

Contents

| | |
|---|-------------|
| Foreword | <i>V</i> |
| Preface | <i>XVII</i> |
| Acknowledgements | <i>XXI</i> |
| Part One A Field Theoretical Approach | <i>1</i> |
| 1 Introduction | <i>3</i> |
| 1.1 An Overview of the Standard Model | <i>3</i> |
| 1.1.1 What is an Elementary Particle? | <i>3</i> |
| 1.1.2 The Four Fundamental Forces and Their Unification | <i>4</i> |
| 1.1.3 The Standard Model | <i>7</i> |
| 1.2 The Accelerator as a Microscope | <i>11</i> |
| 2 Particles and Fields | <i>13</i> |
| 2.1 What is a Particle? | <i>13</i> |
| 2.2 What is a Field? | <i>21</i> |
| 2.2.1 Force Field | <i>21</i> |
| 2.2.2 Relativistic Wave Equation | <i>25</i> |
| 2.2.3 Matter Field | <i>27</i> |
| 2.2.4 Intuitive Picture of a Field and Its Quantum | <i>28</i> |
| 2.2.5 Mechanical Model of a Classical Field | <i>29</i> |
| 2.3 Summary | <i>32</i> |
| 2.4 Natural Units | <i>33</i> |
| 3 Lorentz Invariance | <i>37</i> |
| 3.1 Rotation Group | <i>37</i> |
| 3.2 Lorentz Transformation | <i>41</i> |
| 3.2.1 General Formalism | <i>41</i> |
| 3.2.2 Lorentz Vectors and Scalars | <i>43</i> |
| 3.3 Space Inversion and Time Reversal | <i>45</i> |
| 3.4 Covariant Formalism | <i>47</i> |
| 3.4.1 Tensors | <i>47</i> |
| 3.4.2 Covariance | <i>48</i> |
| 3.4.3 Supplementing the Time Component | <i>49</i> |

| | | |
|----------|---|------------|
| 3.4.4 | Rapidity | 51 |
| 3.5 | Lorentz Operator | 53 |
| 3.6 | Poincaré Group* | 56 |
| 4 | Dirac Equation | 59 |
| 4.1 | Relativistic Schrödinger Equation | 59 |
| 4.1.1 | Dirac Matrix | 59 |
| 4.1.2 | Weyl Spinor | 61 |
| 4.1.3 | Interpretation of the Negative Energy | 64 |
| 4.1.4 | Lorentz-Covariant Dirac Equation | 69 |
| 4.2 | Plane-Wave Solution | 71 |
| 4.3 | Properties of the Dirac Particle | 75 |
| 4.3.1 | Magnetic Moment of the Electron | 75 |
| 4.3.2 | Parity | 77 |
| 4.3.3 | Bilinear Form of the Dirac Spinor | 78 |
| 4.3.4 | Charge Conjugation | 79 |
| 4.3.5 | Chiral Eigenstates | 82 |
| 4.4 | Majorana Particle | 84 |
| 5 | Field Quantization | 89 |
| 5.1 | Action Principle | 89 |
| 5.1.1 | Equations of Motion | 89 |
| 5.1.2 | Hamiltonian Formalism | 90 |
| 5.1.3 | Equation of a Field | 91 |
| 5.1.4 | Noether's Theorem | 95 |
| 5.2 | Quantization Scheme | 100 |
| 5.2.1 | Heisenberg Equation of Motion | 100 |
| 5.2.2 | Quantization of the Harmonic Oscillator | 102 |
| 5.3 | Quantization of Fields | 105 |
| 5.3.1 | Complex Fields | 106 |
| 5.3.2 | Real Field | 111 |
| 5.3.3 | Dirac Field | 112 |
| 5.3.4 | Electromagnetic Field | 114 |
| 5.4 | Spin and Statistics | 119 |
| 5.5 | Vacuum Fluctuation | 121 |
| 5.5.1 | The Casimir Effect* | 122 |
| 6 | Scattering Matrix | 127 |
| 6.1 | Interaction Picture | 127 |
| 6.2 | Asymptotic Field Condition | 131 |
| 6.3 | Explicit Form of the S-Matrix | 133 |
| 6.3.1 | Rutherford Scattering | 135 |
| 6.4 | Relativistic Kinematics | 136 |
| 6.4.1 | Center of Mass Frame and Laboratory Frame | 136 |
| 6.4.2 | Crossing Symmetry | 139 |
| 6.5 | Relativistic Cross Section | 141 |

