Contents

Preface v

Abbreviations ix

Notation and Symbols xi

PART I
Relativistic Kinematics and Quantum Fields 1

1 Introduction 3

2 The Theory of Special Relativity and Relativistic Kinematics 10

2.1 The Basic Principles of Special Relativity 11
2.2 Energy and Momentum of Relativistic Particles 20
2.3 The Relativistic Kinematics of a Collision Between Two Particles 23
Exercises 31

3 Particles and Fields 33

3.1 The Schrödinger, Dirac, and Heisenberg Pictures of Quantum Mechanics 33
3.2 Free Particles and the Fock Space 36

3.3 The Lagrange Formalism and the Noether Theorems 47
3.4 The Canonical Quantization Rules 52
Exercises 53

4 The Dirac Equation and the Dirac Field 55

4.1 The Dirac Equation 55
4.2 Solutions of the Dirac Equation 58
4.3 Transformation Rules for the Dirac Field 61
4.4 Quantization and Interpretation of the Dirac Field 66
4.5 Parity, Charge-Conjugation, and Time-Reversal Invariance of the Free Dirac Field 71
4.5.1 The Parity Transformation P 71
4.5.2 The Charge-Conjugation Transformation C 73
4.5.3 The Time-Reversal Transformation T 75
Exercises 78

5 The Scattering Matrix and the Scattering Cross-Section 80

5.1 The Scattering of Electrons by a Heavy Nucleus 80
5.2 General Definition of the S- and T-Matrix 87
5.3 The Unitary Relation and the Optical Theorem 91
5.4 The Decay Rate of an Unstable Particle 92
Exercises 92

PART II
Quantum Electrodynamics 95

6 Introductory Remarks 97

7 The Quantization of the Free Electromagnetic Field 101

7.1 Commutation Rules and Indefinite Metric 101
7.2 Normal-Ordered and Time-Ordered Products 107
Exercises 112

8 Further Aspects of the Theory of the Free Dirac Field 114

8.1 The Dirac Current 114
8.2 The Magnetic Moment of the Electron in the Dirac Theory 116
8.3 The Free Electron Propagator 119
Exercises 120

9 Electromagnetic Coupling and the Perturbation Expansion 121

9.1 The Electromagnetic Coupling of the Dirac Field 121
9.2 The Feynman Rules 123
Exercises 126

10 Simple Reactions in Quantum Electrodynamics 128

10.1 Electron–Electron Scattering (Møller Scattering) 128
10.2 Electron–Positron Scattering (Bhabha Scattering) 135
10.3 Compton Scattering 137
Exercises 141

11 The Muon and Muon Pair Production in Electron–Positron Annihilation 142

11.1 Properties of the Muon 142
11.2 The Reaction $e^-e^+ \to \mu^-\mu^+$ 144
Exercises 148

12 External Fields 149

12.1 The Scattering of Electrons in an External Potential 151
12.2 Bremsstrahlung 152
12.3 Pair Creation (The Bethe–Heitler Process) 158
Exercises 159

13 Positronium 160

13.1 The Spectrum of Positronium States and Their General Properties 160
13.2 The Decay of Positronium 163
Exercises 170

14 Radiative Corrections 171

14.1 Radiative Corrections to the Scattering in an External Potential 171
14.2 The Lamb Shift 175

PART III
The Strong Interaction 179

15 Historical Overview 181

16 Phenomenology of Hadronic Reactions 195

16.1 Resonance Physics 197
16.2 A Basis for the Hadron States and the Symmetries C, P, and T 199
16.3 Partial Wave Analysis 207
16.4 Total Cross-Sections at High Energies 213
16.5 Multi-Particle Production at High Energies 215
Exercises 221

17 Internal Symmetries of the Strong Interaction and the Quark Model 223

17.1 Mathematics of the SU(3) Group 223
17.2 The Quark Model and the Flavor-SU(3) Group 227
17.3 The Gell-Mann–Okubo Mass Formula 237
17.4 The SU(6) Symmetry 241
Exercises 244

18 The Naïve Parton Model 246

18.1 Electron–Positron Annihilation into Hadrons 248
18.2 Deep Inelastic Lepton–Nucleon Scattering 250
18.3 The Flavor Quantum Numbers of the Partons 259
18.4 Sum Rules and Evidence for Flavor-Neutral Partons, Gluons 266
18.5 The Drell–Yan Process 267
Exercises 271

