CONTENTS

II. QUANTUM ELECTRODYNAMICS 191

A. PHOTONS AND CHARGED FERMIONS 195

1. Field operators 195
2. Photons 196
3. Fermions 198
4. Destruction and creation of particles 204
5. Positrons 208

B. THE ELECTROMAGNETIC INTERACTION; FEYNMAN GRAPHS 212

1. The interactions between field and source 212
   (a) The interaction operator 212
   (b) Helicity rules in ultrarelativistic phenomena 214
   (c) Vertices 216
2. The scattering amplitude 219
3. Compton scattering 221
   (a) Diagrams for Compton scattering 221
   (b) A spin-zero model 222
   (c) Compton amplitudes and the Klein-Nishina formula 225
   (d) Evaluation of cross sections 226
4. Feynman diagrams 228
5. The dimensionality of the coupling constant and the high-energy behavior of amplitudes 230

C. EXAMPLES OF ELECTROMAGNETIC INTERACTIONS 232

1. Scattering of two different fermions 232
2. Colliding beam processes: $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to e^+e^-$ 235
3. Data on e^+e^- collisions; tests of quantum electrodynamics 238
4. Bound states 243
5. Hydrogen, μ-mesic atoms, and muonium 244
6. Positronium 247
7. The decay of positronium: Charge conjugation 248

D. THE SELF-ENERGY OF THE ELECTRON, VACUUM POLARIZATION, AND PRECISION TESTS OF QUANTUM ELECTRODYNAMICS 252

1. Radiative corrections 253
2. The electron self-energy and mass renormalization 255
3. Vacuum polarization 258
4. The Lamb shift 266
5. The anomalous magnetic moment of the electron and muon 270
6. Other spectroscopic tests of quantum electrodynamics 272
7. Summary 273

III. HADRONIC SPECTROSCOPY 275

A. HADRONIC DIMENSIONS AND SPECTRA 278

1. The electromagnetic size of hadrons 279
2. Hadronic diffraction scattering and the size of hadrons 281
3. Excited states of hadrons 283
4. Photoproduction 288
5. Pion-nucleon scattering 291
6. Consequences of the isospin assignments 295
7. Kaon-nucleon scattering and the $S \neq 0$ excited states of the baryon 297
8. Hadron excitations observed by decay 297
9. G-parity 303

B. MESONS COMPOSED OF HEAVY QUARK-ANTIQUARK PAIRS 312

1. $e\bar{e} \rightarrow \mu\bar{\mu}$ revisited 313
2. Narrow hadron resonances in $e\bar{e}$-hadron production 317
3. The $Q\bar{Q}$ spectrum 323
4. Hadronic decays of $Q\bar{Q}$ states 333

IV. QUANTUM CHROMODYNAMICS 339

A. COLOR 342

1. The color variable 342
2. The group *SU(3)* 347
   (a) Definition of groups. *SU(2)* and *SU(3)* 348

(b) An *SU(3)* primer 350
(c) Further aspects of *SU(3)* 358

B. GAUGE FIELDS 364

1. Global vs. local symmetries 364
2. The gauge field 366
3. Quanta of the gauge field and coupling to quarks 371

C. GAUGE FIELD DYNAMICS 374

1. Color analogues of the electromagnetic field strengths 374
2. Self-interactions of the gauge field 377
3. The Yang-Mills field equations 377
4. Asymptotic freedom 380
   (a) Comparison with QED 380
   (b) Antiscreening—A qualitative discussion 381
   (c) Antiscreening by an electromagnetic analogy 386
   (d) The results of an exact perturbation calculation 390
   (e) Renormalization of the coupling constant. Asymptotic freedom 394
5. Confinement 397
   (a) The QCD vacuum 397
   (b) The long-distance interaction 400
   (c) The semiempirical quark–antiquark interaction 401

D. THE BAG MODEL 404

1. The primitive bag model 404
2. The improved bag model 409
3. Quantitative test of the model 414
4. The long-range potential and the Regge slope 417