| | | |
|----------|--|------------|
| 6.5.1 | Transition Rate | 141 |
| 6.5.2 | Relativistic Normalization | 142 |
| 6.5.3 | Incoming Flux and Final State Density | 144 |
| 6.5.4 | Lorentz-Invariant Phase Space | 145 |
| 6.5.5 | Cross Section in the Center of Mass Frame | 145 |
| 6.6 | Vertex Functions and the Feynman Propagator | 147 |
| 6.6.1 | $e\bar{e}\gamma$ Vertex Function | 147 |
| 6.6.2 | Feynman Propagator | 151 |
| 6.7 | Mott Scattering | 157 |
| 6.7.1 | Cross Section | 157 |
| 6.7.2 | Coulomb Scattering and Magnetic Scattering | 161 |
| 6.7.3 | Helicity Conservation | 161 |
| 6.7.4 | A Method to Rotate Spin | 161 |
| 6.8 | Yukawa Interaction | 162 |
| 7 | Qed: Quantum Electrodynamics | 167 |
| 7.1 | $e-\mu$ Scattering | 167 |
| 7.1.1 | Cross Section | 167 |
| 7.1.2 | Elastic Scattering of Polarized $e-\mu$ | 171 |
| 7.1.3 | $e^-e^+ \rightarrow \mu^-\mu^+$ Reaction | 174 |
| 7.2 | Compton Scattering | 176 |
| 7.3 | Bremsstrahlung | 181 |
| 7.3.1 | Soft Bremsstrahlung | 183 |
| 7.4 | Feynman Rules | 186 |
| 8 | Radiative Corrections and Tests of Qed* | 191 |
| 8.1 | Radiative Corrections and Renormalization* | 191 |
| 8.1.1 | Vertex Correction | 191 |
| 8.1.2 | Ultraviolet Divergence | 193 |
| 8.1.3 | Infrared Divergence | 197 |
| 8.1.4 | Infrared Compensation to All Orders* | 199 |
| 8.1.5 | Running Coupling Constant | 204 |
| 8.1.6 | Mass Renormalization | 208 |
| 8.1.7 | Ward-Takahashi Identity | 210 |
| 8.1.8 | Renormalization of the Scattering Amplitude | 211 |
| 8.2 | Tests of QED | 213 |
| 8.2.1 | Lamb Shift | 213 |
| 8.2.2 | $g-2$ | 214 |
| 8.2.3 | Limit of QED Applicability | 216 |
| 8.2.4 | E821 BNL Experiment | 216 |
| 9 | Symmetries | 221 |
| 9.1 | Continuous Symmetries | 222 |
| 9.1.1 | Space and Time Translation | 223 |
| 9.1.2 | Rotational Invariance in the Two-Body System | 227 |
| 9.2 | Discrete Symmetries | 233 |

