

## Contents

<b>Preface to the First Edition</b>	<i>XV</i>
<b>Preface to the Second Edition</b>	<i>XVII</i>
<b>Preface to the Third Edition</b>	<i>XIX</i>
<b>1 About Atomic Physics and Radiation</b>	<b>1</b>
1.1 Classical Physics	1
1.2 Discovery of X Rays	1
1.3 Some Important Dates in Atomic and Radiation Physics	3
1.4 Important Dates in Radiation Protection	8
1.5 Sources and Levels of Radiation Exposure	11
1.6 Suggested Reading	12
<b>2 Atomic Structure and Atomic Radiation</b>	<b>15</b>
2.1 The Atomic Nature of Matter (ca. 1900)	15
2.2 The Rutherford Nuclear Atom	18
2.3 Bohr's Theory of the Hydrogen Atom	19
2.4 Semiclassical Mechanics, 1913–1925	25
2.5 Quantum Mechanics	28
2.6 The Pauli Exclusion Principle	33
2.7 Atomic Theory of the Periodic System	34
2.8 Molecules	36
2.9 Solids and Energy Bands	39
2.10 Continuous and Characteristic X Rays	40
2.11 Auger Electrons	45
2.12 Suggested Reading	47
2.13 Problems	48
2.14 Answers	53
<b>3 The Nucleus and Nuclear Radiation</b>	<b>55</b>
3.1 Nuclear Structure	55

3.2	Nuclear Binding Energies	58
3.3	Alpha Decay	62
3.4	Beta Decay ( $\beta^-$ )	65
3.5	Gamma-Ray Emission	68
3.6	Internal Conversion	72
3.7	Orbital Electron Capture	72
3.8	Positron Decay ( $\beta^+$ )	75
3.9	Suggested Reading	79
3.10	Problems	80
3.11	Answers	82
<b>4</b>	<b>Radioactive Decay</b>	<b>83</b>
4.1	Activity	83
4.2	Exponential Decay	83
4.3	Specific Activity	88
4.4	Serial Radioactive Decay	89
	Secular Equilibrium ( $T_1 \gg T_2$ )	89
	General Case	91
	Transient Equilibrium ( $T_1 \gtrsim T_2$ )	91
	No Equilibrium ( $T_1 < T_2$ )	93
4.5	Natural Radioactivity	96
4.6	Radon and Radon Daughters	97
4.7	Suggested Reading	102
4.8	Problems	103
4.9	Answers	108
<b>5</b>	<b>Interaction of Heavy Charged Particles with Matter</b>	<b>109</b>
5.1	Energy-Loss Mechanisms	109
5.2	Maximum Energy Transfer in a Single Collision	111
5.3	Single-Collision Energy-Loss Spectra	113
5.4	Stopping Power	115
5.5	Semiclassical Calculation of Stopping Power	116
5.6	The Bethe Formula for Stopping Power	120
5.7	Mean Excitation Energies	121
5.8	Table for Computation of Stopping Powers	123
5.9	Stopping Power of Water for Protons	125
5.10	Range	126
5.11	Slowing-Down Time	131
5.12	Limitations of Bethe's Stopping-Power Formula	132
5.13	Suggested Reading	133
5.14	Problems	134
5.15	Answers	137

<b>6</b>	<b>Interaction of Electrons with Matter</b>	<b>139</b>
6.1	Energy-Loss Mechanisms	139
6.2	Collisional Stopping Power	139
6.3	Radiative Stopping Power	144
6.4	Radiation Yield	145
6.5	Range	147
6.6	Slowing-Down Time	148
6.7	Examples of Electron Tracks in Water	150
6.8	Suggested Reading	155
6.9	Problems	155
6.10	answers	158
<b>7</b>	<b>Phenomena Associated with Charged-Particle Tracks</b>	<b>159</b>
7.1	Delta Rays	159
7.2	Restricted Stopping Power	159
7.3	Linear Energy Transfer (LET)	162
7.4	Specific Ionization	163
7.5	Energy Straggling	164
7.6	Range Straggling	167
7.7	Multiple Coulomb Scattering	169
7.8	Suggested Reading	170
7.9	Problems	171
7.10	Answers	172
<b>8</b>	<b>Interaction of Photons with Matter</b>	<b>173</b>
8.1	Interaction Mechanisms	173
8.2	Photoelectric Effect	174
8.3	Energy–Momentum Requirements for Photon Absorption by an Electron	176
8.4	Compton Effect	177
8.5	Pair Production	185
8.6	Photonuclear Reactions	186
8.7	Attenuation Coefficients	187
8.8	Energy-Transfer and Energy-Absorption Coefficients	192
8.9	Calculation of Energy Absorption and Energy Transfer	197
8.10	Suggested Reading	201
8.11	Problems	201
8.12	Answers	207
<b>9</b>	<b>Neutrons, Fission, and Criticality</b>	<b>209</b>
9.1	Introduction	209
9.2	Neutron Sources	209