V. DEEP INELASTIC LEPTON-HADRON SCATTERING 421

1. Introduction 423
2. Kinematic variables 425
3. Deep inelastic electron and muon scattering cross sections 427
4. Deep inelastic electron and muon scattering according to the quark model 428
5. The quark momentum distributions in the nucleon 432

6. Charge-changing neutrino scattering 439
(a) Cross sections for inelastic neutrino scattering 439
(b) Neutrino-quark cross sections 440
(c) Neutrino-nucleon scattering 442
(d) Structure functions 444
7. Theoretical considerations regarding the quark distributions 449
(a) The quark momentum distribution in the nucleon 449
(b) The gluon field in the nucleon 452
(c) The sea quarks 457
(d) The structure functions 459
8. Scaling violations 460

VI. THE ELECTROWEAK INTERACTION 465

A. CHARGE-CHANGING WEAK INTERACTIONS 469

1. The charge-changing weak current 469
2. The Hamiltonian for charge-changing weak interactions 474
(a) The Fermi interaction 474
(b) The strength of the semileptonic interaction 475
3. Defects of the $W^{\pm}$ model of weak interactions 478

B. NEUTRAL CURRENT WEAK INTERACTIONS AND THE ELECTROWEAK CONNECTION 483

1. Conservation of the weak current: The neutral current 483
(a) Demonstration that $J_{\pm}$ are not conserved currents 483
(b) Weak isospin 485
(c) Conservation of weak isospin 487
(d) The symmetric weak interaction 488
2. The electroweak connection 491
(a) Incorporation of electrodynamics 491
(b) The Z^0 and the mixing angle θ_W 493
(c) University and unification 495
3. Neutral current phenomena and the determination of the coupling constants 496
(a) The neutral current weak interaction 496
(b) Deep inelastic neutrino scattering 499
(c) Parity violation in inelastic electron scattering 502

(d) The basic parameters of the electroweak theory 504
(e) Z^0-production in $e\bar{e}$-annihilation 506

C. THE HIDDEN GAUGE INVARIANCE OF THE ELECTROWEAK INTERACTION 509

1. Hidden symmetry in ferromagnetism and superconductivity 509
   (a) Ferromagnetism 509
   (b) Superconductivity 511
2. The generation of mass in the electroweak theory 516
   (a) Analogies between superconductivity and electroweak phenomena 516
   (b) The electroweak gauge group 517
   (c) The Standard Model; the masses of Z and W 519
   (d) The Higgs boson and its couplings 523

D. GRAND UNIFICATION 529

1. Basic assumptions and immediate consequences 530
2. Evaluation of the electroweak angle at low energies 535
3. Other aspects of the Grand Unified Theory 540
   (a) The gauge group 540
   (b) Symmetry breaking 541
   (c) Proton decay 542

Appendix II. Bose fields 545

1. The harmonic oscillator 545
   (a) The classical oscillator 545
   (b) Quantized oscillator 546
2. The scalar field 548
   (a) Real fields 549
   (b) Complex fields 553
3. The electromagnetic field 556

Appendix III. The Dirac field 559

1. The Lorentz transformation of spinors and the Dirac equation 559
   (a) Three-vectors as 2×2 matrices 559
   (b) Four-vectors as 2×2 matrices 560
   (c) Spinors 562
   (d) The Dirac equation 563

(e) Four-currents 566
2. The Dirac field operator 567
(a) The field operator: Anticommutation rules 567
(b) Energy, momentum, and charge 568
(c) The relative parity of particle and antiparticle 570
3. Amplitudes for weak and electromagnetic scattering 571
4. Spin and statistics 573

Appendix IV. Causality and its consequences 577
1. The basic axiom of quantum field theory 577
2. The connection between spin and statistics 579
3. The need for antiparticles; Crossing symmetry 583

Appendix V. Vacuum polarization 587

Appendix VI. The magnetic susceptibility of a massless vector field 593

Appendix VII. Solutions of Dirac's equation in a spherical enclosure 597

Bibliography 600

Index 603