experience not every otherwise scientifically literate person can name Sb and Sn, or distinguish Tb and Yb.

In a practical book, we think it useful to mention particular items of commercial equipment to illustrate particular points. We must make the usual disclaimer that these are not necessarily the best, nor the worst, and in most cases are certainly not the only items available. In general, the manufacturers do a fine job, and choosing one product rather than another is often an invidious task. We can only recommend that the user (1) decides at an early stage what capabilities are required, (2) reads and compares specifications (this text should explain these), (3) is not seduced by the latest 'whizz-bang device', yet (4) bears in mind that more recent products are better than older ones, not just in 'bald' specification but also in manufacturing technology, and should consequently show greater reliability.

Readers may notice the absence of certain terms in common use. The exclusion of some such terms is a deliberate choice. For example, instead of 'photopeak' we prefer 'full-energy peak'; we have avoided the statisticians' use of 'error' to mean uncertainty and reserve that word to indicate bias or error in the sense of 'mistake'. 'Branching ratio' we avoid altogether. This is often used ambiguously and without definition. In other texts, it may mean the relative proportions of different decay modes, or the proportions of different beta-particle transitions, or the ratio of 'de-excitation' routes from a nuclear-energy level. Furthermore, it sometimes appears as a synonym for 'gamma-ray emission probability', where it is not always clear whether or not internal conversion has been taken into account.

We hope sensitive readers are not upset by our use of the word 'program'. This 'Americanized' version is well on its way to being accepted as meaning specifically 'computer program', and enables a nice distinction to be made with the more general (and more elegant-looking) 'programme'.

We have raided unashamedly the manufacturers' literature for information, and our thanks are due particularly to Canberra and Ortec (in alphabetical order) for their cooperation and support in this. The book is not a survey of the latest research nor a historical study, and there are very few specific references in the text. Such that do exist are put at the end of each chapter, where there will also be found a more general short-list of 'Further Reading'. We also acknowledge our continuing debt to two books: *Radiation Detection and Measurement*, by G.F. Knoll, John Wiley & Sons, Ltd (1979, 1989) and *Gammaand X-ray Spectrometry with Semiconductor Detectors*, by K. Debertin and R.G. Helmer, North-Holland (1988). These can be thoroughly recommended. So why write another book? Fine as these works are, we felt that there was a place for a 'plain-man's' guide to gamma spectrometry, a book that would concentrate on day-to-day operations. In short, the sort of book that we wish had been available when we began work with this splendid technique.

Gordon R. Gilmore and John D. Hemingway

Internet Resources within the Book

Throughout this book, I list sources of information of value to gamma spectrometrists. The reality of life in 2007 is that, for very many people, the Internet is the first 'port-of-call' for information. Because of this, I have leaned heavily on Internet sources and quoted links to them as standard URLs – Uniform Resource Locators, i.e. Internet addresses, to suitable websites. URLs are usually not 'case-sensitive'. However, that depends on the type of server used to host the website. It is better to type the URL as given here, i.e. preserving upper/lower-case characters.

A word of caution is necessary. The Internet can be a source of the most up-to-date information and can be far more convenient than waiting for books and articles to be delivered, or a trip to a distant library. However, I feel duty bound to remind readers that, as well as holding the upto-date information, the Internet is also a vast repository of ancient, irrelevant, inaccurate and out-of date information. It is up to the user to check the pedigree, and date, of all downloaded material. I believe the links that I have quoted to be reliable. Because the Internet is essentially an ephemeral entity, reorganization of a website can result in URLs becoming inactive. Usually, however, the information will still be available on the 'parent site' somewhere, but will need looking for. As a convenience for readers of this book, I have created a website, *http://www.gammaspectrometry.co.uk*, hosted by Nuclear Training Services Ltd, which holds links to all of the URLs referred to throughout the book, organized by chapter. The site also carries a number of other resources that readers might find useful:

- All the links quoted in Appendix A Sources of information.
- The data reproduced in Appendices B-E.
- Some of the test spectra referred to in Chapter 15 and a test-spectrum generator.
- Spreadsheet tools to illustrate certain points in the text, including some used to generate figures within the text.
- A number of useful spectra to illustrate points in the text.
- Links to relevant organizations and manufacturers.
- A set of 'taster' modules from the *Online Gamma Spectrometry* course.

