Contents

CHAPTER 1 IONIZING RADIATION 1

I. Introduction 1

II. Types and Sources of Ionizing Radiations 2

III. Description of Ionizing Radiation Fields 5

A. Consequences of the Random Nature of Radiation 5

B. Simple Description of Radiation Fields by Nonstochastic Quantities 8

C. Differential Distributions vs. Energy and Angle of Incidence 10

D. An Alternative Definition of Fluence 15

E. Planar Fluence 15

CHAPTER 2 QUANTITIES FOR DESCRIBING THE INTERACTION OF IONIZING RADIATION WITH MATTER 20

I. Introduction 20

II. Kerma 21

A. Definition 21

B. Relation of Kerma to Energy Fluence for Photons 22

C. Relation of Kerma to Fluence for Neutrons 23
D. Components of Kerma 24
E. Kerma Rate 26
III. Absorbed Dose 26
A. Definition 26
B. Absorbed Dose Rate 27
IV. Comparative Examples of Energy Imparted, Energy Transferred and Net Energy Transferred 27
V. Exposure 29
A. Definition 29
B. Definition of $\overline{W}$ 30
C. Relation of Exposure to Energy Fluence 31
D. Exposure Rate 32
E. Significance of Exposure 32
VI. Quantities and Units for Use in Radiation Protection 34
A. Quality Factor, Q 34
B. Dose Equivalent, H 34
C. Specification of Ambient Radiation Levels 36

CHAPTER 3 EXPONENTIAL ATTENUATION 38
I. Introduction 38
II. Simple Exponential Attenuation 38
III. Exponential Attenuation for Plural Modes of Absorption 40
IV. Narrow-Beam Attenuation of Uncharged Radiation 42
V. Broad-Beam Attenuation of Uncharged Radiation 44
VI. Some Broad-Beam Geometries 46
VII. Spectral Effects 50
VIII. The Buildup Factor 53
IX. The Reciprocity Theorem 55

CHAPTER 4 CHARGED-PARTICLE AND RADIATION EQUILIBRIA 61
I. Introduction 61
II. Radiation Equilibrium 61

III. Charged-Particle Equilibrium 65
A. CPE for Distributed Radioactive Sources 65
B. CPE for Indirectly Ionizing Radiation from External Sources 67
IV. CPE in the Measurement of Exposure 70
V. Relating Absorbed Dose to Exposure for X- and γ-Rays 71
VI. Causes of CPE Failure in a Field of Indirectly Ionizing Radiation 72
A. Proximity to a Source 72
B. Proximity to a Boundary of Inhomogeneity in the Medium 72
C. High-Energy Radiation 74
VII. Transient Charged-Particle Equilibrium (TCPE) 75

CHAPTER 5 ABSORBED DOSE IN RADIOACTIVE MEDIA 80
I. Introduction 80
II. Radioactive Disintegration Processes 86
A. Alpha Disintegration 86
B. Beta Disintegration 88
C. Electron-Capture (EC) Transitions 93
D. Internal Conversion vs. γ-Ray Emission 96
E. Tables for Dose Estimation in Appendix C 99

CHAPTER 6 RADIOACTIVE DECAY 101
I. Total Decay Constants 101
II. Partial Decay Constants 102
III. Units of Activity 102
IV. Mean Life and Half-Life 103
V. Radioactive Parent–Daughter Relationships 105
VI. Equilibria in Parent–Daughter Activities 107
A. Daughter Longer-Lived than Parent, $\lambda_2 < \lambda_1$ 108
B. Daughter Shorter-Lived than Parent, $\lambda_2 > \lambda_1$ 108
C. Only Daughter Much Shorter-Lived than Parent, $\lambda_2 \gg \lambda_1$ 112
VII. Removal of Daughter Products 114

VIII. Radioactivation by Nuclear Interactions 115
IX. Exposure-Rate Constant 117

CHAPTER 7 GAMMA- AND X-RAY INTERACTIONS IN MATTER 124
I. Introduction 124
II. Compton Effect 125
A. Kinematics 126
B. Interaction Cross Section for the Compton Effect 129
C. Energy-Transfer Cross Section for the Compton Effect 134
III. Photoelectric Effect 138
A. Kinematics 138
B. Interaction Cross Section for the Photoelectric Effect 139
C. Energy-Transfer Cross Section for the Photoelectric Effect 142
IV. Pair Production 146
A. Pair Production in the Nuclear Coulomb-Force Field 148
B. Pair Production in the Electron Field 150
C. Pair Production Energy-Transfer Coefficient 152
V. Rayleigh (Coherent) Scattering 153
VI. Photonuclear Interactions 154
VII. Total Coefficients for Attenuation, Energy Transfer, and Energy Absorption 154
A. Mass Attenuation Coefficient 154
B. Mass Energy-Transfer Coefficient 155
C. Mass Energy-Absorption Coefficient 155
D. Coefficients for Compounds and Mixtures 156
E. Tables of Photon Interaction Coefficients 157

