Contents

Preface *page* xiii

Part I Introduction 1

1 Matter and Light 3
- 1.1 Introduction 3
- 1.2 The Nature of Matter 3
- 1.3 Atomic Radiations 4
- 1.4 Rutherford's Atom 6
- 1.5 Two Problems 7

2 Special Relativity 8
- 2.1 Introduction 8
- 2.2 Galilean Relativity 8
- 2.3 The Origins of Special Relativity 10
- 2.4 The Lorentz–Fitzgerald Contraction 10
- 2.5 The Special Theory of Relativity 11
- 2.6 Mass Momentum and Energy 12
- 2.7 The Physical Effects of Special Relativity 13
- 2.8 Using Relativity 14

3 Quantum Mechanics 16
- 3.1 Introduction 16
- 3.2 Planck's Hypothesis 16
- 3.3 Einstein's Explanation of the Photoelectric Effect 17
- 3.4 Bohr's Atom 17
- 3.5 De Broglie's Electron Waves 19
- 3.6 Schrödinger's Wavefunction 20
- 3.7 Heisenberg's Mechanics and the Uncertainty Principle 21
- 3.8 The Interpretation of the Wavefunction ψ 22

3.9 Electron Spin 23
3.10 The Pauli Exclusion Principle 24
4 Relativistic Quantum Theory 26
4.1 Introduction 26
4.2 The Dirac Equation 26
4.3 Antiparticles 27
4.4 Quantum Field Theory (QFT) 29
4.5 Interacting Fields 30
4.6 Perturbation Theory 30
4.7 Virtual Processes 32
4.8 Renormalisation 32
4.9 The Quantum Vacuum 33
4.10 Quantum Electrodynamics 34
4.11 Postscript 35

Part II Basic Particle Physics 37
5 The Fundamental Forces 39
5.1 Introduction 39
5.2 Gravity 39
5.3 Electromagnetism 41
5.4 The Strong Nuclear Force 43
5.5 The Weak Nuclear Force 45
6 Symmetry in the Microworld 47
6.1 Introduction 47
6.2 Space–Time Symmetries 47
6.3 Discrete Symmetries 48
6.4 The CPT Theorem 50
6.5 Dynamical Symmetries 50
6.6 Internal Symmetries 51
6.7 Broken Symmetries 51
7 Mesons 52
7.1 Introduction 52
7.2 Yukawa's Proposal 52
7.3 The Muon 52
7.4 The Real Pion 53
7.5 Terminology 54
7.6 Isotopic Spin 55
8 Strange Particles 56
8.1 Introduction 56
8.2 Associated Production 56
8.3 The Kaons 57
8.4 The Hyperons 59
8.5 Summary 59

Part III Strong Interaction Physics 61
9 Resonance Particles 63
9.1 Introduction 63
9.2 Resonance Particle Experiments 63
10 SU(3) and Quarks 65
10.1 Introduction 65
10.2 Internal Symmetry 65
10.3 Quarks 66

Part IV Weak Interaction Physics I 69
11 The Violation of Parity 71
11.1 Introduction 71
11.2 β Decay of Cobalt 71
11.3 Absolute-handedness and CP Invariance 73
12 Fermi's Theory of the Weak Interactions 75
12.1 Introduction 75
12.2 Fermi's Theory of β Decay 75
12.3 Spin, Helicity and Chirality 76
12.4 The Polarisation of β-decay Electrons 76
12.5 Neutrino Helicity 77
12.6 In Conclusion 78
13 Two Neutrinos 79
13.1 Introduction 79
13.2 A Problem in the Weak Interactions 79
13.3 The Two-neutrino Experiment 80
14 Neutral Kaons and CP Violation 82
14.1 Introduction 82
14.2 What is a Neutral Kaon? 82
14.3 Violation of CP Symmetry 83

Part V Weak Interaction Physics II 85
15 The Current–Current Theory of the Weak Interactions 87
15.1 Introduction 87
15.2 The Lepton Current 87
15.3 Higher-order Interactions 88
16 An Example Leptonic Process: Electron-neutrino Scattering 90
16.1 Introduction 90
16.2 The Role of the Weak Force in Astrophysics 91
17 The Weak Interactions of Hadrons 92
17.1 Introduction 92
17.2 The Hadronic Current 92
17.3 The Hadron Current and Quarks 93
18 The W Boson 94
18.1 Introduction 94
18.2 The W Boson 94
18.3 Observing the W Boson 95

Part VI Gauge Theory of the Weak Interactions 97
19 Motivation for the Theory 99
19.1 Introduction 99
19.2 Problems with the W Bosons 99