This website will also be used to 'post-up' corrections to the text, should any be needed, before they are able to appear in future reprints, which I hope will be useful. In due course, I also intend to create a 'blog' to allow reader feedback and discussion of issues raised.

Radioactive Decay and the Origin of Gamma and X-Radiation

1.1 INTRODUCTION

In this chapter I intend to show how a basic understanding of simple decay schemes, and of the role gamma radiation plays in these, can help in identifying radioactive nuclides and in correctly measuring quantities of such nuclides. In doing so, I need to introduce some elementary concepts of nuclear stability and radioactive decay. X-radiation can be detected by using the same or similar equipment and I will also discuss the origin of X-rays in decay processes and the light that this knowledge sheds on characterization procedures.

I will show how the Karlsruhe Chart of the Nuclides can be of help in predicting or confirming the identity of radionuclides, being useful both for the modest amount of nuclear data it contains and for the ease with which generic information as to the type of nuclide expected can be seen.

First, I will briefly look at the nucleus and nuclear stability. I will consider a nucleus simply as an assembly of uncharged neutrons and positively charged protons; both of these are called **nucleons**.

Number of neutrons = N

Number of protons = Z

Z is the **atomic number**, and defines the element. In the neutral atom, Z will also be the number of extranuclear electrons in their atomic orbitals. An element has a fixed Z, but in general will be a mixture of atoms with different masses, depending on how many neutrons are present in each nucleus. The total number of nucleons is called the **mass number**.

Mass number = N + Z = A

A, N and Z are all integers by definition. In practice, a neutron has a very similar mass to a proton and so there is a real physical justification for this usage. In general, an assembly of nucleons, with its associated electrons, should be referred to as a nuclide. Conventionally, a nuclide of atomic number Z, and mass number A is specified as ${}^{A}_{Z}Sy$, where Sy is the chemical symbol of the element. (This format could be said to allow the physics to be defined before the symbol and leave room for chemical information to follow; for example, Co^{2+} .) Thus, ${}^{58}_{27}Co$ is a nuclide with 27 protons and 31 neutrons. Because the chemical symbol uniquely identifies the element, unless there is a particular reason for including it, the atomic number as subscript is usually omitted – as in ⁵⁸Co. As it happens, this particular nuclide is radioactive and could, in order to impart that extra item of knowledge, be referred to as a radionuclide. Unfortunately, in the world outside of physics and radiochemistry, the word isotope has become synonymous with radionuclide - something dangerous and unpleasant. In fact, isotopes are simply atoms of the same element (i.e. same Z, different N) – radioactive or not. Thus ${}^{58}_{27}$ Co, ${}^{59}_{27}$ Co and ${}^{60}_{27}$ Co are isotopes of cobalt. Here 27 is the atomic number, and 58, 59 and 60 are mass numbers, equal to the total number of nucleons. ⁵⁹Co is stable; it is, in fact, the only stable isotope of cobalt.

Returning to nomenclature, ⁵⁸Co and ⁶⁰Co are **radioisotopes**, as they are unstable and undergo radioactive decay. It would be incorrect to say 'the radioisotopes ⁶⁰Co and ²³⁹Pu...' as two different elements are being discussed; the correct expression would be 'the radionuclides ⁶⁰Co and ²³⁹Pu...'.

If all stable nuclides are plotted as a function of Z (y-axis) and N (x-axis), then Figure 1.1 will result. This is a Segrè chart.



Figure 1.1 A Segrè chart. The symbols mark all known stable nuclides as a function of *Z* and *N*. At high *Z*, the long half-life Th and U nuclides are shown. The outer envelope encloses known radioactive species. The star marks the position of the largest nuclide known to date, ${}^{277}112$, although its existence is still waiting official acceptance

The **Karlsruhe Chart of the Nuclides** has this same basic structure but with the addition of all known radioactive nuclides. The heaviest stable element is bismuth (Z = 83, N = 126). The figure also shows the location of some high Z unstable nuclides – the major thorium (Z = 90) and uranium (Z = 92) nuclides. Theory has predicted that there could be stable nuclides, as yet unknown, called *superheavy nuclides* on an **island of stability** at about Z = 114, N = 184, well above the current known range.