| | | |
|-----------|--|------------|
| 9.2.1 | Parity Transformation | 233 |
| 9.2.2 | Time Reversal | 240 |
| 9.3 | Internal Symmetries | 251 |
| 9.3.1 | $U(1)$ Gauge Symmetry | 251 |
| 9.3.2 | Charge Conjugation | 252 |
| 9.3.3 | CPT Theorem | 258 |
| 9.3.4 | $SU(2)$ (Isospin) Symmetry | 260 |
| 10 | Path Integral: Basics | 267 |
| 10.1 | Introduction | 267 |
| 10.1.1 | Bra and Ket | 267 |
| 10.1.2 | Translational Operator | 268 |
| 10.2 | Quantum Mechanical Equations | 271 |
| 10.2.1 | Schrödinger Equation | 271 |
| 10.2.2 | Propagators | 272 |
| 10.3 | Feynman's Path Integral | 274 |
| 10.3.1 | Sum over History | 274 |
| 10.3.2 | Equivalence with the Schrödinger Equation | 278 |
| 10.3.3 | Functional Calculus | 279 |
| 10.4 | Propagators: Simple Examples | 282 |
| 10.4.1 | Free-Particle Propagator | 282 |
| 10.4.2 | Harmonic Oscillator | 285 |
| 10.5 | Scattering Matrix | 294 |
| 10.5.1 | Perturbation Expansion | 295 |
| 10.5.2 | S-Matrix in the Path Integral | 297 |
| 10.6 | Generating Functional | 300 |
| 10.6.1 | Correlation Functions | 300 |
| 10.6.2 | Note on Imaginary Time | 302 |
| 10.6.3 | Correlation Functions as Functional Derivatives | 304 |
| 10.7 | Connection with Statistical Mechanics | 306 |
| 11 | Path Integral Approach to Field Theory | 311 |
| 11.1 | From Particles to Fields | 311 |
| 11.2 | Real Scalar Field | 312 |
| 11.2.1 | Generating Functional | 312 |
| 11.2.2 | Calculation of $\det A$ | 315 |
| 11.2.3 | n -Point Functions and the Feynman Propagator | 318 |
| 11.2.4 | Wick's Theorem | 319 |
| 11.2.5 | Generating Functional of Interacting Fields | 320 |
| 11.3 | Electromagnetic Field | 321 |
| 11.3.1 | Gauge Fixing and the Photon Propagator | 321 |
| 11.3.2 | Generating Functional of the Electromagnetic Field | 323 |
| 11.4 | Dirac Field | 324 |
| 11.4.1 | Grassmann Variables | 324 |
| 11.4.2 | Dirac Propagator | 331 |
| 11.4.3 | Generating Functional of the Dirac Field | 332 |

| | | |
|-----------|---|------------|
| 11.5 | Reduction Formula | 333 |
| 11.5.1 | Scalar Fields | 333 |
| 11.5.2 | Electromagnetic Field | 337 |
| 11.5.3 | Dirac Field | 337 |
| 11.6 | QED | 340 |
| 11.6.1 | Formalism | 340 |
| 11.6.2 | Perturbative Expansion | 342 |
| 11.6.3 | First-Order Interaction | 343 |
| 11.6.4 | Mott Scattering | 345 |
| 11.6.5 | Second-Order Interaction | 346 |
| 11.6.6 | Scattering Matrix | 351 |
| 11.6.7 | Connected Diagrams | 353 |
| 11.7 | Faddeev–Popov’s Ansatz* | 354 |
| 11.7.1 | A Simple Example* | 355 |
| 11.7.2 | Gauge Fixing Revisited* | 356 |
| 11.7.3 | Faddeev–Popov Ghost* | 359 |
| 12 | Accelerator and Detector Technology | 363 |
| 12.1 | Accelerators | 363 |
| 12.2 | Basic Parameters of Accelerators | 364 |
| 12.2.1 | Particle Species | 364 |
| 12.2.2 | Energy | 366 |
| 12.2.3 | Luminosity | 367 |
| 12.3 | Various Types of Accelerators | 369 |
| 12.3.1 | Low-Energy Accelerators | 369 |
| 12.3.2 | Synchrotron | 373 |
| 12.3.3 | Linear Collider | 377 |
| 12.4 | Particle Interactions with Matter | 378 |
| 12.4.1 | Some Basic Concepts | 378 |
| 12.4.2 | Ionization Loss | 381 |
| 12.4.3 | Multiple Scattering | 389 |
| 12.4.4 | Cherenkov and Transition Radiation | 390 |
| 12.4.5 | Interactions of Electrons and Photons with Matter | 394 |
| 12.4.6 | Hadronic Shower | 401 |
| 12.5 | Particle Detectors | 403 |
| 12.5.1 | Overview of Radioisotope Detectors | 403 |
| 12.5.2 | Detectors that Use Light | 404 |
| 12.5.3 | Detectors that Use Electric Signals | 410 |
| 12.5.4 | Functional Usage of Detectors | 415 |
| 12.6 | Collider Detectors | 422 |
| 12.7 | Statistics and Errors | 428 |
| 12.7.1 | Basics of Statistics | 428 |
| 12.7.2 | Maximum Likelihood and Goodness of Fit | 433 |
| 12.7.3 | Least Squares Method | 438 |

