Contents

Preface to the Third Edition, xv

Prelude: Setting the Scene, xvii

CHAPTER 1 ▪ The Standard Model 1

1.1 THE FUNDAMENTAL PARTICLES OF MATTER 1

1.2 THE FOUR FUNDAMENTAL FORCES 4

1.2.1 The Strong Force 6

1.2.2 The Weak Force 7

1.2.3 Exchange Particles 8

1.3 THE STANDARD MODEL 9

1.4 THE BIG BANG 10

1.5 SUMMARY 12

ENDNOTES 13

CHAPTER 2 ▪ Relativity for Particle Physics 15

2.1 MOMENTUM 15

2.2 KINETIC ENERGY 21

2.3 RELATIVISTIC ENERGY 23

2.3.1 Energy and Mass 24

2.3.2 The Higgs Mechanism 26

2.3.3 Terminology 27

2.3.4 Photons 28

2.3.5 Units 29

2.4 REACTIONS AND DECAYS 30

2.4.1 Particle Reactions 31

2.4.2 Particle Decays 32

2.5 SUMMARY 33

ENDNOTES 34

CHAPTER 3 ▪ Quantum Theory 35
3.1 THE DOUBLE-SLIT EXPERIMENT FOR ELECTRONS 36
3.1.1 Results in Detail 40
3.2 WHAT DOES IT ALL MEAN? 42
3.3 FEYNMAN'S PICTURE 43
3.4 DISTINGUISHING PARTICLES 45
3.4.1 Summarizing the Rules for Combining Amplitudes 49
3.5 HOW TO COMBINE AMPLITUDES 49
3.5.1 Summary of the Rules for Combining Amplitudes 52
3.6 FOLLOWING AMPLITUDES ALONG PATHS 52
3.6.1 Building a Path Amplitude 53
3.6.2 The Lagrangian in Quantum Mechanics 54
3.6.3 The Lagrangian in Classical Physics 55
3.6.4 Relating Classical to Quantum 56
3.6.5 Summarizing 58
3.6.6 Amplitudes, Energy and Momentum 58
3.6.7 Energy Levels 62
3.6.8 Photons and Waves 62
3.7 AMPLITUDES, STATES AND UNCERTAINTIES 63
3.7.1 The State Vector 63
3.7.2 The Collapse of State 65
3.7.3 The Uncertainty Principle 66
3.8 SPIN 68
3.8.1 Spin and Phase 70
3.8.2 Chirality 71
3.9 SUMMARY 71
ENDNOTES 72

CHAPTER 4 ▪ The Leptons 75
4.1 A SPOTTER'S GUIDE TO THE LEPTONS 75
4.2 THE PHYSICAL PROPERTIES OF THE LEPTONS 76
4.3 NEUTRINO REACTIONS WITH MATTER 77
4.3.1 Aspects of the Neutrino–Neutron Reaction 79
4.4 SOME MORE REACTIONS INVOLVING NEUTRINOS 80
4.5 WEAK EXCHANGE PARTICLES 81

4.5.1 And It Was Going So Well ... 84
4.5.2 Lepton Decays 85
4.6 SUMMARY 87
ENDNOTES 87

CHAPTER 5 ■ Antimatter 89
5.1 LEPTON NUMBER 89
5.1.1 Lepton Number Conservation 90
5.1.2 Mystery Neutrinos 91
5.2 POSITRONS AND OTHERS 93
5.3 SOLAR NEUTRINOS AGAIN ... 94
5.3.1 Neutrino Oscillations 96
5.3.2 Neutrino Mass States 98
5.3.3 States, Flavours and Generations 103
5.4 ANTIQUARKS 105
5.5 THE GENERAL NATURE OF ANTIMATTER 107
5.6 ANNIHILATION REACTIONS 108
5.7 SUMMARY 109
ENDNOTES 110

CHAPTER 6 ■ Hadrons 113
6.1 THE PROPERTIES OF THE QUARKS 113
6.1.1 Quantum Numbers of Quarks 114
6.2 BARYONS AND MESONS 115
6.3 BARYON FAMILIES 116
6.3.1 Higher Mass Baryons 119
6.4 MESON FAMILIES 119
6.5 QUANTUM NUMBERS APPLIED TO HADRONS 121
6.6 SUMMARY 122
ENDNOTES 123

