

Quang Ho-Kim Xuan-Yem Pham

Elementary Particles and Their Interactions

Concepts and Phenomena

With 116 Figures, 36 Tables, Numerous Examples,
and 102 Problems with Selected Solutions

This book is a textbook for students of physics, especially for those who are interested in elementary particles and their interactions. It is also a reference book for researchers in the field. The book covers the basic concepts and phenomena of elementary particles and their interactions, including the Standard Model of particle physics, the discovery of new particles, and the search for new physics beyond the Standard Model. The book is written in a clear and concise style, with many examples and problems to help students understand the concepts and phenomena.

The book is divided into two main parts. The first part, "Concepts and Phenomena", covers the basic concepts and phenomena of elementary particles and their interactions. The second part, "Problems and Solutions", contains 102 problems with selected solutions. The book is suitable for students of physics at the undergraduate and graduate levels, as well as for researchers in the field. The book is written in a clear and concise style, with many examples and problems to help students understand the concepts and phenomena.

The book is a valuable resource for students and researchers alike. It provides a comprehensive overview of the field of elementary particles and their interactions, and includes many examples and problems to help students understand the concepts and phenomena. The book is written in a clear and concise style, and is suitable for students of physics at the undergraduate and graduate levels, as well as for researchers in the field.



Springer

Quang Ho-Kim, Xuan-Yem Pham
Department of Physics, University of Science, Ho Chi Minh City, Vietnam
quang.ho-kim@hcmus.edu.vn, xuan-yem.pham@hcmus.edu.vn

Contents

- 1 Particles and Interactions: An Overview 1**
 - 1.1 A Preview 1
 - 1.2 Particles 3
 - 1.2.1 Leptons 4
 - 1.2.2 Quarks 5
 - 1.2.3 Hadrons 6
 - 1.3 Interactions 6
 - 1.4 Symmetries 10
 - 1.5 Physical Units 13
 - Problems 15
 - Suggestions for Further Reading 16
- 2 Boson Fields 17**
 - 2.1 Lorentz Symmetry 18
 - 2.1.1 Lorentz Transformations 18
 - 2.1.2 Tensor Algebra 23
 - 2.1.3 Tensor Fields 24
 - 2.2 Scalar Fields 25
 - 2.2.1 Space-Time Translation of a Scalar Field 25
 - 2.2.2 Lorentz Transformation of a Scalar Field 28
 - 2.3 Vector Fields 30
 - 2.4 The Klein–Gordon Equation 31
 - 2.4.1 Free-Particle Solutions 31
 - 2.4.2 Particle Probability 32
 - 2.4.3 Second Quantization 34
 - 2.4.4 Operator Algebra 35
 - 2.4.5 Physical Significance of the Fock Operators 37
 - 2.5 Quantized Vector Fields 39
 - 2.5.1 Massive Vector Fields 39
 - 2.5.2 The Maxwell Equations 40
 - 2.5.3 Quantization of the Electromagnetic Field 42
 - 2.5.4 Field Energy and Momentum 46
 - 2.6 The Action 47
 - 2.6.1 The Euler–Lagrange Equation 47
 - 2.6.2 Conserved Current 50

Problems	55
Suggestions for Further Reading	56
3 Fermion Fields	57
3.1 The Dirac Equation	57
3.2 Lorentz Symmetry	60
3.2.1 Covariance of the Dirac Equation	60
3.2.2 Spin of the Dirac Field	63
3.2.3 Bilinear Covariants	64
3.3 Free-Particle Solutions	65
3.3.1 Normalized Spinors	66
3.3.2 Completeness Relations	68
3.3.3 Helicities	71
3.4 The Lagrangian for a Free Dirac Particle	73
3.5 Quantization of the Dirac Field	76
3.5.1 Spins and Statistics	77
3.5.2 Dirac Field Observables	79
3.5.3 Fock Space	80
3.6 Zero-Mass Fermions	82
Problems	86
Suggestions for Further Reading	88
4 Collisions and Decays	89
4.1 Interaction Representation	90
4.1.1 The Three Pictures	90
4.1.2 Time Evolution in the Interaction Picture	92
4.1.3 The S -matrix	95
4.2 Cross-Sections and Decay Rates	96
4.2.1 General Formulas	96
4.2.2 Two-Body Reaction to Two-Body Final States	99
4.2.3 Decay Rates	103
4.3 Interaction Models	104
4.4 Decay Modes of Scalar Particles	105
4.4.1 Neutral Decay Mode	105
4.4.2 Charged Decay Mode	108
4.5 Pion Scattering	109
4.5.1 The Scalar Boson Propagator	110
4.5.2 Scattering Processes	112
4.5.3 Summary and Generalization	116

