



# Contents

Preface to the First Edition .....	xix
Preface to the Second Edition .....	xxiii
Preface to the Third Edition .....	xxv
Preface to the Fourth Edition .....	xxvii
Authors .....	xxix
<b>Chapter 1.</b> Introduction to Radiation Measurements .....	1
1.1 What Is Meant by Radiation? .....	1
1.2 Statistical Nature of Radiation Emission .....	2
1.3 Errors and Accuracy and Precision of Measurements .....	2
1.4 Types of Errors .....	4
1.5 Nuclear Instrumentation .....	5
1.5.1 Introduction .....	5
1.5.2 Detector .....	6
1.5.3 Nuclear Instrument Module Concept .....	7
1.5.4 High-Voltage Power Supply .....	8
1.5.5 Preamplifier .....	9
1.5.6 Amplifier .....	10
1.5.7 Oscilloscope .....	11
1.5.8 Discriminator or Single-Channel Analyzer (SCA) .....	12
1.5.9 Scaler .....	13
1.5.10 Timer .....	13
1.5.11 Multichannel Analyzer .....	13
References .....	14
<b>Chapter 2.</b> Errors of Radiation Counting .....	15
2.1 Introduction .....	15
2.2 Definition of Probability .....	15
2.3 Basic Probability Theorems .....	17

2.4	Probability Distributions and Random Variables	20
2.5	Location Indexes (Mode, Median, Mean)	22
2.6	Dispersion Indexes, Variance, and Standard Deviation	25
2.7	Covariance and Correlation	26
2.8	Binomial Distribution	28
2.9	Poisson Distribution	30
2.10	Normal (Gaussian) Distribution	33
2.10.1	Standard Normal Distribution	34
2.10.2	Importance of the Gaussian Distribution for Radiation Measurements	36
2.11	Lorentzian Distribution	38
2.12	Standard, Probable, and Other Errors	38
2.13	Arithmetic Mean and Its Standard Error	40
2.14	Confidence Limits	42
2.15	Propagation of Errors	44
2.15.1	The Average and Its Standard Deviation for Quantities with More than One Random Variable	44
2.15.2	Examples of Error Propagation—Uncorrelated Variables	46
2.16	Goodness of Data— $\chi^2$ Criterion—Rejection of Data	49
2.17	Statistical Error of Radiation Measurements	52
2.18	Standard Error of Counting Rates	54
2.18.1	Combining Counting Rates	57
2.19	Methods of Error Reduction	58
2.19.1	Background Is Constant and There Is No Time Limit for Its Measurement	58
2.19.2	There Is a Fixed Time $t$ Available for Counting Both Background and Gross Counts	59
2.19.3	Calculation of the Counting Time Necessary to Measure a Counting Rate with a Predetermined Statistical Error	60
2.19.4	Relative Importance of Error Components	61
2.20	Minimum Detectable Activity	61
2.21	Detector Dead-Time Correction and Measurement of Dead Time	63
2.22	Loss-Free Counting and Zero Dead Time	66
	Problems	67
	References	70
	Bibliography	70
<b>Chapter 3.</b>	<b>Review of Atomic and Nuclear Physics</b>	<b>71</b>
3.1	Introduction	71
3.2	Elements of Relativistic Kinematics	71
3.3	Atoms	76
3.4	Nuclei	77
3.5	Nuclear Binding Energy	79
3.6	Nuclear Energy Levels	83
3.7	Energetics of Nuclear Decays	85
3.7.1	Gamma Decay	85
3.7.2	Alpha Decay	88

