Contents

Preface to the Third Edition vii

Preface to the Second Edition ix

Preface to the First Edition xi

1. Introduction 1

1.1 Radiation and Particle Interactions 3
1.2 Particles and Types of Interaction 5
1.2.1 Quarks and Leptons 6
1.3 Relativistic Kinematics 7
1.3.1 The Two-Body Scattering 10
1.3.2 The Invariant Mass 13
1.3.2.1 Lorentz-Invariant Quantities and Phase Space . . 14
1.3.3 Relativistic Doppler Effect 18
1.3.3.1 Redshift Parameter and Astronomy 21
1.4 Atomic Mass, Weight, Standard Weight and Mass Unit 23
1.5 Cross Section and Differential Cross Section 24
1.6 Coulomb Single-Scattering Cross Section 26
1.6.1 Rutherford's Formula and Average Energy Transferred . . 30
1.7 Detectors and Large Experimental Apparata 33
1.7.1 Trigger, Monitoring, Data Acquisition, Slow Control 35
1.7.2 General Features of Particle Detectors and Detection Media 36
1.7.3 Radiation Environments and Silicon Devices 42

2. Electromagnetic Interaction of Radiation in Matter 45

2.1 Passage of Ionizing Particles through Matter 46
2.1.1 The Collision Energy-Loss of Massive Charged Particles . . 46
2.1.1.1 The Barkas–Andersen Effect 56
2.1.1.2 The Shell Correction Term 58

2.1.1.3 Energy-Loss Minimum, Density Effect and Relativistic Rise 60
2.1.1.4 Restricted Energy-Loss and Fermi Plateau 63
2.1.1.5 Energy-Loss Formula for Compound Materials . . 67
2.1.2 Energy-Loss Fluctuations 68
2.1.2.1 δ-Rays, Straggling Function, and Transport Equation 68
2.1.2.2 The Landau–Vavilov Solutions for the Transport Equation 71
2.1.2.3 The Most Probable Collision Energy-Loss for Massive Charged Particles 73
2.1.2.4 Improved Energy-Loss Distribution and Distant Collisions 77
2.1.2.5 Distant Collision Contribution to Energy Straggling in Thin Silicon Absorbers 80
2.1.2.6 Improved Energy-Loss Distribution for Multi-Particles in Silicon 83
2.1.3 Range of Heavy Charged Particles and Bragg Curve 84
2.1.4 Heavy Ions 91
2.1.4.1 Nuclear Stopping Power at Non-Relativistic Energies 93
2.1.4.2 Nuclear Stopping Power at Relativistic Energies . 99
2.1.5 Ionization Yield in Gas Media 106
2.1.6 Passage of Electrons and Positrons through Matter 108
2.1.6.1 Collision Losses by Electrons and Positrons 109
2.1.6.2 Most Probable Energy-Loss of Electrons and Positrons 112
2.1.6.3 Practical Range of Electrons 114
2.1.7 Radiation Energy-Loss by Electrons and Positrons 117
2.1.7.1 The Landau–Pomeranchuk–Migdal Effect: The Bremsstrahlung Suppression 130
2.1.7.2 Collision and Radiation Stopping Powers 138
2.1.7.3 Radiation Yield and Bremsstrahlung Angular Distribution 138
2.1.7.4 Radiation Length and Complete Screening Approximation 146
2.1.7.5 Critical Energy 150
2.2 Multiple and Extended Volume Coulomb Interactions 151
2.2.1 The Multiple Coulomb Scattering 151
2.2.2 Emission of Čerenkov Radiation 156
2.2.3 Emission of Transition Radiation 162