9.3	Classification of Neutrons	214
9.4	Interactions with Matter	215
9.5	Elastic Scattering	216
9.6	Neutron-Proton Scattering Energy-Loss Spectrum	219
9.7	Reactions	223
9.8	Energetics of Threshold Reactions	226
9.9	Neutron Activation	228
9.10	Fission	230
9.11	Criticality	232
9.12	Suggested Reading	235
9.13	Problems	235
9.14	Answers	239
<b>10</b>	<b>Methods of Radiation Detection</b>	<b>241</b>
10.1	Ionization in Gases	241
	Ionization Current	241
	W Values	243
	Ionization Pulses	245
	Gas-Filled Detectors	247
10.2	Ionization in Semiconductors	252
	Band Theory of Solids	252
	Semiconductors	255
	Semiconductor Junctions	259
	Radiation Measuring Devices	262
10.3	Scintillation	266
	General	266
	Organic Scintillators	267
	Inorganic Scintillators	268
10.4	Photographic Film	275
10.5	Thermoluminescence	279
10.6	Other Methods	281
	Particle Track Registration	281
	Optically Stimulated Luminescence	282
	Direct Ion Storage (DIS)	283
	Radiophotoluminescence	285
	Chemical Dosimeters	285
	Calorimetry	286
	Cerenkov Detectors	286
10.7	Neutron Detection	287
	Slow Neutrons	287
	Intermediate and Fast Neutrons	290
10.8	Suggested Reading	296
10.9	Problems	296
10.10	Answers	301

<b>11</b>	<b>Statistics</b>	<b>303</b>
11.1	The Statistical World of Atoms and Radiation	303
11.2	Radioactive Disintegration—Exponential Decay	303
11.3	Radioactive Disintegration—a Bernoulli Process	304
11.4	The Binomial Distribution	307
11.5	The Poisson Distribution	311
11.6	The Normal Distribution	315
11.7	Error and Error Propagation	321
11.8	Counting Radioactive Samples	322
	Gross Count Rates	322
	Net Count Rates	324
	Optimum Counting Times	325
	Counting Short-Lived Samples	326
11.9	Minimum Significant Measured Activity—Type-I Errors	327
11.10	Minimum Detectable True Activity—Type-II Errors	331
11.11	Criteria for Radiobioassay, HPS N13.30-1996	335
11.12	Instrument Response	337
	Energy Resolution	337
	Dead Time	339
11.13	Monte Carlo Simulation of Radiation Transport	342
11.14	Suggested Reading	348
11.15	Problems	349
11.16	Answers	359
<b>12</b>	<b>Radiation Dosimetry</b>	<b>361</b>
12.1	Introduction	361
12.2	Quantities and Units	362
	Exposure	362
	Absorbed Dose	362
	Dose Equivalent	363
12.3	Measurement of Exposure	365
	Free-Air Ionization Chamber	365
	The Air-Wall Chamber	367
12.4	Measurement of Absorbed Dose	368
12.5	Measurement of X- and Gamma-Ray Dose	370
12.6	Neutron Dosimetry	371
12.7	Dose Measurements for Charged-Particle Beams	376
12.8	Determination of LET	377
12.9	Dose Calculations	379
	Alpha and Low-Energy Beta Emitters Distributed in Tissue	379
	Charged-Particle Beams	380
	Point Source of Gamma Rays	381
	Neutrons	383
12.10	Other Dosimetric Concepts and Quantities	387