Radioactive decay is a spontaneous change within the nucleus of an atom which results in the emission of particles or electromagnetic radiation. The modes of radioactive decay are principally alpha and beta decay, with spontaneous fission as one of a small number of rarer processes. Radioactive decay is driven by mass change – the mass of the product or products is smaller than the mass of the original nuclide. Decay is always exoergic; the small mass change appearing as energy in an amount determined by the equation introduced by Einstein:

$$\Delta E = \Delta m \times c^2$$

where the energy difference is in joules, the mass in kilograms and the speed of light in $m s^{-1}$. On the website relating to this book, there is a spreadsheet to allow the reader to calculate the mass/energy differences available for different modes of decay. The units of energy we use in gamma spectrometry are electron-volts (eV), where $1 \text{ eV} = 1.602 \text{ } 177 \times 10^{-19} \text{ J.}^1$ Hence, $1 \text{ eV} \equiv 1.782 663 \times 10^{-36} \text{ kg}$ or $1.073 533 \times 10^{-9} \text{ u}$ ('u' is the unit of atomic mass, defined as 1/12th of the mass of ¹²C). Energies in the gamma radiation range are conveniently in keV.

Gamma-ray emission is not, strictly speaking a decay process; it is a de-excitation of the nucleus. I will now explain each of these decay modes and will show, in particular, how gamma emission frequently appears as a by-product of alpha or beta decay, being one way in which residual excitation energy is dissipated

1.2 BETA DECAY

Figure 1.2 shows a three-dimensional version of the lowmass end of the Segrè chart with energy/mass plotted on the third axis, shown vertically here. We can think of the stable nuclides as occupying the bottom of a nuclearstability valley that runs from hydrogen to bismuth. The stability can be explained in terms of particular relationships between Z and N. Nuclides outside this valley bottom are unstable and can be imagined as sitting on the sides of the valley at heights that reflect their relative nuclear masses or energies.

The dominant form of radioactive decay is movement down the hillside directly to the valley bottom. This is



Figure 1.2 The beta stability valley at low *Z*. Adapted from a figure published by *New Scientist*, and reproduced with permission

¹ Values given are rounded from those recommended by the UK National Physical Laboratory in *Fundamental Physical Constants and Energy Conversion Factors* (1991).

beta decay. It corresponds to transitions along an **isobar** or line of constant *A*. What is happening is that neutrons are changing to protons (β^- decay), or, on the opposite side of the valley, protons are changing to neutrons (β^+ decay or electron capture). Figure 1.3 is part of the (Karlsruhe) Nuclide Chart.



Figure 1.3 Part of the Chart of the Nuclides. Heavy boxes indicate the stable nuclides



Figure 1.4 The energy parabola for the isobar A = 61. ⁶¹Ni is stable, while other nuclides are beta-active (EC, electron capture)

If we consider the isobar A = 61, ⁶¹Ni is stable, and beta decay can take place along a diagonal (in this format) from either side. ⁶¹Ni has the smallest mass in this sequence and the driving force is the mass difference; this appears as energy released. These energies are shown in Figure 1.4. There are theoretical grounds, based on the liquid drop model of the nucleus, for thinking that these points fall on a parabola.

1.2.1 β^- or negatron decay

The decay of ⁶⁰Co is an example of β^- or **negatron** decay (negatron = negatively charged beta particle). All nuclides unstable to β^- decay are on the neutron rich side of stability. (On the Karlsruhe chart, these are coloured blue.) The decay process addresses that instability. An example of β^- decay is:

$$^{60}Co \longrightarrow ^{60}Ni + \beta^- + \bar{\nu}$$

A **beta particle**, β^- , is an electron; in all respects it is identical to any other electron. Following on from Section 1.1, the sum of the masses of the ⁶⁰Ni plus the mass of the β^- , and $\bar{\nu}$, the anti-neutrino, are less than the mass of ⁶⁰Co. That mass difference drives the decay and appears as energy of the decay products. What happens during the decay process is that a neutron is converted to a proton within the nucleus. In that way the atomic number increases by one and the nuclide drops down the side of the valley to a more stable condition. A fact not often realized is that the neutron itself is radioactive when it is not bound within a nucleus. A free neutron has a half-life of only 10.2 min and decays by beta emission:

$$n \longrightarrow p^+ + \beta^- + \bar{\nu}$$

That process is essentially the conversion process happening within the nucleus.