3.7.3	Beta Decay	89
3.7.4	Particles, Antiparticles, and Electron–Positron Annihilation	93
3.7.5	Complex Decay Schemes	94
3.8	Radioactive Decay Law	94
3.9	Nuclear Reactions	98
3.9.1	General Remarks	98
3.9.2	Kinematics of Nuclear Reactions	100
3.9.3	Endothermic and Exothermic Reactions	102
3.10	Fission	104
	Problems	108
	References	110
	Bibliography	110
<b>Chapter 4.</b>	<b>Energy Loss and Penetration of Radiation through Matter</b>	<b>111</b>
4.1	Introduction	111
4.2	Mechanisms of Charged-Particle Energy Loss	112
4.2.1	Coulomb Interactions	112
4.2.2	Emission of Electromagnetic Radiation (Bremsstrahlung)	113
4.3	Stopping Power due to Ionization and Excitation	114
4.4	Energy Loss due to Bremsstrahlung Emission	118
4.5	Calculation of $dE/dx$ for a Compound or Mixture	120
4.6	Range of Charged Particles	122
4.6.1	Range of Heavy Charged Particles ( $p, d, t, \alpha; 1 \leq A \leq 4$ )	122
4.6.2	Range of Electrons and Positrons	127
4.6.3	Transmission of Beta Particles	131
4.6.4	Energy Loss after Traversing a Material of Thickness $t < R$	133
4.7	Stopping Power and Range of Heavy Ions ( $Z > 2, A > 4$ )	134
4.7.1	Introduction	134
4.7.2	$dE/dx$ Calculation	135
4.7.3	Range of Heavy Ions	138
4.8	Interactions of Photons with Matter	141
4.8.1	Photoelectric Effect	141
4.8.2	Compton Scattering or Compton Effect	142
4.8.3	Pair Production	145
4.8.4	Total Photon Attenuation Coefficient	146
4.8.5	Photon Energy Absorption Coefficient	149
4.8.6	Buildup Factors	150
4.9	Interactions of Neutrons with Matter	153
4.9.1	Types of Neutron Interactions	153
4.9.1.1	Scattering	153
4.9.1.2	Absorption	154
4.9.2	Neutron Reaction Cross Sections	154
4.9.3	Neutron Flux	158
4.9.4	Interaction Rates of Polyenergetic Neutrons	160
	Problems	161
	References	163
	Bibliography	164

<b>Chapter 5.</b>	Gas-Filled Detectors.....	165
5.1	Introduction .....	165
5.2	Relationship between High Voltage and Charge Collected.....	166
5.3	Various Types of Gas-Filled Detectors.....	168
5.4	Ionization Chambers.....	170
5.4.1	Pulse Formation in an Ionization Chamber.....	170
5.4.2	Current Ionization Chambers .....	173
5.5	Proportional Counters .....	175
5.5.1	Charge Multiplication in Proportional Counters .....	175
5.5.2	Pulse Shape of a Proportional Counter .....	178
5.5.3	Change of Counting Rate with High Voltage: The High-Voltage Plateau .....	179
5.6	Geiger-Müller Counters.....	182
5.6.1	Operation of a GM Counter and Quenching of the Discharge .....	182
5.6.2	Pulse Shape and Dead Time of a GM Counter .....	183
5.7	Gas-Flow Detectors.....	183
5.7.1	Long-Range Alpha Detector.....	186
5.7.2	Internal Gas Counting.....	187
5.8	Rate Meters .....	187
5.9	General Comments about Construction of Gas-Filled Detectors.....	189
5.9.1	Geometry.....	189
5.9.2	Gases and Pressures Used .....	190
5.9.3	Detector Window .....	190
5.10	Applications of Gas-Filled Detectors.....	190
	Problems.....	192
	References .....	192
	Bibliography.....	193
<b>Chapter 6.</b>	Scintillation Detectors .....	195
6.1	Introduction .....	195
6.2	Inorganic (Crystal) Scintillators .....	196
6.2.1	Mechanism of the Scintillation Process .....	196
6.2.2	Time Dependence of Photon Emission .....	198
6.2.3	Important Properties of Certain Inorganic Scintillators .....	200
6.2.3.1	Nal(Tl) .....	200
6.2.3.2	CsI(Tl) .....	200
6.2.3.3	CsI(Na) .....	200
6.2.3.4	CaF <sub>2</sub> (Eu) .....	200
6.2.3.5	LiI(Eu) .....	200
6.2.3.6	Other Inorganic Scintillators .....	201
6.2.4	Applications of Inorganic Scintillators.....	201
6.3	Organic Scintillators.....	201
6.3.1	Mechanism of the Scintillation Process .....	201
6.3.2	Organic Crystal Scintillators.....	202
6.3.3	Organic Liquid Scintillators .....	203