19 The Basic Principles of Quantum Chromodynamics 273

19.1 The Lagrange Density of Quantum Chromodynamics (QCD) 273
19.2 Violation of the Bjorken Scale Invariance in Deep Inelastic Scattering 279
19.3 The Calculation of Anomalous Dimensions in QCD 284
19.4 Comparison of Deep Inelastic Scattering Data with QCD 288
Exercises 294

20 Jet and Quarkonium Physics 295

20.1 The Naïve Jet Model 295
20.2 Jets and QCD Effects in Electron–Positron Annihilation into Hadrons 302
20.3 Quarkonium 309
20.4 Jets in Hadron–Hadron Collisions 315
Exercises 320

PART IV
The Electroweak Interaction 323

21 From β-Decay to the W-Boson. A Historical Survey 325

21.1 The Early Days, the Neutrino Hypothesis, Four-Fermion Coupling 325
21.2 Parity Violation and the (V − A) Theory 328
21.3 The Universality of the Weak Interaction and the Cabibbo Theory 332
21.4 Neutral Currents, the W- and Z-Bosons, and the Glashow–Weinberg–Salam Theory 335
Exercises 337

22 The Lagrange Densities of Quantum Flavor Dynamics and of the Standard Model 338

22.1 The Gauge Group of the Electroweak Interaction 338
22.2 The Higgs Field and Spontaneous Symmetry Breaking 346
22.3 The Extension of Quantum Flavor Dynamics to Other Leptons and to Quarks, and the Effective Lagrange Density at Low Energies 355
22.4 The Mass Matrix and the Cabibbo Angles 361
22.5 The Lagrange Density of the Standard Model 369
Exercises 371

23 Decay Processes in the Standard Model and the Determination of the Quark Mixing Angles in the Charged Current 372

23.1 The Decay of the Muon 372
23.2 The Decay of the τ-Lepton 375
23.3 The β-Decay of the Neutron and the Determination of the Kobayashi–Maskawa Matrix Element V_{11} 377
23.4 Hyperon Decay Processes and the Determination of V_{12} 381
23.5 The Decays of Charged Pions 383
23.6 The Decay of Particles Containing a Heavy Quark c or b 386
Exercises 393

24 The Neutral Current and the Determination of $\sin^2 \vartheta_W$ 395

24.1 Neutrino–Electron Scattering 395
24.2 Neutrino–Nucleon Scattering 400
24.3 Effects of the Weak Interaction in Electron–Positron Annihilation 404
Exercises 412

25 The Physics of the Z-, W-, and Higgs Bosons 413

25.1 The Z-Boson 413
25.2 The W-Boson 420
25.3 The Production of W- and Z-Bosons in $p\bar{p}$ Collisions 423
25.4 The Spin of the W-Boson 430
25.5 The Higgs Boson 434
Exercises 437

26 The System of Neutral K-Mesons and CP Violation 439

26.1 Phenomenology of the Neutral K-Mesons 439
26.2 CP Violation and CPT Invariance in the Standard Model 449
26.2.1 CP Violation in the Lagrange Density 449
26.2.2 CPT Invariance 452
26.2.3 CP Violation in the Neutral K-Meson System in the Standard Model 454
Exercises 458

27 Order and Disorder in Elementary Particle Physics 460

27.1 Grand Unification 463
27.2 Further Symmetries at Intermediate Energies 466
27.3 Supersymmetry, Strings, and Superstrings 467
27.4 Order Out of Chaos 468

APPENDICES

A Dirac Matrices and Spinors 470

B The Feynman Rules of QED 473

C The Groups SU(2) and SU(3) 478

C.1 The Group SU(2) 478
C.2 The Group SU(3) 482

D The Feynman Rules of QCD 485

E The Q^2-Evolution of Quark and Gluon Distribution Functions of the Nucleons in QCD 490

F The Fierz Transformation 496

G The Feynman Rules for the Standard Model in the Unitary Gauge 499

H The Kobayashi–Maskawa Matrix for Three Families 506

I The Wigner–Weisskopf Approximation for the Description of the Decay of Unstable Particles and the K^0–$\bar{K}^0$ System 509

I.1 General Formalism 509
I.2 Application to the System of Neutral K-Mesons 517

J Solutions to Selected Exercises 522

References 537

Index 555