The decay energy is shared between the particles in inverse ratio to their masses in order to conserve momentum. The mass of ⁶⁰Ni is very large compared to the mass of the beta particle and neutrino and, from a gamma spectrometry perspective, takes a very small, insignificant portion of the decay energy. The beta particle and the anti-neutrino share almost the whole of the decay energy in variable proportions; each takes from zero to 100% in a statistically determined fashion. For that reason, beta particles are not mono-energetic, as one might expect from the decay scheme, and their energy is usually specified as $E_{\beta max}$. The term 'beta particle' is reserved for an electron that has been emitted during a nuclear decay process. This distinguishes it from electrons emitted as a result of other processes, which will usually have defined energies. The anti-neutrino need not concern us as it is detectable only in elaborate experiments. Anti-neutrinos (and neutrinos from β^+ decay) are theoretically crucial in maintaining the universality of the conservation laws of energy and angular momentum.

The lowest energy state of each nuclide is called the **ground state**, and it would be unusual for a transition to be made directly from one ground state to the next – unusual, but unfortunately far from unknown. There are a number of technologically important pure beta emitters, which are either widely used as radioactive tracers (3 H, 14 C, 35 S) or have significant yields in fission (90 Sr/ 90 Y, 99 Tc, 147 Pm). Table 1.1 lists the most common.

 Table 1.1
 Some pure beta emitters^a

Nuclide	Half-life ^{bc}	Maximum beta energy (keV)
³ H	12.312 (25) year	19
¹⁴ C	5700 (30) year	156
^{32}P	14.284 (36) d	1711
³⁵ S	87.32 (16) d	167
³⁶ Cl	$3.01(2) \times 10^5$ year	1142
⁴⁵ Ca	162.6 1(9) d ^b	257
⁶³ Ni	98.7 (24) year	66
⁹⁰ Sr	28.80 (7) year	546
⁹⁰ Y	2.6684 (13) d	2282
⁹⁹ Tc	2.111 (12) $\times 10^5$ year ^b	294
¹⁴⁷ Pm	2.6234 (2) year ^{b}	225
²⁰⁴ Tl	3.788 (15) year	763

^a Data taken from DDEP (1986), with the exception of

^b-latter taken from *Table of Isotopes* (1978, 1998).

 c Figures in parentheses represent the 1 σ uncertainties on the last digit or digits.

The decay scheme of these will be of the form shown in Figure 1.5.

The difficulty for gamma spectrometrists is that no gamma radiation is emitted by these radionuclides and thus they cannot be measured by the techniques described in this text. To determine pure beta emitters in a mixture of radionuclides, a degree of chemical separation is required, followed by measurement of the beta radiation, perhaps by liquid scintillation or by using a gas-filled detector.

However, many beta transitions do not go to the ground state of the daughter nucleus, but to an excited state. This behaviour can be seen superimposed on the isobaric energy parabola in Figure 1.6. Excited states are shown



Figure 1.5 The decay scheme of a pure beta emitter, ³²P

for both radioactive (Ag, Cd, In, Sb, Te) and stable (Sn) isobaric nuclides, and it should be noted that these states are approached through the preceding or parent nuclide.



Figure 1.6 The isobar A = 117 with individual decay schemes superimposed. ¹¹⁷Sn is stable

The **decay scheme** for a single beta-emitting radionuclide is part of this energy parabola with just the two components of parent and daughter. Figure 1.7 shows the simple case of 137 Cs. Here, some beta decays (6.5% of the total) go directly to the ground state of 137 Ba; most (93.5%) go to an excited nuclear state of 137 Ba.

The gamma radiation is released as that excited state de-excites and drops to the ground state. Note that the energy released, 661.7 keV, is actually a property of ¹³⁷Ba, but is accessed from ¹³⁷Cs. It is conventionally regarded as 'the ¹³⁷Cs gamma', and is listed in data tables as such.



Figure 1.7 The decay scheme of ¹³⁷Cs

However, when looking for data about **energy levels** in the nucleus, as opposed to gamma-ray energies, it would be necessary to look under the daughter, ¹³⁷Ba.