6.3.4	Plastic Scintillators.....	204
6.4	Gaseous Scintillators.....	204
6.5	Relationship between Pulse Height and Energy and Type of Incident Particle .....	205
6.5.1	Response of Inorganic Scintillators .....	205
6.5.1.1	Photons .....	205
6.5.1.2	Charged Particles.....	205
6.5.1.3	Neutrons .....	206
6.5.2	Response of Organic Scintillators.....	206
6.5.2.1	Charged Particles.....	206
6.5.2.2	Photons and Neutrons.....	206
6.6	The Photomultiplier Tube .....	207
6.6.1	General Description .....	207
6.6.2	Electron Multiplication in a Photomultiplier.....	209
6.7	Assembly of a Scintillation Detector and the Role of Light Pipes.....	210
6.8	Dead Time of Scintillation Detectors .....	211
6.9	Sources of Background in a Scintillation Detector .....	212
6.10	Phoswich Detector .....	212
	Problems.....	214
	References .....	214
	Bibliography.....	216
<b>Chapter 7.</b>	Semiconductor Detectors .....	217
7.1	Introduction .....	217
7.2	Electrical Classification of Solids.....	218
7.2.1	Electronic States in Solids: Fermi Distribution Function .....	218
7.2.2	Insulators .....	220
7.2.3	Conductors .....	220
7.3	Semiconductors.....	221
7.3.1	Change of the Energy Gap with Temperature.....	222
7.3.2	Conductivity of Semiconductors.....	222
7.3.3	Extrinsic and Intrinsic Semiconductors: Role of Impurities .....	225
7.4	The p-n Junction .....	227
7.4.1	Formation of a p-n Junction .....	227
7.4.2	The p-n Junction Operating as a Detector .....	229
7.5	Different Types of Semiconductor Detectors.....	230
7.5.1	Surface-Barrier Detectors.....	231
7.5.2	Diffused-Junction Detectors.....	232
7.5.3	Silicon Lithium-Drifted [Si(Li)] Detectors .....	232
7.5.4	Germanium Lithium-Drifted [Ge(Li)] Detectors.....	235
7.5.5	Germanium Detectors .....	236
7.5.6	CdTe, CdZnTe, and HgI <sub>2</sub> Detectors.....	237
7.6	Radiation Damage to Semiconductor Detectors .....	238
	Problems.....	240
	References .....	240
	Bibliography.....	242

<b>Chapter 8.</b>	Relative and Absolute Measurements.....	243
8.1	Introduction .....	243
8.2	Geometry Effects.....	245
8.2.1	Effect of the Medium between Source and Detector .....	245
8.2.2	Solid Angle: General Definition .....	245
8.2.3	Solid Angle for a Point Isotropic Source and a Detector with a Circular Aperture.....	247
8.2.4	Solid Angle for a Disk Source Parallel to a Detector with a Circular Aperture.....	249
8.2.5	Solid Angle for a Point Isotropic Source and a Detector with a Rectangular Aperture .....	250
8.2.6	Solid Angle for a Disk Source and a Detector with a Rectangular Aperture.....	251
8.2.7	Use of the Monte Carlo Method for the Calculation of the Solid Angle.....	252
8.3	Source Effects.....	253
8.3.1	Source Self-Absorption Factor ( $f_a$ ) .....	253
8.3.2	Source Backscattering Factor ( $f_b$ ) .....	255
8.4	Detector Effects .....	257
8.4.1	Scattering and Absorption due to the Window of the Detector .....	257
8.4.2	Detector Efficiency ( $\epsilon$ ).....	258
8.4.2.1	Effect of Density and Size of Detector Material .....	259
8.4.2.2	Effect of Type and Energy of Radiation .....	259
8.4.2.3	Effect of Electronics .....	259
8.4.3	Determination of Detector Efficiency.....	260
8.5	Relationship between Counting Rate and Source Strength.....	262
8.6	Reference Materials for Relative and Absolute Measurements .....	264
	Problems.....	265
	References .....	267
	Bibliography.....	267
<b>Chapter 9.</b>	Introduction to Spectroscopy.....	269
9.1	Introduction .....	269
9.2	Definition of Energy Spectra.....	269
9.3	Measurement of an Integral Spectrum with a Discriminator.....	271
9.4	Measurement of a Differential Spectrum with a Single-Channel Analyzer .....	272
9.5	Relationship between Pulse-Height Distribution and Energy Spectrum .....	272
9.6	Energy Resolution of a Detection System.....	273
9.6.1	Effect of Statistical Fluctuations: Fano Factor .....	274
9.6.2	Effect of Electronic Noise on Energy Resolution .....	275
9.6.3	Effect of Incomplete Charge Collection.....	276
9.6.4	Total Width $\Gamma$ .....	277
9.7	Determination of the Energy Resolution: The Response Function.....	277
9.8	Importance of Good Energy Resolution .....	278
9.9	Brief Description of a Multichannel Analyzer .....	278
9.10	Calibration of a Multichannel Analyzer .....	281