	Kerma	387
	Microdosimetry	387
	Specific Energy	388
	Lineal Energy	388
12.11	Suggested Reading	389
12.12	Problems	390
12.13	Answers	398
<b>13</b>	<b>Chemical and Biological Effects of Radiation</b>	<b>399</b>
13.1	Time Frame for Radiation Effects	399
13.2	Physical and Prechemical Changes in Irradiated Water	399
13.3	Chemical Stage	401
13.4	Examples of Calculated Charged-Particle Tracks in Water	402
13.5	Chemical Yields in Water	404
13.6	Biological Effects	408
13.7	Sources of Human Data	411
	The Life Span Study	411
	Medical Radiation	413
	Radium-Dial Painters	415
	Uranium Miners	416
	Accidents	418
13.8	The Acute Radiation Syndrome	419
13.9	Delayed Somatic Effects	421
	Cancer	421
	Life Shortening	423
	Cataracts	423
13.10	Irradiation of Mammalian Embryo and Fetus	424
13.11	Genetic Effects	424
13.12	Radiation Biology	429
13.13	Dose–Response Relationships	430
13.14	Factors Affecting Dose Response	435
	Relative Biological Effectiveness	435
	Dose Rate	438
	Oxygen Enhancement Ratio	439
	Chemical Modifiers	439
	Dose Fractionation and Radiotherapy	440
13.15	Suggested Reading	441
13.16	Problems	442
13.17	Answers	447
<b>14</b>	<b>Radiation-Protection Criteria and Exposure Limits</b>	<b>449</b>
14.1	Objective of Radiation Protection	449
14.2	Elements of Radiation-Protection Programs	449

14.3	The NCRP and ICRP	451
14.4	NCRP/ICRP Dosimetric Quantities	452
	Equivalent Dose	452
	Effective Dose	453
	Committed Equivalent Dose	455
	Committed Effective Dose	455
	Collective Quantities	455
	Limits on Intake	456
14.5	Risk Estimates for Radiation Protection	457
14.6	Current Exposure Limits of the NCRP and ICRP	458
	Occupational Limits	458
	Nonoccupational Limits	460
	Negligible Individual Dose	460
	Exposure of Individuals Under 18 Years of Age	461
14.7	Occupational Limits in the Dose-Equivalent System	463
14.8	The “2007 ICRP Recommendations”	465
14.9	ICRU Operational Quantities	466
14.10	Probability of Causation	468
14.11	Suggested Reading	469
14.12	Problems	470
14.13	Answers	473
<b>15</b>	<b>External Radiation Protection</b>	<b>475</b>
15.1	Distance, Time, and Shielding	475
15.2	Gamma-Ray Shielding	476
15.3	Shielding in X-Ray Installations	482
	Design of Primary Protective Barrier	485
	Design of Secondary Protective Barrier	491
	NCRP Report No. 147	494
15.4	Protection from Beta Radiation	495
15.5	Neutron Shielding	497
15.6	Suggested Reading	500
15.7	Problems	501
15.8	Answers	509
<b>16</b>	<b>Internal Dosimetry and Radiation Protection</b>	<b>511</b>
16.1	Objectives	511
16.2	ICRP Publication 89	512
16.3	Methodology	515
16.4	ICRP-30 Dosimetric Model for the Respiratory System	517
16.5	ICRP-66 Human Respiratory Tract Model	520
16.6	ICRP-30 Dosimetric Model for the Gastrointestinal Tract	523
16.7	Organ Activities as Functions of Time	524

- 16.8 Specific Absorbed Fraction, Specific Effective Energy, and Committed Quantities 530
- 16.9 Number of Transformations in Source Organs over 50 Y 534
- 16.10 Dosimetric Model for Bone 537
- 16.11 ICRP-30 Dosimetric Model for Submersion in a Radioactive Gas Cloud 538
- 16.12 Selected ICRP-30 Metabolic Data for Reference Man 540
- 16.13 Suggested Reading 543
- 16.14 Problems 544
- 16.15 Answers 550

### Appendices

- A Physical Constants 551**
  
- B Units and Conversion Factors 553**
  
- C Some Basic Formulas of Physics (MKS and CCS Units) 555**
  - Classical Mechanics 555
  - Relativistic Mechanics (units same as in classical mechanics) 555
  - Electromagnetic Theory 556
  - Quantum Mechanics 556
  
- D Selected Data on Nuclides 557**
  
- E Statistical Derivations 569**
  - Binomial Distribution 569
  - Mean 569
  - Standard Deviation 569
  - Poisson Distribution 570
  - Normalization 571
  - Mean 571
  - Standard Deviation 572
  - Normal Distribution 572
  - Error Propagation 573
  
- Index 575**