In this particular case, 661.7 keV is the *only* gamma in the decay process. More commonly, many gamma transitions are involved. This is seen in Figure 1.6 and also in Figure 1.8, where the great majority of beta decays (those labelled β_1) go to the 2505.7 keV level which falls to the ground state in two steps. Thus, two gamma-rays appear with their energies being the difference between the energies of the upper and lower levels:

$$\gamma_1 = (2505.7 - 1332.5) = 1173.2 \text{ keV}$$

 $\gamma_2 = (1332.5 - 0) = 1332.5 \text{ keV}$



Figure 1.8 The decay scheme of ⁶⁰Co

The two gammas are said to be **in cascade**, and if they appear at essentially the same time, that is, if the intermediate level (in ⁶⁰Ni at 1332.5 keV) does not delay emission of the second gamma, then they are also said to be **coincident**. This phenomenon of two gamma-rays appearing

from the same atom at the same instant can have a significant influence on counting efficiency, as will be discussed in Chapter 8.

1.2.2 β^+ or positron decay

Just as β^- active nuclides are neutron rich, nuclides unstable to β^+ decay are neutron deficient. (The red nuclides on the Karlsruhe chart.) The purpose of positron decay, again driven by mass difference, is to convert a proton into a neutron. Again, the effect is to slide down the energy parabola in Figure 1.4, this time on the neutrondeficient side, towards stability, resulting in an atom of a lower atomic number than the parent. An example is:

$$^{64}_{29}$$
Cu $\longrightarrow ^{64}_{28}$ Ni + β^+ + ν (neutrino)

During this decay a positron, a positively charged electron (anti-electron), is emitted, and conservation issues are met by the appearance of a neutrino. This process is analogous to the reverse of beta decay of the neutron. However, such a reaction would require the presence of an electron to combine with an excess proton. Electrons are not found within the nucleus and one must be created by the process known as **pair production**, in which some of the decay energy is used to create an electron/positron pair - imagine decay energy condensing into two particles. The electron combines with the proton and the positron is emitted from the nucleus. Positron emission is only possible if there is a sufficiently large energy difference, that is, mass difference, between the consecutive isobaric nuclides. The critical value is 1022 keV, which is the combined rest mass of an electron plus positron. As with negatrons, there is a continuous energy spectrum ranging up to a maximum value, and emission of complementary neutrinos.

The positron has a short life; it is rapidly slowed in matter until it reaches a very low, close to zero, kinetic energy. Positrons are anti-particles to electrons, and the slowed positron will inevitably find itself near an electron. The couple may exist for a short time as positro**nium** – then the process of **annihilation** occurs. Both the positron and electron disappear and two photons are produced, each with energy equal to the electron mass, 511.00 keV (Figure 1.9). These photons are called annihilation radiation and the annihilation peak is a common feature in gamma spectra, which is much enhanced when β^+ nuclides are present. To conserve momentum, the two 511 keV photons will be emitted in exactly opposite directions. I will mention here, and treat the implications more fully later, that the annihilation peak in the spectrum will be considerably broader than a peak



Figure 1.9 The annihilation process, showing how the resultant 511 keV photons could have a small energy shift: (a) possible momenta before interaction giving (b) differing photon energies after interaction

produced by a direct nuclear-generated gamma-ray of the same energy. This can help in distinguishing between the two. The reason for such broadening is due to a Doppler effect. At the point where the positron–electron interaction takes place, neither positron nor electron is likely to be at complete rest; the positron may have a small fraction of its initial kinetic energy, the electron – if we regard it as a particle circling the nucleus – because of its orbital momentum. Thus, there may well be a resultant net momentum of the particles at the moment of interaction, so that the conservation laws mean that one 511 keV photon will be slightly larger in energy and the other slightly smaller. This increases the statistical uncertainty and widens the peak. Note that the sum of the two will still be (in a centre of mass system) precisely 1022.00 keV.

1.2.3 Electron capture (EC)

As described above, β^+ can only occur if more than 1022 keV of decay energy is available. For neutron deficient nuclides close to stability where that energy is not available, an alternative means of decay is available. In this, the electron needed to convert the proton is captured by the nucleus from one of the extranuclear electron shells. The process is known as **electron capture** decay. As the K shell is closest to the nucleus (the wave functions of the nucleus and K shell have a greater degree of overlap than with more distant shells), then the capture of a K electron is most likely and indeed sometimes the process is called **K-capture**. The probability of capture from the less strongly bound higher shells (L, M, etc.) increases as the decay energy decreases.

Loss of an electron from the K shell leaves a vacancy there (Figure 1.10). This is filled by an electron dropping in from a higher, less tightly bound, shell. The energy released in this process often appears as an X-ray, in what is referred to as **fluorescence**. One X-ray may well be followed by others (of lower energy) as electrons cascade down from shell to shell towards greater stability.