Problems.....	285
References .....	287

<b>Chapter 10.</b>	Electronics for Radiation Counting .....	289
10.1	Introduction .....	289
10.2	Resistance, Capacitance, Inductance, and Impedance .....	289
10.3	Differentiating Circuit .....	293
10.4	Integrating Circuit .....	294
10.5	Delay Lines .....	296
10.6	Pulse Shaping .....	297
10.7	Timing.....	298
10.7.1	Leading-Edge Timing Method.....	299
10.7.2	Zero-Crossing Timing Method.....	299
10.7.3	Constant-Fraction Timing Method .....	300
10.7.4	Applications of Novel Timing Methods .....	300
10.8	Coincidence–Anticoincidence Measurements .....	300
10.9	Pulse-Shape Discrimination (PSD).....	305
10.10	Preamplifiers.....	307
10.11	Amplifiers.....	308
10.12	Analog-to-Digital Converters (ADC) .....	310
10.13	Multiparameter Analyzers .....	312
10.14	High Count Rates.....	314
10.15	Digital Processing .....	314
10.16	Data Manipulation.....	314
10.17	International Atomic Energy Agency Nuclear Electronics Manuals .....	314
	Problems.....	316
	References .....	316
	Bibliography.....	318
<b>Chapter 11.</b>	Data Analysis Methods .....	319
11.1	Introduction .....	319
11.2	Curve Fitting .....	320
11.3	Interpolation Schemes.....	321
11.4	Least-Squares Fitting.....	324
11.4.1	Least-Squares Fit for a Straight Line.....	326
11.4.2	Least-Squares Fit for General Functions.....	327
11.5	Folding and Unfolding.....	329
11.5.1	Examples of Folding .....	331
11.5.2	General Method of Unfolding .....	334
11.5.3	An Iteration Method of Unfolding.....	336
11.5.4	Least-Squares Unfolding .....	337
11.6	Data Smoothing.....	339
11.7	Quality Assurance and Quality Control .....	341
	Problems.....	343
	References .....	344
	Bibliography.....	345