| | | |
|-----------------|--|------------|
| Part Two | A Way to the Standard Model | 441 |
| 13 | Spectroscopy | 443 |
| 13.1 | Pre-accelerator Age (1897–1947) | 444 |
| 13.2 | Pions | 449 |
| 13.3 | πN Interaction | 454 |
| 13.3.1 | Isospin Conservation | 454 |
| 13.3.2 | Partial Wave Analysis | 462 |
| 13.3.3 | Resonance Extraction | 466 |
| 13.3.4 | Argand Diagram: Digging Resonances | 472 |
| 13.4 | ρ (770) | 475 |
| 13.5 | Final State Interaction | 478 |
| 13.5.1 | Dalitz Plot | 478 |
| 13.5.2 | K Meson | 481 |
| 13.5.3 | Angular Momentum Barrier | 484 |
| 13.5.4 | ω Meson | 485 |
| 13.6 | Low-Energy Nuclear Force | 487 |
| 13.6.1 | Spin–Isospin Exchange Force | 487 |
| 13.6.2 | Effective Range | 490 |
| 13.7 | High-Energy Scattering | 491 |
| 13.7.1 | Black Sphere Model | 491 |
| 13.7.2 | Regge Trajectory* | 494 |
| 14 | The Quark Model | 501 |
| 14.1 | $SU(3)$ Symmetry | 501 |
| 14.1.1 | The Discovery of Strange Particles | 502 |
| 14.1.2 | The Sakata Model | 505 |
| 14.1.3 | Meson Nonets | 507 |
| 14.1.4 | The Quark Model | 509 |
| 14.1.5 | Baryon Multiplets | 510 |
| 14.1.6 | General Rules for Composing Multiplets | 511 |
| 14.2 | Predictions of $SU(3)$ | 513 |
| 14.2.1 | Gell-Mann–Okubo Mass Formula | 513 |
| 14.2.2 | Prediction of Ω | 514 |
| 14.2.3 | Meson Mixing | 516 |
| 14.3 | Color Degrees of Freedom | 519 |
| 14.4 | $SU(6)$ Symmetry | 522 |
| 14.4.1 | Spin and Flavor Combined | 522 |
| 14.4.2 | $SU(6) \times O(3)$ | 525 |
| 14.5 | Charm Quark | 525 |
| 14.5.1 | J/ψ | 525 |
| 14.5.2 | Mass and Quantum Number of J/ψ | 527 |
| 14.5.3 | Charmonium | 527 |
| 14.5.4 | Width of J/ψ | 533 |
| 14.5.5 | Lifetime of Charmed Particles | 536 |
| 14.5.6 | Charm Spectroscopy: $SU(4)$ | 537 |

| | | |
|-----------|---|------------|
| 14.5.7 | The Fifth Quark b (Bottom) | 539 |
| 14.6 | Color Charge | 539 |
| 14.6.1 | Color Independence | 542 |
| 14.6.2 | Color Exchange Force | 544 |
| 14.6.3 | Spin Exchange Force | 545 |
| 14.6.4 | Mass Formulae of Hadrons | 547 |
| 15 | Weak Interaction | 553 |
| 15.1 | Ingredients of the Weak Force | 553 |
| 15.2 | Fermi Theory | 555 |
| 15.2.1 | Beta Decay | 555 |
| 15.2.2 | Parity Violation | 562 |
| 15.2.3 | π Meson Decay | 564 |
| 15.3 | Chirality of the Leptons | 567 |
| 15.3.1 | Helicity and Angular Correlation | 567 |
| 15.3.2 | Electron Helicity | 569 |
| 15.4 | The Neutrino | 571 |
| 15.4.1 | Detection of the Neutrino | 571 |
| 15.4.2 | Mass of the Neutrino | 572 |
| 15.4.3 | Helicity of the Electron Neutrino | 576 |
| 15.4.4 | The Second Neutrino ν_μ | 578 |
| 15.5 | The Universal V–A Interaction | 579 |
| 15.5.1 | Muon Decay | 579 |
| 15.5.2 | CVC Hypothesis | 584 |
| 15.6 | Strange Particle Decays | 589 |
| 15.6.1 | $\Delta S = \Delta Q$ Rule | 589 |
| 15.6.2 | $\Delta I = 1/2$ Rule | 591 |
| 15.6.3 | $K_{l3} : K^+ \rightarrow \pi^0 + l^+ + \nu$ | 592 |
| 15.6.4 | Cabibbo Rotation | 596 |
| 15.7 | Flavor Conservation | 598 |
| 15.7.1 | GIM Mechanism | 598 |
| 15.7.2 | Kobayashi–Maskawa Matrix | 600 |
| 15.7.3 | Tau Lepton | 601 |
| 15.7.4 | The Generation Puzzle | 605 |
| 15.8 | A Step Toward a Unified Theory | 608 |
| 15.8.1 | Organizing the Weak Phenomena | 608 |
| 15.8.2 | Limitations of the Fermi Theory | 610 |
| 15.8.3 | Introduction of $SU(2)$ | 614 |
| 16 | Neutral Kaons and CP Violation* | 617 |
| 16.1 | Introduction | 618 |
| 16.1.1 | Strangeness Eigenstates and CP Eigenstates | 618 |
| 16.1.2 | Schrödinger Equation for $K^0 - \bar{K}^0$ States | 619 |
| 16.1.3 | Strangeness Oscillation | 622 |
| 16.1.4 | Regeneration of K_1 | 626 |