Figure 1.10 (a) Electron capture from the K shell, followed by (b) electron movement (X-ray emission) from L to K, and then M to L, resulting in X-radiations

Sometimes, the energy released in rearranging the electron structure does not appear as an X-ray. Instead, it is used to free an electron from the atom as a whole. This is the Auger effect, emitting Auger electrons. The probability of this alternative varies with Z: at higher Z there will be more X-rays and fewer Auger electrons; it is said that the fluorescence yield is greater. Auger electrons are mono-energetic, and are usually of low energy, being emitted from an atomic orbital (L or M) where the electron binding energies are smaller. There is a small probability of both Auger electrons and X-rays being emitted together in one decay; this is the radiative Auger effect. Note that whenever X-rays are emitted, they will be characteristic of the daughter, rather than the parent, as the rearrangement of the electron shells is occurring after the electron capture.

For neutron deficient nuclides with a potential decay energy somewhat above the 1022 keV threshold, both positron decay and electron capture decay will occur, in a proportion statistically determined by the different decay energies of the two processes. Figure 1.11 shows the major components of the decay scheme of ²²Na, where both



Figure 1.11 The decay scheme of $^{22}Na.$ Note the representation of positron emission, where 1022 keV is lost before emission of the β^+

positron decay and electron capture are involved. We can deduce from this that the spectrum will show a gamma-ray at 1274.5 keV, an annihilation peak at 511.0 keV (from the β^+), and probably X-rays due to electron rearrangement after the EC.

1.2.4 Multiple stable isotopes

In Figures 1.4 and 1.6, I suggested that the ground states of the nuclides of isobaric chains lay on a parabola, and the decay involved moving down the sides of the parabola to the stable point at the bottom. The implication must be that there is only one stable nuclide per isobaric chain. Examination of the Karlsruhe chart shows quite clearly that this is not true - there are many instances of two, or even three, stable nuclides on some isobars. More careful examination reveals that what is true is that every oddisobar only has one stable nuclide. It is the even numbered isobars that are the problem. If a parabola can only have one bottom, the implication is that for even-isobars there must be more than one stability parabola. Indeed that is so. In fact, there are two parabolas; one corresponding to even-Z/even-N (even-even) and the other to odd-Z/odd-N (odd-odd). Figure 1.12 shows this. The difference arises because pairing of nucleons give a small increase in stability - a lowering of energy. In even-even nuclides there are more paired nucleons than in odd-odd nuclides and so the even-even parabola is lower in energy. As shown in Figure 1.12 for the A = 128 isobaric chain, successive decays make the nucleus jump from odd-odd to even-even and back. There will be occasions, as here,



Figure 1.12 The two energy parabolas for the isobar A = 128. ¹²⁸Te and ¹²⁸Xe are stable

where a nucleus finds itself above the ultimate lowest point of the even–even parabola, but below the neighbouring odd–odd points. It will, therefore be stable. (It is the theoretical possibility that a nuclide such as ¹²⁸Te could decay to ¹²⁸Xe, which fuels the search for double beta decay, which I will refer to from time to time.) In all, depending upon the particular energy levels of neighbouring isobaric nuclides, there could be up to three stable nuclides per even-*A* isobaric chain.

In the case of A = 128, there are two stable nuclides, ¹²⁸Te and ¹²⁸Xe. ¹²⁸I has a choice of destination, and 93.1% decays by β^- to ¹²⁸Xe and 6.98% decays by EC to ¹²⁸Te. The dominance of the ¹²⁸Xe transition reflects the greater energy release, as indicated in Figure 1.12. This behaviour is quite common for even mass parabolas and this choice of decay mode is available for such wellknown nuclides as ⁴⁰K and ¹⁵²Eu. Occasionally, if the decay energy for β^+ is sufficient, a nuclide will decay sometimes by β^- and sometimes by EC and β^+ .