4.6 Electron-Proton Scattering	118
4.6.1 The Electromagnetic Interaction	119
4.6.2 Electron-Proton Scattering Cross-Section	120
4.7 Electron-Positron Annihilation	127
4.8 Compton Scattering	133
Problems	141
Suggestions for Further Reading	142
5 Discrete Symmetries	143
5.1 Parity	144
5.1.1 Parity in Quantum Mechanics	144
5.1.2 Parity in Field Theories	146
5.1.3 Parity and Interactions	150
5.2 Time Inversion	155
5.2.1 Time Inversion in Quantum Mechanics	156
5.2.2 Time Inversion in Field Theories	158
5.2.3 $\mathcal{T}$ and Interactions	162
5.3 Charge Conjugation	163
5.3.1 Additive Quantum Numbers	164
5.3.2 Charge Conjugation in Field Theories	169
5.3.3 Interactions	174
5.4 The CPT Theorem	178
5.4.1 Implications of CPT Invariance	180
5.4.2 C, P, T, and CPT	181
Problems	182
Suggestions for Further Reading	184
6 Hadrons and Isospin	185
6.1 Charge Symmetry and Charge Independence	185
6.2 Nucleon Field in Isospin Space	187
6.3 Pion Field in Isospin Space	193
6.4 G-Parity	198
6.4.1 Nucleon and Pion Fields	199
6.4.2 Other Unflavored Hadrons	204
6.5 Isospin of Strange Particles	205
6.6 Isospin Violations	207
6.6.1 Electromagnetic Interactions	207
6.6.2 Weak Interactions	208
Problems	213
Suggestions for Further Reading	214

7 Quarks and SU(3) Symmetry	215
7.1 Isospin: SU(2) Symmetry	216
7.2 Hypercharge: SU(3) Symmetry	222
7.2.1 The Fundamental Representation	222
7.2.2 Higher-Dimensional Representations	224
7.2.3 Physical Significance of F_3 and F_8	228
7.2.4 $3 \times 3^*$ Equal Mesons	230
7.2.5 $3 \times 3 \times 3$ Equal Baryons	233
7.3 Mass Splitting of the Hadron Multiplets	236
7.3.1 Baryons	238
7.3.2 Mesons	239
7.4 Including Spin: SU(6)	241
7.4.1 Mesons	243
7.4.2 Baryons	245
7.4.3 Application: Magnetic Moments of Hadrons	246
7.5 The Color of Quarks	248
7.6 The New Particles	250
7.6.1 J/ψ and Charm	250
7.6.2 The Tau Lepton	258
7.6.3 From Bottom to Top	260
Problems	263
Suggestions for Further Reading	265
8 Gauge Field Theories	267
8.1 Symmetries and Interactions	267
8.2 Abelian Gauge Invariance	269
8.3 Non-Abelian Gauge Invariance	271
8.4 Quantum Chromodynamics	277
8.5 Spontaneous Breaking of Global Symmetries	283
8.5.1 The Basic Idea	284
8.5.2 Breakdown of Discrete Symmetry	286
8.5.3 Breakdown of Abelian Symmetry	287
8.5.4 Breakdown of Non-Abelian Symmetry	289
8.6 Spontaneous Breaking of Local Symmetries	293
8.6.1 Abelian Symmetry	293
8.6.2 Non-Abelian Symmetry	298
Problems	301
Suggestions for Further Reading	303
9 The Standard Model of the Electroweak Interaction	305
9.1 The Weak Interaction Before the Gauge Theories	305
9.2 Gauge-Invariant Model of One-Lepton Family	307
9.2.1 Global Symmetry	308
9.2.2 Gauge Invariance	312

9.2.3 Spontaneous Symmetry Breaking	313
9.2.4 Feynman Rules for One-Lepton Family	322
9.3 Including u and d Quarks	326
9.4 Multigeneration Model	330
9.4.1 The GIM Mechanism	330
9.4.2 Classification Scheme for Fermions	333
9.4.3 Fermion Families and the CKM Matrix	333
9.4.4 Summary and Extensions	338
Problems	341
Suggestions for Further Reading	342
10 Electron-Nucleon Scattering	343
10.1 Electromagnetic and Weak Form Factors	343
10.2 Analyticity and Dispersion Relation	352
10.3 Exclusive Reaction: Elastic Scattering	355
10.4 Inclusive Reaction: Deep Inelastic Scattering	361
10.4.1 Structure Functions	362
10.4.2 Bjorken Scaling and the Feynman Quark Parton	366
Problems	373
Suggestions for Further Reading	375
11 Neutral K Mesons and CP Violation	377
11.1 The Two Neutral K Mesons	378
11.2 Strangeness Oscillations	380
11.3 Regeneration of K_S^0	383
11.4 Calculation of Δm	385
11.5 CP Violation	389
11.5.1 General Formalism	389
11.5.2 Model-Independent Analysis of $K_L \rightarrow 2\pi$	393
11.5.3 The Superweak Scenario	398
11.5.4 Calculations of ϵ and ϵ' in the Standard Model	399
11.5.5 The Gluonic Penguin and $ \epsilon'/\epsilon $	402
Problems	406
Suggestions for Further Reading	406
12 The Neutrinos	407
12.1 On the Neutrino Masses	407
12.1.1 General Properties	408
12.1.2 Dirac or Majorana Neutrino?	409
12.1.3 Lepton Mixing	411
12.2 Oscillations in the Vacuum	412
12.3 Oscillations in Matter	415
12.3.1 Index of Refraction, Effective Mass	416
12.3.2 The MSW Effect	420