2.3 Photon Interaction and Absorption in Matter 168
2.3.1 The Photoelectric Effect 170
2.3.1.1 The Auger Effect 176
2.3.2 The Compton Scattering 177
2.3.2.1 The Klein–Nishina Equation for Unpolarized Photons 180
2.3.2.2 Electron Binding Corrections to Compton and Rayleigh Scatterings 187
2.3.2.3 The Thomson Cross Section 190
2.3.2.4 Radiative Corrections and Double Compton Effect 192
2.3.2.5 Inverse Compton Scattering 193
2.3.2.6 Power Loss of Electrons due to Inverse Compton Scattering 199
2.3.3 Pair Production 204
2.3.3.1 Pair Production in the Field of a Nucleus 204
2.3.3.2 Pair Production in the Electron Field 216
2.3.3.3 Angular Distribution of Electron and Positron Pairs 218
2.3.4 Photonuclear Scattering, Absorption and Production . . . 218
2.3.5 Attenuation Coefficients, Dosimetric and Radiobiological Quantities 223
2.4 Electromagnetic Cascades in Matter 237
2.4.1 Phenomenology and Natural Units of Electromagnetic Cascades 238
2.4.2 Propagation and Diffusion of Electromagnetic Cascades in Matter 240
2.4.2.1 Rossi's Approximation B and Cascade Multiplication of Electromagnetic Shower 240
2.4.2.2 Longitudinal Development of the Electromagnetic Shower 243
2.4.2.3 Lateral Development of Electromagnetic Showers 247
2.4.2.4 Energy Deposition in Electromagnetic Cascades . 254
2.4.3 Shower Propagation and Diffusion in Complex Absorbers . 255

3. Nuclear Interactions in Matter 257

3.1 General Properties of the Nucleus 257
3.1.1 Radius of Nuclei and the Liquid Droplet Model 260
3.1.1.1 Droplet Model and Semi-Empirical Mass Formula 261
3.1.2 Form Factor and Charge Density of Nuclei 263

3.1.3 Angular and Magnetic Moment, Shape of Nuclei 266
3.1.4 Stable and Unstable Nuclei 267
3.1.4.1 The β-Decay and the Nuclear Capture 269
3.1.4.2 The α-Decay 271
3.1.5 Fermi Gas Model and Nuclear Shell Model 273
3.1.5.1 γ Emission by Nuclei 278
3.2 Phenomenology of Interactions on Nuclei at High Energy 279
3.2.1 Energy and A-Dependence of Cross Sections 280
3.2.1.1 Collision and Inelastic Length 281
3.2.2 Coherent and Incoherent Interactions on Nuclei 281
3.2.2.1 Kinematics for Coherent Condition 285
3.2.2.2 Coherent and Incoherent Scattering 288
3.2.3 Multiplicity of Charged Particles and Angular-Distribution of Secondaries 293
3.2.3.1 Rapidity and Pseudorapidity Distributions 298
3.2.4 Emission of Heavy Prongs 302
3.2.5 The Nuclear Spallation Process 305
3.2.6 Nuclear Temperature and Evaporation 308
3.3 Hadronic Shower Development and Propagation in Matter 312
3.3.1 Phenomenology of the Hadronic Cascade in Matter 313
3.3.2 Natural Units in the Hadronic Cascade 316
3.3.3 Longitudinal and Lateral Hadronic Development 318

4. Radiation Environments and Damage in Silicon Semiconductors 325
4.1 Radiation Environments 327
4.1.1 High-Luminosity Machines Environments for Particle Physics Experiments 327
4.1.1.1 Ionization Process and LHC Collider Environment 331
4.1.1.2 Non-Ionization Processes, NIEL Scaling Hypothesis and Collider Environments 332
4.1.2 Space Radiation Environment 335
4.1.2.1 Solar Wind 339
4.1.2.2 Solar and Heliospheric Magnetic Field 346
4.1.2.3 Extension of the Heliosphere and the Earth Magnetosphere 357
4.1.2.4 Propagation of Galactic Cosmic Rays through Interplanetary Space 362
4.1.2.5 Diffusion Tensor 372
4.1.2.6 Modulated Differential Intensities of Cosmic Rays and Drift Velocity 375