| | | |
|-----------|--|------------|
| 16.1.5 | Discovery of CP Violation | 630 |
| 16.2 | Formalism of CP and CPT Violation | 632 |
| 16.2.1 | CP, T, CPT Transformation Properties | 632 |
| 16.2.2 | Definition of CP Parameters | 635 |
| 16.3 | CP Violation Parameters | 640 |
| 16.3.1 | Observed Parameters | 640 |
| 16.3.2 | ϵ and ϵ' | 644 |
| 16.4 | Test of T and CPT Invariance | 653 |
| 16.4.1 | Definition of T- and CPT-Violating Amplitudes | 654 |
| 16.4.2 | T Violation | 654 |
| 16.4.3 | CPT violation | 656 |
| 16.4.4 | Possible Violation of Quantum Mechanics | 662 |
| 16.5 | Experiments on CP Parameters | 664 |
| 16.5.1 | CPLEAR | 664 |
| 16.5.2 | NA48/KTeV | 666 |
| 16.6 | Models of CP Violation | 673 |
| 17 | Hadron Structure | 679 |
| 17.1 | Historical Overview | 679 |
| 17.2 | Form Factor | 680 |
| 17.3 | e - p Elastic Scattering | 683 |
| 17.4 | Electron Proton Deep Inelastic Scattering | 687 |
| 17.4.1 | Cross-Section Formula for Inelastic Scattering | 687 |
| 17.4.2 | Bjorken Scaling | 690 |
| 17.5 | Parton Model | 693 |
| 17.5.1 | Impulse Approximation | 693 |
| 17.5.2 | Electron-Parton Scattering | 696 |
| 17.6 | Scattering with Equivalent Photons | 699 |
| 17.6.1 | Transverse and Longitudinal Photons | 699 |
| 17.6.2 | Spin of the Target | 702 |
| 17.6.3 | Photon Flux | 703 |
| 17.7 | How to Do Neutrino Experiments | 705 |
| 17.7.1 | Neutrino Beams | 705 |
| 17.7.2 | Neutrino Detectors | 709 |
| 17.8 | ν - p Deep Inelastic Scattering | 712 |
| 17.8.1 | Cross Sections and Structure Functions | 712 |
| 17.8.2 | ν , $\bar{\nu}$ - q Scattering | 715 |
| 17.8.3 | Valence Quarks and Sea Quarks | 716 |
| 17.8.4 | Comparisons with Experimental Data | 717 |
| 17.8.5 | Sum Rules | 719 |
| 17.9 | Parton Model in Hadron-Hadron Collisions | 721 |
| 17.9.1 | Drell-Yan Process | 721 |
| 17.9.2 | Other Hadronic Processes | 724 |
| 17.10 | A Glimpse of QCD's Power | 725 |