CHAPTER 7 ■ Hadron Reactions 125
7.1 BASIC IDEAS 125
7.2 BASIC PROCESSES 126
7.2.1 Conservation of Energy and Momentum 127

7.2.2 Conservation of Charge 127
7.2.3 Conservation of Baryon Number 129
7.2.4 Conservation of Flavour 130
7.3 USING CONSERVATION LAWS 131
7.4 THE PHYSICS OF HADRON REACTIONS 132
7.4.1 The Field of the Strong Force 132
7.5 SUMMARY 135
ENDNOTES 136

CHAPTER 8 ▪ Particle Decays 137
8.1 THE EMISSION OF LIGHT BY ATOMS 137
8.2 BARYON DECAY 137
8.2.1 Electromagnetic Decays 137
8.2.2 Strong Decays 139
8.2.3 Weak Decays 143
8.2.4 Neutron Decay 144
8.3 MESON DECAYS 146
8.4 STRANGENESS 148
8.5 LEPTON DECAYS 148
8.6 SUMMARY 149
ENDNOTE 149

CHAPTER 9 ▪ The Evidence for Quarks 151
9.1 THE THEORETICAL IDEA 151
9.2 TWO EXPERIMENTS 151
9.2.1 Rutherford Scattering 151
9.2.2 The SLAC Experiment 153
9.2.3 Deep Inelastic Scattering 153
9.3 JETS 155
9.3.1 Colored Quarks 158
9.3.2 Colored Gluons 159
9.3.3 Glueballs 161
9.4 HISTORICAL DEVELOPMENTS 162
9.4.1 Decays GIM, But Not as We Know Them 162
9.4.2 The November Revolution 163
9.4.3 Three Generations 164

9.5 SUMMARY 165
ENDNOTES 166

CHAPTER 10 ■ Experimental Techniques 167
10.1 BASIC IDEAS 167
10.2 ACCELERATORS 168
10.2.1 Lawrence's Cyclotron 168
10.2.2 A Modern Synchrotron 170
10.2.3 Storage Rings 172
10.2.4 Linear Accelerators 172
10.2.5 A List of Significant Accelerators 173
10.3 TARGETS 174
10.3.1 Fixed Targets 174
10.3.2 Colliders 174
10.4 DETECTORS 175
10.4.1 Bubble Chambers 176
10.4.2 Scintillation Counters 177
10.4.3 Cerenkov Detectors 177
10.4.4 Multiwire Proportional Chambers 178
10.4.5 Drift Chambers 179
10.4.6 Silicon Detectors 180
10.4.7 Calorimeters 180
10.4.8 Muon Chambers 181
10.5 A CASE STUDY: DELPHI 181
10.6 SUMMARY 184
ENDNOTES 185

CHAPTER 11 ■ Exchange Forces 187
11.1 QUANTUM FIELD THEORIES 187
11.1.1 Amplitudes for Quantum Fields 189
11.1.2 Field Theory and Lagrangians 191
11.1.3 Scattering 193
11.1.4 Feynman Diagrams 194
11.1.5 Approximation Series 196
11.1.6 The Problem of Attraction 198
11.2 EXTENDING THE IDEA 199

11.2.1 Quantum Chromodynamics 199
11.2.2 Gauge Theory 201
11.3 THE HIGGS MECHANISM 202
11.3.1 Symmetry Breaking 205
11.3.2 Last Point on Electroweak Symmetry Breaking 206
11.4 MASS SHELL AND EXCHANGE PARTICLES 206
11.5 PERTURBING MATTERS 208
11.5.1 Getting Rid of Λ 212
11.5.2 Running Coupling Constants 212
11.5.3 Be Free Quark … 214
11.5.4 Hadronic Mass Again 214
11.6 THE VACUUM 215
11.7 GRAND UNIFICATION 216
11.7.1 Exotic Theories 217
11.7.2 Final Thoughts 218
11.8 SUMMARY 218
ENDNOTES 219