4.1.2.7 Solar, Heliospheric and Galactic Cosmic Rays in the Interplanetary Space . . . 381
4.1.2.8 Trapped Particles and Earth Magnetosphere . . . 386
4.1.3 Neutron Spectral Fluence in Nuclear Reactor Environment . . . 393
4.1.3.1 Fast Neutron Cross Section on Silicon . . . 394
4.1.3.2 Energy Distribution of Reactor Neutrons and Classification . . . 395
4.2 Relevant Processes of Energy Deposition and Damage . . . 396
4.2.1 NIEL and Displacement Damage . . . 397
4.2.1.1 Knock-On Atoms and Displacement Cascade . . . 402
4.2.1.2 Norgett–Robinson–Torrens Expression . . . 405
4.2.1.3 Neutron Interactions . . . 406
4.2.1.4 Interactions of Protons, α-Particles and Heavy-Isotopes . . . 407
4.2.1.5 Electron Interactions . . . 412
4.2.1.6 Damage Function . . . 421
4.2.2 Radiation Induced Defects . . . 424
4.2.3 Ionization Energy-Loss and NIEL Processes . . . 431
4.2.3.1 Imparted Dose in Silicon . . . 431
4.2.3.2 Ionization Damage . . . 435
4.3 Radiation Induced Defects and Modification of Silicon Bulk and $p-n$ Junction Properties . . . 437
4.3.1 Displacement Damage Effect on Minority Carrier Lifetime . . . 438
4.3.2 Carrier Generation and Leakage Current . . . 440
4.3.3 Diode Structure and Rectification Down to Cryogenic Temperature . . . 442
4.3.3.1 Rectification Property Up to Large Fast-Neutron Fluences at Room Temperature . . . 443
4.3.3.2 Large Radiation Damage and $p-i-n$ Structure at Room Temperature . . . 448
4.3.3.3 $I-V$ Characteristics Down to Cryogenic Temperature . . . 449
4.3.4 Complex Impedance of Junctions and Cryogenic Temperatures . . . 454
4.3.5 Resistivity, Hall Coefficient and Hall Mobility at Large Displacement Damage . . . 461
4.3.6 AFM Structure Investigation in Irradiated Devices . . . 472
5. Scintillating Media and Scintillator Detectors 475
5.1 Scintillators . . . 475

5.1.1 Organic Scintillators 476
5.1.2 Inorganic Scintillators 479
5.2 The Čerenkov Detectors 482
5.2.1 Threshold Čerenkov Detectors 485
5.2.2 Differential Čerenkov Detectors 489
5.2.3 Ring Imaging Čerenkov (RICH) Detectors 490
5.3 Wavelength Shifters 491
5.4 Transition Radiation Detectors (TRD) 493
5.5 Scintillating Fibers 495
5.6 Detection of the Scintillation Light 498
5.7 Applications in Calorimetry 503
5.8 Application in Time-of-Flight (ToF) Technique 504

6. Solid State Detectors 507

6.1 Basic Principles of Operation 508
6.1.1 Unpolarized $p-n$ Junction 510
6.1.2 Polarized $p-n$ Junction 513
6.1.3 Capacitance 516
6.1.4 Charge Collection Measurements 517
6.1.5 Charge Transport in Silicon Diodes 518
6.1.6 Leakage or Reverse Current 529
6.1.7 Noise Characterization of Silicon Detectors 531
6.2 Charge Collection Efficiency and Hecht Equation 533
6.3 Spectroscopic Characteristics of Standard Planar Detectors 538
6.3.1 Energy Resolution of Standard Planar Detectors 541
6.4 Microstrip Detectors 542
6.5 Pixel Detector Devices 548
6.5.1 The MediPix-Type Detecting Device 549
6.5.2 Examples of Application: Particle Physics 552
6.5.2.1 Electrons and Photons 552
6.5.2.2 Neutrons 552
6.5.2.3 Muons, Pions and Protons 554
6.5.2.4 α-Particles and Heavier Ions 555
6.5.2.5 Charge Sharing 555
6.6 Photovoltaic and Solar Cells 559
6.7 Neutrons Detection with Silicon Detectors 564
6.7.1 Principles of Neutron Detection with Silicon Detectors . . 565
6.7.1.1 Signal in Silicon Detectors for Thermal Neutrons 568
6.7.1.2 Signals in Silicon Detectors by Fast Neutrons . . . 573
6.7.2 3-D Neutron Detectors 577
6.8 Radiation Effects on Silicon Semiconductor Detectors 578