CHAPTER 8 CHARGED-PARTICLE INTERACTIONS IN MATTER 160
I. Introduction 160
II. Types of Charged-Particle Coulomb-Force Interactions 161

A. "Soft" Collisions ($b \gg a$) 161
B. Hard (or "Knock-On") Collisions ($b \sim a$) 162
C. Coulomb-Force Interactions with the External Nuclear Field ($b \ll a$) 163
D. Nuclear Interactions by Heavy Charged Particles 164
III. Stopping Power 165
A. The Soft-Collision Term 166
B. The Hard-Collision Term for Heavy Particles 167
C. Shell Correction 171
D. Mass Collision Stopping Power for Electrons and Positrons 171
E. Polarization or Density-Effect Correction 172
F. Mass Radiative Stopping Power 175
G. Radiation Yield 177
H. Stopping Power in Compounds 178
I. Restricted Stopping Power 179
IV. Range 180
A. CSDA Range 180
B. Projected Range 183
C. Straggling and Multiple Scattering 184
D. Electron Range 184
E. Photon "Projected Range" 186
V. Calculation of Absorbed Dose 187
A. Dose in Thin Foils 187
B. Mean Dose in Thicker Foils 190
C. Mean Dose in Foils Thicker than the Maximum Projected Range of the Particles 192
D. Electron Backscattering 193
E. Dose vs. Depth for Charged-Particle Beams 195

CHAPTER 9 X-RAY PRODUCTION AND QUALITY 203
I. Introduction 203
II. X-Ray Production and Energy Spectra 203
A. Fluorescence X-Rays 203
B. Bremsstrahlung X-Rays 210

III. X-Ray Filtration and Beam Quality 219
A. X-Ray Filtration 220
B. X-Ray Beam-Quality Specification 221

CHAPTER 10 CAVITY THEORY 231
I. Bragg–Gray Theory 231
II. Corollaries of the Bragg–Gray Relation 235
A. First Bragg–Gray Corollary 235
B. Second Bragg–Gray Corollary 235
III. Spencer's Derivation of the Bragg–Gray Theory 237
IV. Averaging of Stopping Powers 239
V. Spencer Cavity Theory 242
VI. Burlin Cavity Theory 248
VII. The Fano Theorem 255
VIII. Other Cavity Theories 257
IX. Dose Near Interfaces between Dissimilar Media under γ-Irradiation 259

CHAPTER 11 DOSIMETRY FUNDAMENTALS 264
I. Introduction 264
A. What Is Radiation Dosimetry? 264
B. What Is a Dosimeter? 264
C. Simple Dosimeter Model in Terms of Cavity Theory 265
II. General Guidelines on the Interpretation of Dosimeter Measurements 266
A. For Photons and Neutrons 266
B. For Charged Particles 274
III. General Characteristics of Dosimeters 277
A. Absoluteness 277
B. Precision and Accuracy 277
C. Dose Range 279
D. Dose-Rate Range 281
E. Stability 282
F. Energy Dependence 283
G. Miscellany 290

CHAPTER 12 IONIZATION CHAMBERS 292
I. Introduction 292
II. Free-Air Ion Chambers 292
A. Conventional Designs 292
B. Novel Free-Air-Chamber Designs 300
III. Cavity Ionization Chambers 304
A. Thimble-Type Chambers 304
B. Flat Cavity Chambers; Extrapolation Chambers 311
C. Transmission Monitor Chambers 315
IV. Charge and Current Measurements 315
A. General Considerations 315
B. Charge Measurement 319
C. Current Measurement 323
D. Atmospheric Corrections 326
V. Ion-Chamber Saturation and Ionic Recombination 330
A. Charge Produced vs. Charge Collected 330
B. Types of Recombination 332
C. Types of Gases 332
D. Electric Field Strength vs. Chamber Geometry 333
E. Boag's Treatment of Mie's Theory of General or Volume Recombination for Constant Dose Rate in an Electronegative Gas such as Air 334
F. Extrapolation for Initial Recombination 336
G. Pulsed Radiation 337
VI. Ionization, Excitation and W 339
A. Definition of W and $\overline{W}$ 339
B. Calculation of W 340
C. Experimental Measurement of W or $\overline{W}$ 341
D. Energy Dependence of W 342
E. Dependence of W on Type of Radiation 343
F. W for Gas Mixtures 343
G. "W" in Semiconductors 343

CHAPTER 13 DOSIMETRY AND CALIBRATION OF PHOTON AND ELECTRON BEAMS WITH CAVITY ION CHAMBERS 346
I. Introduction 346
II. Absolute Cavity Ion Chambers 346
III. Calibration of Ion Chambers Using X-Rays or γ-Rays 347
A. Exposure Calibration of Ion Chambers 347
B. N_{gas} Calibration of Ion Chambers 350
C. Calibration of Ion Chambers in Terms of Absorbed Dose in Water 356
IV. Calibration of Photon Beams with an Exposure-Calibrated Ion Chamber 357
A. Calibrations in Free Space 357
B. Calibration of Photon Beams in Phantoms by Means of an Exposure-Calibrated Ion Chamber 366
C. Substitution of Plastics for Water in Photon-Beam Phantoms 372
V. Calibration of Photon Beams in Phantoms by the N_{gas} Method 376
A. Chamber Wall Material Same as Phantom 376
B. Chamber Wall Material Different from Phantom 378
VI. Calibration of Electron Beams in Phantoms 380
A. Absolute Cavity-Chamber Measurements 380
B. Electron-Beam Perturbation Corrections for Cavity Chambers in Phantoms 380
C. The C_E Method 385
D. The N_{gas} Method 388

