

Particle physics

B.R. Martin, G. Shaw

4th ed. - ©2017

TABLE OF CONTENTS

Editors' preface to the Manchester Physics Series xiii

Authors' preface xv

Suggested Short Course xvii

Notes xix

Physical Constants, Conversion Factors and Natural Units xxi

1 Some basic concepts 1

1.1 Introduction 1

1.2 Antiparticles 3

1.2.1 Relativistic wave equations 3

1.2.2 Hole theory and the positron 6

1.3 Interactions and Feynman diagrams 9

1.3.1 Basic electromagnetic processes 10

1.3.2 Real processes 11

1.3.3 Electron-positron pair production and annihilation 13

1.3.4 Other processes 15

1.4 Particle exchange 15

1.4.1 Range of forces 15

1.4.2 The Yukawa potential 17

1.4.3 The zero-range approximation 18

1.5 Units and dimensions 19

Problems 1 22

2 Leptons and the weak interaction 24

2.1 Lepton multiplets and lepton numbers 24

2.1.1 Electron neutrinos 25

2.1.2 Further generations 28

2.2 Leptonic weak interactions 31

2.2.1 $W^\pm$ and Z^0 exchange 31

2.2.2 Lepton decays and universality	33
2.3 Neutrino masses and neutrino mixing	35
2.3.1 Neutrino mixing	35
2.3.2 Neutrino oscillations	38
2.3.3 Neutrino masses	46
2.3.4 Lepton numbers revisited	48
Problems 2	50

3 Quarks and hadrons 52

3.1 Quarks	53
3.2 General properties of hadrons	55
3.3 Pions and nucleons	58
3.4 Strange particles, charm and bottom	61
3.5 Short-lived hadrons	66
3.6 Allowed and exotic quantum numbers	72
Problems 3	75

4 Experimental methods 77

4.1 Overview	77
4.2 Accelerators and beams	79
4.2.1 Linear accelerators	80
4.2.2 Cyclic accelerators	81
4.2.3 Fixed-target machines and colliders	83
4.2.4 Neutral and unstable particle beams	85
4.3 Particle interactions with matter	86
4.3.1 Short-range interactions with nuclei	86
4.3.2 Ionisation energy losses	89
4.3.3 Radiation energy losses	92
4.3.4 Interactions of photons in matter	93
4.3.5 Ranges and interaction lengths	94
4.4 Particle detectors	95
4.4.1 Introduction	96
4.4.2 Gaseous ionisation detectors	97
4.4.3 Semiconductor detectors	103
4.4.4 Scintillation counters	104