1.3 ALPHA DECAY

An alpha particle is an He-4 nucleus, ${}_{2}^{4}$ He⁺, and the emission of this particle is commonly the preferred mode of decay at high atomic numbers, Z > 83. In losing an alpha particle, the nucleus loses four units of mass and two units of charge:

$$Z \longrightarrow Z - 2$$
$$A \longrightarrow A - 4$$

Typical is the decay of the most common isotope of radium:

$$^{226}_{88}$$
Ra $\longrightarrow ^{222}_{86}$ Rn $+ ^{4}_{2}$ He $+ Q$

The product in this case is the most common isotope of radon, 222 Rn (usually just called 'radon' and which incidentally is responsible for the largest radiation dose from a single nuclide to the general population). A fixed quantity of energy, Q, equal to the difference in mass between the initial nuclide and final products, is released. This energy must be shared between the Rn and the He in a definite ratio because of the conservation of momentum. Thus, the alpha-particle is mono-energetic and alpha spectrometry becomes possible. In contrast to beta decay, there are no neutrinos to take away a variable fraction of the energy.

In many cases, especially in the lower Z range of α decay, the emission of an alpha particle takes the nucleus directly to the ground state of the daughter, analogous to the 'pure- β ' emission described above. However, with

heavier nuclei, α decay can lead to excited states of the daughter. Figure 1.13, the decay scheme of ²²⁸Th, shows gamma emission following alpha decay, but even here it will be seen that most alpha transitions go directly to the ²²⁴Ra ground state.



Figure 1.13 The decay scheme of ²²⁸Th

Calculation of the alpha decay energy reveals that even nuclides, such as 152 Eu and the stable 151 Eu, are unstable towards alpha decay. Alpha decay of 151 Eu would release 1.96 MeV of energy. The reason that this, and most other nuclides, do not decay by alpha emission is the presence of an energy barrier – it takes energy to prise an alpha particle out of the nucleus. Unless the nucleus is excited enough or is large enough so that the decay energy is greater than the energy barrier, it will be stable to alpha emission. That does not preclude it from being unstable to beta decay; 151 Eu is stable, 152 Eu is radioactive.

1.4 SPONTANEOUS FISSION (SF)

Spontaneous fission is a natural decay process in which a heavy nucleus spontaneously splits into two large fragments. An example is:

$$^{252}_{98}$$
Cf $\longrightarrow ^{140}_{54}$ Xe $+ ^{108}_{44}$ Ru $+ ^{1}_{0}$ n $+ Q$

The two product nuclides are only examples of what is produced; these are fission fragments or (when in their ground states) fission products. The range of products, the energies involved (Q) and the number and energies of neutrons emitted are all similar to those produced in more familiar neutron-induced fission of fissile or fissionable nuclides. ²⁵²Cf is mentioned here as it is a commercially available nuclide, which is bought either as a source of fission fragments or as a source of neutrons.

Once more, the driving force for the process is the release of energy. Q is of the order of 200 MeV, a large quantity, indicating that the fission products have a substantially smaller joint mass than the fissioning nucleus. This is because the binding energy per nucleon is significantly greater for nuclides in the middle of the Periodic Table than at the extremes. ¹⁰⁸Ru, for example, has a binding energy of about 8.55 MeV per nucleon, while the corresponding figure for ²⁵²Cf is about 7.45 MeV per nucleon. Despite the emission of neutrons in this process. fission products are overwhelmingly likely to find themselves on the neutron rich, β -active side of the nuclear stability line. They will then undergo β^- decay along an isobar, as, for example, along the left-hand side of Figure 1.12, until a stable nucleus is reached. During this sequence, gamma emission is almost always involved, as described earlier. The distribution of fission product masses will be discussed in Section 1.9.

As with alpha decay, calculation of mass differences for notional fission outcomes suggest that even mid-range nuclides, in terms of mass, would be unstable to fission. Fission is prevented in all but very large nuclei by the **fission barrier** – the energy needed to deform the nucleus from a sphere to a situation where two nearly spherical fission product nuclei can split off.

1.5 MINOR DECAY MODES

A number of uncommon decay modes exist which are of little direct relevance to gamma spectrometrists and I will content myself with just listing them: delayed neutron emission, delayed proton emission, double beta decay (the simultaneous emission of two β^- particles), two proton decay and the emission of 'heavy ions' or 'clusters', such as ¹⁴C and ²⁴Ne. Some detail can be found in the more recent general texts in the Further Reading section, such as the one by Ehmann and Vance (1991).

1.6 GAMMA EMISSION

This is not a form of decay like alpha, beta or spontaneous fission, in that there is no change in the number or type of nucleons in the nucleus; there is no change in Z, N or A. The process is solely that of losing surplus excitation energy, and as I have shown is usually a by-product of alpha or beta decay. First – what is a gamma-ray?