CHAPTER 14 INTEGRATING DOSIMETERS 395
I. Thermoluminescence Dosimetry 395
A. The Thermoluminescence Process 395
B. TLD Readers 400
C. TLD Phosphors 403

D. TLD Forms 403
E. Calibration of Thermoluminescent Dosimeters 405
F. Advantages and Disadvantages 410
G. References 411
II. Photographic Dosimetry 411
A. Photographic Process 411
B. Optical Density of Film 412
C. Practical Exposure Range for X-Ray Film 414
D. X-Ray Energy Dependence 414
E. Nuclear Track Emulsions 415
F. Advantages and Disadvantages of Photographic Dosimetry 416
G. References 418
III. Chemical Dosimetry 418
A. Introduction 418
B. Basic Principles 418
C. General Procedures 419
D. The Fricke Ferrous Sulfate Dosimeter 421
E. Other Chemical Dosimeters 423
F. General Advantages and Disadvantages of Aqueous Chemical Dosimetry Systems 424
G. References 425
IV. Calorimetric Dosimetry 426
A. Temperature Measurement 426
B. Calorimeter Design 427
C. Advantages and Disadvantages of Calorimetric Dosimetry 435
D. Conclusions 435

CHAPTER 15 DOSIMETRY BY PULSE-MODE DETECTORS 438
I. Introduction 438
II. Geiger–Müller and Proportional Counters 438
A. Gas Multiplication 438
B. Proportional Counters 441
C. Geiger–Müller Counters 446

III. Scintillation Dosimetry 450
A. Introduction 450
B. Light Output Efficiency 451
C. Scintillator Types 452
D. Light Collection and Measurement 452
E. Comparison with an Ionization Chamber 455
F. Pulse-Shape Discrimination 456
G. Beta-Ray Dosimetry 457
IV. Semiconductor Detectors for Dosimetry 457
A. Introduction 457
B. Basic Operation of Reverse-Biased Semiconductor Junction Detectors 457
C. Silicon Diodes without Bias 459
D. Lithium-Drifted Si and Ge Detectors 459
E. Use of Si(Li) as an Ion-Chamber Substitute 461
F. Use of Si(Li) Junctions with Reverse Bias as Counting Dose-Rate Meters 461
G. Fast-Neutron Dosimetry 461

CHAPTER 16 NEUTRON INTERACTIONS AND DOSIMETRY 463
I. Introduction 463
II. Neutron Kinetic Energy 464
A. Thermal Neutrons 464
B. Intermediate-Energy Neutrons 465
C. Fast Neutrons 465
III. Neutron Interactions in Tissue 465
A. Tissue Composition 465
B. Kerma Calculations 466
C. Thermal-Neutron Interactions in Tissue 467
D. Interaction by Intermediate and Fast Neutrons 468
IV. Neutron Sources 468
V. Neutron Quality Factor 472
VI. Calculation of the Absorbed Dose in a Cylindrical Phantom Representing the Human Body 472

VII. $n + \gamma$ Mixed-Field Dosimetry 475
A. Occurrence of $n + \gamma$ Mixed Fields 475
B. Equation for $n + \gamma$ Dosimeter Response 476
C. Separate Measurement of Neutron and γ-Ray Dose Components by Paired Dosimeters 477
D. Relative n vs. γ Sensitivity of Dosimeters 479
E. Calibration of a Tissue-Equivalent Ion Chamber for $n + \gamma$ Dosimetry 495
F. Calibration of the Low-Neutron-Sensitivity Dosimeter for Use in the Paired-Dosimeter Method 498
VIII. Microdosimetry 501
A. Track-Descriptive Approach: Linear Energy Transfer 501
B. Site-Relevant Approach 503
C. Stochastic Quantities 503

REFERENCES 506

APPENDIXES 525
A.1 Physical Constants 525
A.2 Conversion Factors 526
B.1 Data Table of the Elements 527
B.2 Data Table for Compounds and Mixtures 531
B.3 Compositions of Mixtures 532
C Radionuclide Output Data 533
D.1 Klein–Nishina Interaction Cross Sections for Free Electrons 537
D.2 Photon Interaction Cross Sections 538
D.3 Mass Attenuation Coefficients, Mass Energy-Transfer Coefficients, and Mass Energy-Absorption Coefficients for Photon Interactions in Various Media 556
D.4 Mass Energy-Absorption Coefficients for Various Media 562
E Electron Mass Stopping Powers, Ranges, Radiation Yields, and Density Corrections 563
F Neutron Kerma Factors F_n 587

INDEX 599