6.8.1 MESA Radiation Detectors 578
6.8.1.1 Electrical Features of Planar MESA Detectors . . 579
6.8.1.2 Spectroscopic Characteristics of MESA Detectors 581
6.8.2 Results of Irradiation Tests of Planar MESA Detectors . . 582
6.8.3 Irradiation with Low-Energy Protons in High-Resistivity Silicon Detectors and NIEL 587

7. Displacement Damage and Particle Interactions in Silicon Devices 595

7.1 Displacement Damage in Irradiated Bipolar Transistors 597
7.1.1 Transit Time of Minority Carriers Across the Base 601
7.1.2 Gain Degradation of Bipolar Transistors and Messenger–Spratt Equation 602
7.1.3 Surface and Total Dose Effects on the Gain Degradation of Bipolar Transistors 606
7.1.4 Generalized Messenger–Spratt Equation for Gain Degradation of Bipolar Transistors 608
7.1.4.1 Experimental Evidence of Approximate NIEL Scaling 609
7.1.5 Transistor Gain and Self-Annealing 611
7.1.6 Radiation Effects on Low-Resistivity Base Spreading-Resistance 612
7.2 Single Event Effects 614
7.2.1 Classification of SEE 617
7.2.2 SEE in Spatial Radiation Environment 618
7.2.3 SEE in Atmospheric Radiation Environment 620
7.2.4 SEE in Terrestrial Radiation Environment 621
7.2.5 SEE Produced by Radioactive Sources 621
7.2.6 SEE in Accelerator Radiation Environment 624
7.2.7 SEE Generation Mechanisms 625
7.2.7.1 Direct Ionization 625
7.2.7.2 Indirect Ionization 627
7.2.7.3 Linear Energy Transfer (LET) 629
7.2.7.4 Sensitive Volume 630
7.2.7.5 Critical Charge 630
7.2.8 SEE Cross Section 634
7.2.8.1 Calculation of SEU Rate for Ions 635
7.2.8.2 Calculation of SEU Rate for Protons and Neutrons 638
7.2.9 SEE Mitigation 641

8. Gas Filled Chambers 643

8.1 The Ionization Chamber . . . 643
8.2 Recombination Effects . . . 646
8.2.1 Germinate or Initial Recombination . . . 647
8.2.2 Columnar Recombination . . . 647
8.2.3 The Box Model . . . 648
8.2.4 Recombination with Impurities . . . 649
8.3 Example of Ionization Chamber Application: The α-Cell . . . 652
8.3.1 The α-Cell . . . 652
8.3.2 Charge Measurement with the α-Cell . . . 655
8.3.3 Examples of Pollution Tests Using the α-Cell . . . 660
8.4 Proportional Counters . . . 662
8.4.1 Avalanche Multiplication . . . 662
8.5 Proportional Counters: Cylindrical Coaxial Wire Chamber . . . 665
8.6 Multiwire Proportional Chambers (MWPC) . . . 672
8.7 The Geiger–Mueller Counter . . . 674

9. Principles of Particle Energy Determination 677
9.1 Experimental Physics and Calorimetry . . . 677
9.1.1 Natural Units in Shower Propagation . . . 681
9.2 Electromagnetic Sampling Calorimetry . . . 681
9.2.1 Electromagnetic Calorimeter Response . . . 681
9.2.2 The e/mip Ratio . . . 684
9.2.2.1 e/mip Dependence on Z-Values of Readout and Passive Absorbers . . . 688
9.2.2.2 e/mip Dependence on Absorber Thickness . . . 692
9.2.3 e/mip Reduction in High-Z Sampling Calorimeters: The Local Hardening Effect . . . 692
9.3 Principles of Calorimetry with Complex Absorbers . . . 696
9.3.1 The Filtering Effect and How to Tune the e/mip Ratio . . . 698
9.3.2 e/mip Reduction by Combining Local Hardening and Filtering Effects . . . 703
9.4 Energy Resolution in Sampling Electromagnetic Calorimetry . . . 705
9.4.1 Visible Energy Fluctuations . . . 705
9.4.1.1 Calorimeter Energy Resolution for Dense Readout Detectors . . . 707
9.4.1.2 Calorimeter Energy Resolution for Gas Readout Detectors . . . 711
9.4.2 Effect of Limited Containment on Energy Resolution . . . 715
9.5 Homogeneous Calorimeters . . . 719
9.5.1 General Considerations . . . 719
9.5.2 Energy Measurement . . . 722
9.6 Position Measurement . . . 729