<b>Chapter 12. Photon (<math>\gamma</math>-Ray and X-Ray) Spectroscopy</b> .....	347
12.1 Introduction .....	347
12.2 Modes of Energy Deposition in the Detector .....	347
12.2.1 Energy Deposition by Photons with $E < 1.022$ MeV .....	348
12.2.2 Energy Deposition by Photons with $E > 1.022$ MeV .....	350
12.3 Efficiency of X-Ray and $\gamma$ -Ray Detectors: Definitions .....	353
12.4 Detection of Photons with NaI(Tl) Scintillation Detectors .....	355
12.4.1 Efficiency of NaI(Tl) Detectors .....	356
12.5 Detection of Gammas with Ge Detectors .....	358
12.5.1 Efficiency of Ge Detectors .....	359
12.5.2 Energy Resolution of Ge Detectors .....	366
12.5.3 Analysis of Ge Detector Energy Spectra .....	368
12.5.4 Timing Characteristics of the Pulse .....	372
12.6 Detection of X-Rays with a Si(Li) Detector .....	373
12.7 CdTe, CZT, HgI <sub>2</sub> , LaBr, and LaCl <sub>2</sub> Detectors as Gamma Spectrometers .....	375
Problems .....	378
References .....	379
Bibliography .....	380
<b>Chapter 13. Charged-Particle Spectroscopy</b> .....	381
13.1 Introduction .....	381
13.2 Energy Straggling .....	382
13.3 Electron Spectroscopy .....	386
13.3.1 Electron Backscattering .....	386
13.3.2 Energy Resolution and Response Function of Electron Detectors .....	388
13.3.3 Energy Calibration of Electron Spectrometers .....	389
13.4 Alpha, Proton, Deuteron, and Triton Spectroscopy .....	390
13.4.1 Energy Resolution and Response Function of Alpha Detectors .....	390
13.4.2 Energy Calibration .....	391
13.4.3 Source Preparation .....	391
13.5 Heavy-Ion ( $Z > 2$ ) Spectroscopy .....	391
13.5.1 Pulse Height Defect .....	392
13.5.2 Energy Calibration: The Schmitt Method .....	394
13.5.3 Calibration Sources .....	394
13.5.4 Fission Foil Preparation .....	396
13.6 Time-of-Flight Spectrometer .....	396
13.7 Detector Telescopes ( $E$ $dE/dx$ Detectors) .....	398
13.8 Position-Sensitive Detectors .....	399
13.8.1 Position-Sensitive Semiconductor Detectors .....	399
13.8.2 Multiwire Proportional Chambers .....	400
Problems .....	402
References .....	403
Bibliography .....	405
<b>Chapter 14. Neutron Detection and Spectroscopy</b> .....	407
14.1 Introduction .....	407

14.2 Neutron Detection by ( $n$ , Charged Particle) Reaction .....	408
14.2.1 BF <sub>3</sub> Detector .....	408
14.2.2 Boron-Lined Detectors .....	413
14.2.3 <sup>6</sup> Li Detectors .....	414
14.2.4 <sup>3</sup> He Detectors .....	415
14.3 Fission Chambers .....	416
14.4 Neutron Detection by Foil Activation .....	417
14.4.1 Basic Equations .....	417
14.4.2 Determination of the Neutron Flux by Counting the Foil Activity .....	420
14.5 Measurement of a Neutron Energy Spectrum by Proton Recoil .....	422
14.5.1 Differentiation Unfolding of Proton Recoil Spectra .....	424
14.5.2 Proportional Counters Used as Fast-Neutron Spectrometers .....	425
14.5.3 Organic Scintillators Used as Fast-Neutron Spectrometers .....	428
14.6 Detection of Fast Neutrons Using Threshold Activation Reactions .....	431
14.7 Neutron Energy Measurement with a Crystal Spectrometer .....	436
14.8 Time-of-Flight (TOF) Method .....	437
14.8.1 Neutron Velocity Selector (Neutron Chopper) .....	439
14.8.2 Pulsed-Ion Beams .....	440
14.9 Compensated Ion Chambers .....	441
14.10 Self-Powered Neutron Detectors .....	441
14.10.1 SPNDs with Delayed Response .....	443
14.10.2 SPNDs with Prompt Response .....	447
14.11 Concluding Remarks .....	447
Problems .....	449
References .....	451
Bibliography .....	453
<b>Chapter 15. Activation Analysis and Related Techniques</b> .....	455
15.1 Introduction .....	455
15.2 Selection of the Optimum Nuclear Reaction .....	456
15.3 Preparation of the Sample for Irradiation .....	458
15.4 Sources of Radiation .....	459
15.4.1 Sources of Neutrons .....	459
15.4.2 Sources of Charged Particles .....	461
15.4.3 Sources of Photons .....	461
15.5 Irradiation of the Sample .....	461
15.6 Counting of the Sample .....	463
15.7 Analysis of the Results .....	463
15.8 Sensitivity of Activation Analysis .....	465
15.9 Interference Reactions .....	467
15.10 Advantages and Disadvantages of the Activation Analysis Method .....	468
15.11 Prompt Gamma Activation Analysis .....	468
15.12 Neutron Depth Profile .....	469
15.13 Neutron Radiography .....	469
Problems .....	471
References .....	471
Bibliography .....	472