4.4.5 γ Cerenkov counters and transition radiation 105

4.4.6 Calorimeters 109

4.5 Detector systems and accelerator experiments 112

4.5.1 Discovery of the $W^\pm$ and Z^0 bosons 113

4.5.2 Some modern detector systems 117

4.6 Non-accelerator experiments 121

Problems 4 123

5 Space-time symmetries 126

5.1 Translational invariance 127

5.2 Rotational invariance 129

5.2.1 Angular momentum conservation 129

5.2.2 Classification of particles 132

5.2.3 Angular momentum in the quark model 134

5.3 Parity 135

5.3.1 Leptons and antileptons 137

5.3.2 Quarks and hadrons 139

5.3.3 Parity of the charged pion 140

5.3.4 Parity of the photon 141

5.4 Charge conjugation 142

5.4.1 π^0 and η decays 144

5.5 Positronium 145

5.5.1 Fine structure 147

5.5.2 C -parity and annihilations 148

5.6 Time reversal 149

5.6.1 Principle of detailed balance 151

5.6.2 Spin of the charged pion 152

Problems 5 153

6 The quark model 155

6.1 Isospin symmetry 156

6.1.1 Isospin quantum numbers 157

6.1.2 Allowed quantum numbers 158

6.1.3 An example: the sigma (Σ) baryons 159

6.1.4 The u , d quark mass splitting 161

6.2 The lightest hadrons 162

6.2.1 The light mesons 162

6.2.2 The light baryons 164

6.2.3 Baryon magnetic moments 167

6.2.4 Hadron mass splittings 169

6.3 The $L = 0$ heavy quark states 174

6.4 Colour 177

6.4.1 Colour charges and confinement 178

6.4.2 Colour wavefunctions and the Pauli principle 182

6.5 Charmonium and bottomonium 184

6.5.1 Charmonium 185

6.5.2 Bottomonium 189

6.5.3 The quark–antiquark potential 189

Problems 6 191

7 QCD, jets and gluons 193

7.1 Quantum chromodynamics 193

7.1.1 The strong coupling constant 197

7.1.2 Screening, antiscreening and asymptotic freedom 199

7.1.3 Exotic hadrons 201

7.1.4 The quark–gluon plasma 208

7.2 Electron–positron annihilation 210

7.2.1 Two-jet events 211

7.2.2 Three-jet events 213

7.2.3 The total cross-section 214

Problems 7 215

8 Quarks and partons 217

8.1 Elastic electron scattering: the size of the proton 217

8.1.1 Static charge distributions 218

8.1.2 Proton form factors 219

8.1.3 The basic cross-section formulas 221

8.2 Inelastic electron and muon scattering 222

8.2.1 Bjorken scaling 224

8.2.2 The parton model 226

8.2.3 Parton distributions and scaling violations 228

8.3 Inelastic neutrino scattering 231

8.3.1 Quark identification and quark charges 234

8.4 Other processes 236

8.4.1 Lepton pair production 239

8.4.2 Jets in pp collisions 242

8.5 Current and constituent quarks 243

Problems 8 246

9 Weak interactions: quarks and leptons 248

9.1 Charged current reactions 250

9.1.1 $W^\pm$ -lepton interactions 250

9.1.2 Lepton-quark symmetry and mixing 254

9.1.3 W boson decays 258

9.1.4 Selection rules in weak decays 259

9.2 The third generation 262

9.2.1 More quark mixing 263

9.2.2 Properties of the top quark 265

9.2.3 Discovery of the top quark 267

Problems 9 274

10 Weak interactions: electroweak unification 276

10.1 Neutral currents and the unified theory 277

10.1.1 The basic vertices 277

10.1.2 The unification condition and the $W^\pm$ and Z^0 masses 279

10.1.3 Electroweak reactions 281

10.1.4 Z^0 formation: how many generations are there? 284

10.2 Gauge invariance and the Higgs boson 287

10.2.1 Unification and the gauge principle 289

10.2.2 Particle masses and the Higgs field 290

10.2.3 Properties of the Higgs boson 294

10.2.4 The discovery of the Higgs boson 297

Problems 10 305

11 Discrete symmetries: C, P, CP and CPT 308

11.1 P violation, C violation and CP conservation 308

11.1.1 Muon decay symmetries	310
11.1.2 Left-handed neutrinos and right-handed antineutrinos	312
11.1.3 Pion and muon decays revisited	314
11.2 CP violation and particle–antiparticle mixing	316
11.2.1 CP eigenstates of neutral kaons	316
11.2.2 The discovery of CP violation	319
11.2.3 CP -violating K_L^0 decays	321
11.2.4 Flavour oscillations and the CPT theorem	324
11.2.5 Direct CP violation in decay rates	328
11.2.6 $B^0 - \bar{B}^0$ mixing	329
11.2.7 CP violation in interference	335
11.2.8 Derivation of the mixing formulas	338
11.3 CP violation in the standard model	340
Problems 11	343

12 Beyond the standard model 346

12.1 Grand unification	347
12.1.1 Quark and lepton charges	349
12.1.2 The weak mixing angle	349
12.1.3 Proton decay	350
12.2 Supersymmetry	354
12.2.1 The search for supersymmetry	356
12.3 Strings and things	358
12.4 Particle physics and cosmology	360
12.4.1 Dark matter	360
12.4.2 Matter–antimatter asymmetry	367
12.4.3 CP violation and electric dipole moments	369
12.4.4 Axions and the strong CP problem	371
12.5 Dirac or Majorana neutrinos?	373
12.5.1 Double beta decay	375
Problems 12	381

A Relativistic kinematics 383

A.1 The Lorentz transformation for energy and momentum	383
A.2 The invariant mass	385

A.2.1 Beam energies and thresholds	385
A.2.2 Masses of unstable particles	387
A.3 Transformation of the scattering angle	388
Problems A	390

B Amplitudes and cross-sections 392

B.1 Rates and cross-sections	392
B.2 The total cross-section	394
B.3 Differential cross-sections	395
B.4 The scattering amplitude	397
B.5 The Breit-Wigner formula	400
B.5.1 Decay distributions	401
B.5.2 Resonant cross-sections	404
Problems B	406

C The isospin formalism 408

C.1 Isospin operators	409
C.2 Isospin states	411
C.3 Isospin multiplets	411
C.3.1 Hadron states	412
C.4 Branching ratios	414
C.5 Spin states	416
Problems C	416

D Gauge theories 418

D.1 Electromagnetic interactions	419
D.2 Gauge transformations	420
D.3 Gauge invariance and the photon mass	421
D.4 The gauge principle	423
D.5 The Higgs mechanism	425
D.5.1 Charge and current densities	425
D.5.2 Spin-0 bosons	427
D.5.3 Spontaneous symmetry breaking	428
D.6 Quantum chromodynamics	429
D.7 Electroweak interactions	434
D.7.1 Weak isospin	434

D.7.2 Gauge invariance and charged currents 436

D.7.3 The unification condition 437

D.7.4 Spin structure and parity violation 440

Problems D 441

E Answers to selected questions 443

References 448

Index 451