# CONTENTS

Preface vii

INTRODUCTION

**1 The Klein–Gordon and Dirac equations and the interpretation of their negative-energy solutions 3**
1.1 The Klein–Gordon equation 3
1.2 The Dirac equation 6
1.3 The Dirac and Feynman interpretations of negative-energy solutions 11

PART I: THE BEST THEORY WE HAVE: QUANTUM ELECTRODYNAMICS

**2 The electromagnetic interactions of spin-0 particles 21**
2.1 First-order perturbation theory 21
2.2 Electromagnetic scattering of charged spinless bosons 24
2.3 The Feynman diagram for the matrix element 29
2.4 More examples: $\pi^+\pi^+$ and $\pi^+\pi^-$ scattering 31
2.5 Derivation of the cross section 33
2.6 Explicit evaluation of the $\pi^+K^+$ cross section in the CM frame 35
2.7 Pion Compton scattering I 39
2.8 Polarisation vectors for spin-1 particles 41
2.9 The propagator for a virtual pion 44
2.10 Pion Compton scattering II 45
2.11 Higher-order calculations: trees and loops 50

**3 The electromagnetic interactions of spin-$\frac{1}{2}$ particles 54**
3.1 Positive- and negative-energy spinors 54
3.2 Feynman interpretation of negative-energy solutions 56
3.3 Electrons interacting with potential $A^\mu$ 57
3.4 Normalisation of Dirac spinors 60
3.5 $\pi^+e^-$ elastic scattering 62

3.6 Trace techniques for spin summations 65
3.7 Cross sections for $e^-\pi^+$ and $e^+\pi^+$ scattering 69
3.8 The pion form factor and invariance arguments 70
3.9 Electron–muon elastic scattering 74
3.10 Electron–proton elastic scattering and nucleon form factors 77
3.11 Higher-order calculations and tests of QED 81

**4 Deep inelastic electron–nucleon scattering and the quark parton model 89**
4.1 Inelastic ep scattering: kinematics and structure functions 89
4.2 Bjorken scaling and the parton model 92
4.3 The quark parton model 99
4.4 The Drell–Yan process 102
4.5 $e^+e^-$ annihilation into hadrons 104

PART II: NOT QUITE A THEORY: PHENOMENOLOGY OF WEAK INTERACTIONS

**5 Introduction to weak interactions 111**
5.1 Fermi theory and intermediate vector bosons 111
5.2 Parity violation in weak interactions 116
5.3 Vector and axial vector currents 117
5.4 Left-handed neutrinos 120
5.5 $V-A$ theory 123

**6 The hadronic weak current and neutral currents 130**
6.1 Universality and Cabibbo theory 130
6.2 Deep inelastic neutrino scattering 133
6.3 Neutral currents 135
6.4 Charm and the Glashow–Iliopoulos–Maiani Mechanism 138
6.5 Historical footnote 141

PART III: DISEASES AND THEIR CURE: THE GAUGE PRINCIPLE

**7 Difficulties with weak interaction phenomenology 147**
7.1 Violation of unitarity in the pointlike four-fermion model 147
7.2 Violation of unitarity bounds in the IVB model 149
7.3 Renormalisation 154
7.4 The problem of nonrenormalisability in weak interactions 162

**8 Gauge invariance as a dynamical principle** **168**
8.1 Gauge invariance and the Maxwell equations 168
8.2 Gauge invariance in quantum mechanics 172
8.3 The argument reversed: the gauge principle 175
8.4 Other global phase invariances 179
8.5 Non-Abelian gauge theories 184

**9 Hidden gauge invariance** **192**
9.1 Introduction 192
9.2 Screening currents and the generation of 'photon mass' 193
9.3 The nature of the physical vacuum: spontaneous symmetry breakdown 203
9.4 Gauge invariance when the symmetry is hidden 206
9.5 't Hooft's gauges 212
9.6 Postscript 216

PART IV: APPLICATIONS OF THE GAUGE PRINCIPLE

**10 An introduction to quantum chromodynamics** **221**
10.1 Introduction 221
10.2 $SU(3)_c$ as a local symmetry: a first look at the Feynman rules for QCD 224
10.3 Electromagnetic interactions of vector particles and the three-gluon vertex 228
10.4 The four-gluon vertex 234
10.5 Applications of perturbative QCD 235

**11 The Glashow–Salam–Weinberg gauge theory of electroweak interactions** **238**
11.1 Introduction 238
11.2 Weak isospin and hypercharge: the $SU(2) \times U(1)$ group of the electroweak interactions 239
11.3 $SU(2)_L \times U(1)$ as a local symmetry: charged-current vertices 243
11.4 Hidden $SU(2)_L \times U(1)$ gauge invariance 244
11.5 Feynman rules for tree graphs in the GSW theory and the Higgs sector 253
11.6 The problem of the fermion masses 258
11.7 Some phenomenological implications of the GSW theory 260

## PART V: BEYOND THE TREES

**12 Four last things** **271**
12.1 Ghost loops and unitarity in non-Abelian gauge theories 271
12.2 Asymptotic freedom 281
12.3 Grand unification 287
12.4 Confinement 292

**Appendix A:** Revision Notes 298

**Appendix B:** Natural units 305

**Appendix C:** Maxwell's equations: Choice of units 308

**Appendix D:** Dirac algebra and trace theorems 310

**Appendix E:** Example of a cross section evaluation 314

**Appendix F:** Feynman rules for tree graphs in QED, QCD and the standard model 320

References 329

Index 333