20 Gauge Theory 101
20.1 Introduction 101
20.2 The Formulation of QED 101
20.3 Generalised Gauge Invariance 102
20.4 Gauge Invariance and the Weak Interactions 103
21 Spontaneous Symmetry Breaking 105
21.1 Introduction 105
21.2 Spontaneous Breaking of Global Symmetry 105
21.3 Spontaneous Breaking of Local Symmetry – the Higgs Mechanism 106
22 The Glashow–Weinberg–Salam Model 108
22.1 Introduction 108
22.2 Formulation 108
22.3 Reprise 111
22.4 An Academic Postscript – Renormalisability 111
23 Consequences of the Model 112
23.1 Introduction 112
23.2 Neutral Currents 112
23.3 The Incorporation of Hadrons – Charm 113
23.4 Parity-violating Tests of the Glashow–Weinberg-Salam Model 115
24 The Hunt for the $W^{\pm}$, Z^0 Bosons 116
24.1 Introduction 116
24.2 The CERN $\mathbf{p\bar{p}}$ Collider Experiment 116
24.3 Detecting the Bosons 118
24.4 Epilogue 121

Part VII Deep Inelastic Scattering 123
25 Deep Inelastic Processes 125
25.1 Introduction 125
25.2 Two Key Ideas 126
26 Electron–Nucleon Scattering 127
26.1 Introduction 127
26.2 The Scaling Hypothesis 127
26.3 Exploring the Structure Functions 129
27 The Deep Inelastic Microscope 131
27.1 Introduction 131
27.2 Free Quarks and Strong Forces 131
28 Neutrino–Nucleon 134
28.1 Introduction 134
28.2 Neutrino Experiments 134
28.3 The Cross-section 135
28.4 The Scaling Hypothesis 135
29 The Quark Model of the Structure Functions 138
29.1 Introduction 138
29.2 Electromagnetic Structure Functions 138
29.3 Weak Interaction Structure Functions 139
29.4 Electron and Neutrino Structure Functions Compared 140
29.5 Sum Rules 140
29.6 Summary 141

Part VIII Quantum Chromodynamics – the Theory of Quarks 143
30 Coloured Quarks 145
30.1 Introduction 145
30.2 Colour 145
30.3 Invisible Colour 147
31 Colour Gauge Theory 150
31.1 Introduction 150
31.2 The Formulation of QCD 150
32 Asymptotic Freedom 154
32.1 Introduction 154
32.2 Violations of Scaling 157
33 Quark Confinement 160
33.1 Introduction 160
33.2 Quark Forces – Hadron Forces 162

Part IX Electron–Positron Collisions 165
34 Probing the Vacuum 167
34.1 Introduction 167
34.2 The Experiments 167
34.3 The Basic Reactions 168
35 Quarks and Charm 171
35.1 Introduction 171
35.2 The Quark Picture 171
35.3 The Advent of Charm 172
35.4 Psichology 174
35.5 Charmed Particles 176
36 Another Generation 178
36.1 Introduction 178
36.2 The Upsilon 178
36.3 The Tau Heavy Lepton 179
36.4 Completing the Third Generation 181

Part X The Standard Model 183
37 The Model in Summary 185
37.1 Introduction 185
37.2 Summary of the Standard Model 185
37.3 Consistency of the Standard Model 186
38 Precision Tests of the Model 189
38.1 Introduction 189
38.2 Precision Tests of the Gauge Interactions 191

39 Flavour Mixing and CP Violation 195
39.1 Introduction 195
39.2 CP Violation in the Standard Model 195
39.3 CP-Violation Experiments 196
39.4 B-Physics Experiments 197
39.5 K-Meson Experiments 198
40 The Large Hadron Collider 199
40.1 Introduction 199
40.2 Historical Constraints on the Higgs Boson Mass 199
40.3 The Large Hadron Collider Concept 200
40.4 Construction Timeline 200
40.5 The LHC Experiments 200
40.6 CERN and the World Wide Web 201
41 Discovery and Properties of the Higgs Boson 204
41.1 Introduction 204
41.2 Decays of the Higgs Boson 204
41.3 Production of the Higgs Boson 205
41.4 Discovery of the Higgs Boson 205
41.5 Properties of the Higgs Boson 206
41.6 The Future of Higgs Physics 207