CHAPTER 12 ▪ The Big Bang 223
12.1 THE STANDARD MODEL OF COSMOLOGY 223
12.2 THE EVOLUTION OF THE UNIVERSE 224
12.3 OBSERVATIONAL EVIDENCE FOR THE BIG BANG 225
12.3.1 Redshift 226
12.3.2 Helium Abundance 228
12.3.3 The Cosmic Background Radiation 229
12.3.4 Filaments and Voids 231
12.4 EXPLAINING THE EVIDENCE 233
12.4.1 RedShift and the Expansion of the Universe 234
12.4.2 The Temperature of the Universe 239
12.4.3 The Early History of the Universe 241
12.5 SUMMARY 245
ENDNOTES 246

CHAPTER 13 ■ The Geometry of Space 249
13.1 GENERAL RELATIVITY AND GRAVITY 249
13.1.1 When Is a Force Not a Force? 249
13.2 GEOMETRY 250
13.2.1 Breaking the Rules 251
13.3 THE GEOMETRY OF THE UNIVERSE 253
13.3.1 The Metric 255
13.3.2 The Overall Shape of the Universe 257
13.3.3 The Energy Density of the Universe 260
13.4 THE NATURE OF GRAVITY 262
13.5 GRAVITATIONAL WAVES 264
13.5.1 The Next Steps in Gravitational Wave Research 267
13.6 QUANTUM GRAVITY 269
13.7 SUMMARY 270
ENDNOTES 271

CHAPTER 14 ■ Contributions to Ω 273
14.1 THE RECIPE FOR A UNIVERSE 273
14.2 BARYONIC MATTER 273
14.2.1 Helium 4 274
14.2.2 Deuterium 274
14.2.3 Lithium 7 274
14.3 DARK MATTER 276
14.3.1 The Motion of Stars in Galaxies 276
14.3.2 The Motion of Galaxies in Clusters 279
14.3.3 Gravitational Lensing 280
14.3.4 The Bullet Cluster 282
14.3.5 The Large-Scale Structure of the Universe 282
14.3.6 Conclusions Regarding Dark Matter 284
14.4 CANDIDATES FOR DARK MATTER 284
14.4.1 Baryonic Dark Matter 284
14.4.2 Exotic Forms of Dark Matter 286
14.4.3 Cold Dark Matter Candidates 290
14.4.4 The Experimental Search for WIMPs 291

14.5 THE RETURN OF Λ 292
14.5.1 Supernova Observations 292
14.5.2 Scale and Hubble's Law 293
14.6 SUMMARY 299
ENDNOTES 300

CHAPTER 15 ■ Inflation: A Cure for All Ills 303
15.1 PROBLEMS WITH THE BIG BANG THEORY 303
15.1.1 The Flatness Problem 304
15.1.2 The Horizon Problem 305
15.2 INFLATION 309
15.2.1 When Is a Vacuum Not a Vacuum? 311
15.2.2 Inflation and Λ 315
15.3 QUANTUM COSMOLOGY 317
15.4 SUMMARY 317
ENDNOTES 318

CHAPTER 16 ■ Precision Cosmology 319
16.1 RIPPLES IN A SMOOTH BACKGROUND 319
16.2 PROBING THE COSMIC BACKGROUND 322
16.2.1 Superhorizon Fluctuations 322
16.2.2 Subhorizon Fluctuations 324
16.2.3 Baryon Acoustic Oscillations 325
16.2.4 Galaxy Distributions 328
16.2.5 Higher Order Peaks in the Power Spectrum 329
16.3 THE ERA OF PRECISION COSMOLOGY 330
16.4 GALAXY FORMATION 331
16.4.1 Dark Matter to the Rescue 333
16.4.2 Making Galaxies 334
16.4.3 Simulated Universes 337
16.5 MAINSTREAM SCIENCE 339
16.6 SUMMARY 340
ENDNOTES 340

CONCLUSION, 343

APPENDIX A, 347

APPENDIX B, 353

APPENDIX C, 359

APPENDIX D, 365

INDEX, 367