| | | |
|-----------|---|-----|
| 18 | Gauge Theories | 729 |
| 18.1 | Historical Prelude | 729 |
| 18.2 | Gauge Principle | 731 |
| 18.2.1 | Formal Definition | 731 |
| 18.2.2 | Gravity as a Geometry | 733 |
| 18.2.3 | Parallel Transport and Connection | 734 |
| 18.2.4 | Rotation in Internal Space | 737 |
| 18.2.5 | Curvature of a Space | 739 |
| 18.2.6 | Covariant Derivative | 741 |
| 18.2.7 | Principle of Equivalence | 743 |
| 18.2.8 | General Relativity and Gauge Theory | 745 |
| 18.3 | Aharonov–Bohm Effect | 748 |
| 18.4 | Nonabelian Gauge Theories | 754 |
| 18.4.1 | Isospin Operator | 754 |
| 18.4.2 | Gauge Potential | 755 |
| 18.4.3 | Isospin Force Field and Equation of Motion | 757 |
| 18.5 | QCD | 760 |
| 18.5.1 | Asymptotic Freedom | 762 |
| 18.5.2 | Confinement | 767 |
| 18.6 | Unified Theory of the Electroweak Interaction | 770 |
| 18.6.1 | $SU(2) \times U(1)$ Gauge Theory | 770 |
| 18.6.2 | Spontaneous Symmetry Breaking | 774 |
| 18.6.3 | Higgs Mechanism | 778 |
| 18.6.4 | Glashow–Weinberg–Salam Electroweak Theory | 782 |
| 18.6.5 | Summary of GWS Theory | 784 |
| 19 | Epilogue | 787 |
| 19.1 | Completing the Picture | 788 |
| 19.2 | Beyond the Standard Model | 789 |
| 19.2.1 | Neutrino Oscillation | 789 |
| 19.2.2 | GUTs: Grand Unified Theories | 791 |
| 19.2.3 | Supersymmetry | 792 |
| 19.2.4 | Superstring Model | 795 |
| 19.2.5 | Extra Dimensions | 796 |
| 19.2.6 | Dark Matter | 797 |
| 19.2.7 | Dark Energy | 798 |
| | Appendix A Spinor Representation | 803 |
| A.1 | Definition of a Group | 803 |
| A.1.1 | Lie Group | 804 |
| A.2 | $SU(2)$ | 805 |
| A.3 | Lorentz Operator for Spin 1/2 Particle | 809 |
| A.3.1 | $SL(2, C)$ Group | 809 |
| A.3.2 | Dirac Equation: Another Derivation | 811 |

| | |
|--|-----|
| Appendix B Coulomb Gauge | 813 |
| B.1 Quantization of the Electromagnetic Field in the Coulomb Gauge | 814 |
| Appendix C Dirac Matrix and Gamma Matrix Traces | 817 |
| C.1 Dirac Plane Wave Solutions | 817 |
| C.2 Dirac γ Matrices | 817 |
| C.2.1 Traces of the γ Matrices | 818 |
| C.2.2 Levi-Civita Antisymmetric Tensor | 819 |
| C.3 Spin Sum of $ \mathcal{M}_{fi} ^2$ | 819 |
| C.3.1 A Frequently Used Example | 820 |
| C.3.2 Polarization Sum of the Vector Particle | 822 |
| C.4 Other Useful Formulae | 823 |
| Appendix D Dimensional Regularization | 825 |
| D.1 Photon Self-Energy | 825 |
| D.2 Electron Self-Energy | 830 |
| Appendix E Rotation Matrix | 833 |
| E.1 Angular Momentum Operators | 833 |
| E.2 Addition of the Angular Momentum | 835 |
| E.3 Rotational Matrix | 835 |
| Appendix F C, P, T Transformation | 839 |
| Appendix G $SU(3)$, $SU(n)$ and the Quark Model | 841 |
| G.1 Generators of the Group | 841 |
| G.1.1 Adjoint Representation | 842 |
| G.1.2 Direct Product | 843 |
| G.2 $SU(3)$ | 844 |
| G.2.1 Structure Constants | 844 |
| G.2.2 Irreducible Representation of a Direct Product | 846 |
| G.2.3 Tensor Analysis | 851 |
| G.2.4 Young Diagram | 854 |
| Appendix H Mass Matrix and Decaying States | 859 |
| H.1 The Decay Formalism | 859 |
| Appendix I Answers to the Problems | 865 |
| Appendix J Particle Data | 915 |
| Appendix K Constants | 917 |
| References | 919 |
| Index | 929 |