<b>Chapter 16. Health Physics Fundamentals</b> .....	475
16.1 Introduction .....	475
16.2 Units of Exposure and Absorbed Dose .....	476
16.3 Relative Biological Effectiveness: Dose Equivalent .....	478
16.4 Dosimetry from Radiation External to the Body .....	481
16.4.1 Dose Rate due to Charged Particles .....	481
16.4.2 Dose Rate due to Photons .....	483
16.4.3 Dose Rate due to Neutrons .....	486
16.5 Dosimetry for Radiation Inside the Body .....	489
16.5.1 Dose Rate from a Source of Charged Particles inside the Body .....	489
16.5.2 Dose Rate from a Photon Source inside the Body .....	491
16.5.3 Dose Rate from a Neutron Source inside the Body .....	492
16.6 Internal Dose Rate Time Dependence: Biological Half-Life .....	493
16.7 Biological Effects of Radiation .....	497
16.7.1 Basic Description of the Human Cell .....	497
16.7.2 Stochastic and Nonstochastic Biological Effects .....	498
16.8 Radiation Protection Guides and Exposure Limits .....	501
16.8.1 Various Dose Equations Used in Setting Exposure Limits .....	501
16.8.2 Occupational Dose Limits for Adults .....	503
16.9 Health Physics Instruments .....	503
16.9.1 Survey Instruments .....	505
16.9.2 Thermoluminescent Dosimeters .....	505
16.9.3 Optically Stimulated Luminescence Dosimetry .....	507
16.9.4 Bonner Sphere (Rem Ball) .....	509
16.9.5 Neutron Bubble Detector .....	510
16.9.6 Pocket Ionization Dosimeter .....	511
16.9.7 Electronic Personal Dosimeter .....	511
16.9.8 Foil Activation Used for Neutron Dosimetry .....	512
16.10 Proper Use of Radiation .....	512
16.11 Health Physics within Nuclear Power Plants and Radiological Facilities .....	514
16.11.1 Active Personal Dosimeters .....	514
16.11.2 Continuous Air Monitors (CAM) and Continuous Air Particulate Monitors (CAPM) .....	515
16.11.3 Area Monitors and Environmental Monitoring .....	515
16.11.4 Foot and Hand Surface Contamination Monitors .....	516
16.11.5 Whole-Body Counters .....	516
Problems .....	517
References .....	519
Bibliography .....	521
<b>Chapter 17. Nuclear Forensics</b> .....	523
17.1 Introduction .....	523
17.2 Nuclear Forensics Instrumentation .....	524
17.2.1 Passive Detection of Nuclear Materials .....	525
17.2.2 Interrogation Radiation Detection Systems .....	526
17.2.3 Alpha Spectrometry .....	527

17.2.4 Gamma Ray Spectrometry-Coincidence Techniques .....	527
17.3 Chronometry .....	529
17.4 Unmanned Aerial Vehicles Used for Radiation Detection .....	530
Problems .....	532
References .....	532
Bibliography .....	534
<b>Chapter 18. Nuclear Medicine Instrumentation</b> .....	535
18.1 Introduction .....	535
18.2 Areas of Nuclear Medicine .....	537
18.3 Imaging Technologies .....	538
18.3.1 Computed Tomography (CT) .....	538
18.3.2 Single-Photon Emission Computed Tomography (SPECT) .....	538
18.3.3 Positron Emission Tomography (PET) .....	538
18.4 Dose Calibrator .....	538
18.5 Novel Radiation Detection Systems in Nuclear Medicine .....	539
18.6 Production of Radioisotopes by Accelerators or Nuclear Reactors .....	540
18.7 Commercially Available Nuclear Medicine Imaging Systems .....	541
Problems .....	542
References .....	542
Bibliography .....	543
<b>Appendix A: Useful Constants and Conversion Factors</b> .....	545
<b>Appendix B: Atomic Masses and Other Properties of Isotopes</b> .....	547
<b>Appendix C: Alpha, Beta, and Gamma Sources Commonly Used</b> .....	551
<b>Appendix D: Tables of Photon Attenuation Coefficients</b> .....	555
<b>Appendix E: Table of Buildup Factor Constants</b> .....	561
<b>Index</b> .....	563