9.7 Electron Hadron Separation 733
9.8 Hadronic Calorimetry 734
9.8.1 Intrinsic Properties of the Hadronic Calorimeter 734
9.8.1.1 The e/h, e/π, h/mip and π/mip Ratios 735
9.8.1.2 Compensating Condition $e/h = e/\pi = 1$ and Linear Response 739
9.9 Methods to Achieve the Compensation Condition 743
9.9.1 Compensation Condition by Detecting Neutron Energy . . 744
9.9.2 Compensation Condition by Tuning the e/mip Ratio . . . 750
9.10 Compensation and Hadronic Energy Resolution 760
9.10.1 Non-Compensation Effects and the $\phi(e/\pi)$ Term 766
9.10.2 Determination of Effective Intrinsic Resolutions 768
9.10.3 Effect of Visible-Energy Losses on Calorimeter Energy Resolution 770
9.11 Calorimetry at Very High Energy 771
9.11.1 General Considerations 771
9.11.2 Air Showers (AS) and Extensive Air Showers (EAS) 775
9.11.3 Electromagnetic Air Showers 778
9.11.3.1 Longitudinal Development 778
9.11.3.2 Lateral Development 779
9.11.4 Hadronic Extensive Air Showers 781
9.11.5 The Muon Component of Extensive Air Showers 783

10. Superheated Droplet (Bubble) Detectors and CDM Search 785
10.1 The Superheated Droplet Detectors and their Operation 788
10.1.1 Neutron Response Measurement 792
10.1.2 Alpha-Particle Response Measurement 796
10.1.3 Radon Detection 799
10.1.4 Spontaneous Nucleation 800
10.1.5 Signal Measurement with Piezoelectric Sensors 801
10.2 Search of Cold Dark Matter (CDM) 802
10.2.1 Calculation of the Neutralino–Nucleon Exclusion Limits . . 803
10.2.1.1 Spin-Independent or Coherent Cross Section . . . 804
10.2.1.2 Spin-Dependent or Incoherent Cross Section . . . 807
10.2.1.3 Calculation of $\langle S_p \rangle$ and $\langle S_n \rangle$ in Nuclei 811
10.2.1.4 Shell Models Calculation and Validation of $\langle S_p \rangle$ and $\langle S_n \rangle$ 817
10.2.2 The PICASSO Experiment, an Example 817
10.2.3 Status of Dark Matter Searches 819
10.3 Double Beta Decay 821

11. Medical Physics Applications 827

11.1 Single Photon Emission Computed Tomography (SPECT) 829
11.2 Positron Emission Tomography (PET) 841
11.3 Magnetic Resonance Imaging (MRI) 845
11.3.1 Physical Basis of MRI 845
11.3.2 Forming an Image 848
11.3.2.1 Spin-Echo 848
11.3.2.2 Gradient-Echo 848
11.3.2.3 Space Positioning 849
11.3.2.4 Flows 850
11.3.2.5 Functional MRI 850
11.4 *X*-Ray Medical Imaging with MediPix Devices 851
11.4.1 The Contrast 852
11.4.2 The Modulation Transfer Function 852
11.4.3 The Detective Quantum Efficiency 853

Appendix A General Properties and Constants 857

A.1 Physical Constants 858
A.2 Periodic Table of Elements 862
A.3 Conversion Factors 864
A.4 Electronic Structure of the Elements 876
A.5 Isotopic Abundances 879
A.6 Commonly Used Radioactive Sources 881
A.7 Free Electron Fermi Gas 882
A.8 Gamma-Ray Energy and Intensity Standards 885

Appendix B Mathematics and Statistics 889

B.1 Probability and Statistics for Detection Systems 890
B.2 Table of Integrals 901

Bibliography 903

Index 967