James E. Turner

Atoms, Radiation, and Radiation Protection

Third, Completely Revised and Enlarged Edition

WILEY-VCH Verlag GmbH & Co. KGaA

Contents

Preface to the First Edition *XV*
Preface to the Second Edition *XVII*
Preface to the Third Edition *XIX*

1 About Atomic Physics and Radiation 1
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*

2 Atomic Structure and Atomic Radiation 15
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*

3 The Nucleus and Nuclear Radiation 55
3.1 Nuclear Structure *55*

Atoms, Radiation, and Radiation Protection. James E. Turner
Copyright © 2007 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
ISBN: 978-3-527-40606-7

3.2 Nuclear Binding Energies 58
3.3 Alpha Decay 62
3.4 Beta Decay (β^-) 65
3.5 Gamma-Ray Emission 68
3.6 Internal Conversion 72
3.7 Orbital Electron Capture 72
3.8 Positron Decay (β^+) 75
3.9 Suggested Reading 79
3.10 Problems 80
3.11 Answers 82

4 Radioactive Decay 83
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

5 Interaction of Heavy Charged Particles with Matter 109
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

6 Interaction of Electrons with Matter 139
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*

7 Phenomena Associated with Charged-Particle Tracks 159
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*

8 Interaction of Photons with Matter 173
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*

9 Neutrons, Fission, and Criticality 209
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*

10 Methods of Radiation Detection 241
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*

11 Statistics 303
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 Nl3.30-1996 *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*

12 Radiation Dosimetry 361
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

13 Chemical and Biological Effects of Radiation 399
13.1 Time Frame for Radiation Effects 399
13.2 Physical and Prechemical Chances 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

14 Radiation-Protection Criteria and Exposure Limits 449
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*

15 External Radiation Protection 475
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*

16 Internal Dosimetry and Radiation Protection 511
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