Part XI Beyond the Standard Model 209
42 Reasons to Go Beyond 211
42.1 Introduction 211
43 Neutrino Masses and Mixing 213
43.1 Introduction 213
43.2 The Solar Neutrino Problem 213
43.3 Neutrino Oscillations 214
43.4 Neutrino Oscillation Experiments 214
43.5 Solar Experiments 214
43.6 Atmospheric Experiments 215
43.7 Short Baseline Experiments 217
43.8 Theory of Neutrino Masses and Mixings 218
43.9 A Minimal Extension of the Standard Model 218
44 Grand Unification 220
44.1 Introduction 220
45 Supersymmetry 223
45.1 Introduction 223
45.2 Miracles of SUSY 223
45.3 SUSY and the Real World 224
45.4 The Hierarchy Problem 224
45.5 SUSY as a Resolution of the Hierarchy Problem 224
45.6 Supersymmetrising the Standard Model 225
45.7 Supersymmetry Breaking and the MSSM 225
45.8 Another Prediction of SUSY 225
45.9 Supersymmetry and Dark Matter 225
45.10 Supersymmetry and the LHC 226
46 Composite Higgs Models 228
46.1 Introduction 228
46.2 A World without the Higgs 228
46.3 Technicolour 229
46.4 Composite Higgs 229
46.5 Composite Higgs at Colliders 230
47 Axions and the Strong CP Problem 231
47.1 The Strong CP Problem 231
47.2 The Axion 231
47.3 The Axion Window 232

Part XII Particle Physics and Cosmology 233
48 The Big Bang and Inflation 235
48.1 Introduction 235
48.2 Big Bang Cosmology 235
48.3 Beyond the Big Bang 238
48.4 Inflation 238
48.5 Theories of Inflation 239
49 The Cosmic Microwave Background 240
49.1 Introduction 240
49.2 Observations of the CMB Anisotropy 240
49.3 Physics of the CMB Anisotropy 241
49.4 CMB Polarisation 242
50 The Matter–Antimatter Asymmetry 243
50.1 Introduction 243
50.2 GUT Baryogenesis 243
50.3 Baryogenesis via Leptogenesis 244
50.4 Electroweak Baryogenesis 245
51 Dark Matter 246
51.1 Introduction 246
51.2 Gravitational Evidence for Dark Matter 246
51.3 Dark Matter Candidates 247
51.4 Searches for Dark Matter 248
52 Dark Energy 249
52.1 Introduction 249
52.2 Einstein's Cosmological Constant 249
52.3 Supernovae and Dark Energy 249
52.4 The Cosmological Hierarchy Problem 251
52.5 The 'Why Now?' Problem 251

52.6 The Anthropic Principle 251
52.7 Summary 251

Part XIII Gravity and Gravitational Waves 253
53 From General Relativity to Gravitational Waves 255
53.1 Introduction 255
53.2 Hulse–Taylor Variation in Binary Pulsar Periodicity 256
53.3 Modern Astrophysics 256
54 The Discovery of Gravitational Waves 259
54.1 Introduction 259
54.2 LIGO 259
54.3 The Detection of GW150914 259
54.4 Subsequent Events 262
55 Gravitational-wave and Multi-messenger Astronomy 263
55.1 Introduction 263
55.2 Gravitational-wave Astronomy 263
55.3 GW170817 – a Binary Neutron Star Merger 264
56 The Future: Super LIGO and LISA 266

Part XIV String Theory 269
57 Origins – the Hadronic String 271
57.1 The Success of QFT 271
57.2 The Problem of Gravity 271
57.3 Strings versus Particles 272
57.4 The Hadronic String 273
58 String Theory to M-theory 275
58.1 The Search for a Consistent String Theory 275
58.2 String Theories Contain More Than String 276
59 The AdS–CFT Correspondence 278
59.1 The Miracle of Duality 278
59.2 The String Theory Side 278
59.3 The Quantum Field Theory Side 279
59.4 The AdS–CFT Dictionary 279
59.5 Applications of AdS–CFT 279
60 Consequences of the Theory 280
60.1 The Richness of String and M-theory 280
60.2 Back to the Anthropic Principle 281
60.3 A Theory in Search of Experiment 281
60.4 Conclusion 282

Part XV The Future: To Boldly Go! 283
61 Accelerators, Observatories and Other Experiments 285
61.1 Accelerators 285
61.2 Observatories and Other Experiments 286
62 Known Unknowns 289
62.1 The Current In-tray 289
63 Glittering Prizes 291
63.1 The Class of 1984 291
64 Unknown Unknowns: It Must Be Beautiful 292
64.1 The Challenges of Quantum Gravity 292
64.2 The Beautiful Equations 293

Appendices 295
A Units and Constants 297
B Glossary 298
C List of Symbols 306
D Bibliography 308
E Elementary Particle Data 312

Name Index 313
Subject Index 314