12.3.3	Adiabaticity	423
12.4	Neutral Currents by Neutrino Scattering	426
12.4.1	Neutral Currents, Why Not?	427
12.4.2	Neutrino-Electron Scattering	428
12.5	Neutrino-Nucleon Elastic Scattering	435
12.6	Neutrino-Nucleon Deep Inelastic Collision	438
12.6.1	Deep Inelastic Cross-Section	439
12.6.2	Quarks as Partons	441
	Problems	445
	Suggestions for Further Reading	446
13	Muon and Tau Lepton Decays	447
13.1	Weak Decays: Classification and Generalities	447
13.2	Leptonic Modes	450
13.2.1	Leptonic Branching Ratio	450
13.2.2	Parity Violation. Energy Spectrum	451
13.2.3	Angular Distribution. Decay Rate	456
13.3	Semileptonic Decays	460
13.3.1	The One-Pion Mode: $\tau^- \rightarrow \nu_\tau + \pi^-$	460
13.3.2	The 2 π -Pion Mode and CVC	462
13.4	The Method of Spectral Functions	465
13.4.1	The Three-Pion Mode	467
13.4.2	Spectral Functions of Quark Pairs	470
	Problems	473
	Suggestions for Further Reading	474
14	One-Loop QCD Corrections	475
14.1	Vertex Function	477
14.2	Quark Self-Energy	484
14.3	Mass and Field Renormalization	485
14.3.1	Renormalized Form Factor $\tilde{F}_1^{\text{ren}}(q^2)$	489
14.3.2	Important Consequence of Mass Renormalization	491
14.4	Virtual Gluon Contributions	492
14.5	Real Gluon Contributions	496
14.5.1	Infrared Divergence	497
14.5.2	Three-Particle Phase Space	498
14.5.3	Bremsstrahlung Rate	500
14.6	Final Result	501
	Problems	502
	Suggestions for Further Reading	504
15	Asymptotic Freedom in QCD	505
15.1	Running Coupling Constant	506
15.1.1	Vacuum Polarization	507

15.1.2 Dressed and Renormalized Photon Propagator	509
15.1.3 Vertex Renormalization	512
15.1.4 Renormalized Vacuum Polarization $\tilde{\Pi}_{\text{ren}}(q^2)$	515
15.1.5 Physical Effects of $\tilde{\Pi}_{\text{ren}}(q^2)$	517
15.2 The Renormalization Group	518
15.2.1 The Callan–Symanzik Equation	520
15.2.2 Calculation of the β - and γ -Functions	523
15.2.3 Running Coupling from the Renormalization Group	525
15.2.4 Solution of the Renormalization Group Equation	526
15.3 One-Loop Computation of the QCD β -Function	529
15.3.1 Quark Self-Energy Counterterm Z_q	529
15.3.2 Quark–Gluon Vertex Counterterm Z_1	529
15.3.3 Gluon Self-Energy Counterterm Z_{glu}	531
15.3.4 The Running QCD Coupling	535
15.4 Ghosts	538
15.4.1 The Faddeev–Popov Gauge-Fixing Method	538
15.4.2 Ghosts and Unitarity	541
Problems	547
Suggestions for Further Reading	548
16 Heavy Flavors	549
16.1 QCD Renormalization of Weak Interactions	550
16.1.1 Corrections to Single Currents	551
16.1.2 Corrections to Product of Currents	553
16.1.3 Renormalization Group Improvement	557
16.1.4 The $\Delta I = 1/2$ in Strangeness Hadronic Decays	560
16.2 Heavy Flavor Symmetry	562
16.2.1 Basic Physical Pictures	563
16.2.2 Elements of Heavy Quark Effective Theory (HQET)	565
16.3 Inclusive Decays	567
16.3.1 General Formalism	568
16.3.2 Inclusive Semileptonic Decay: $\bar{B} \rightarrow e^- + \bar{\nu}_e + X_c$	572
16.3.3 Inclusive Nonleptonic Decay: $\bar{B} \rightarrow \text{Hadrons}$	573
16.4 Exclusive Decays	576
16.4.1 Form Factors in $B_{\ell 3}$ Decays	577
16.4.2 Semileptonic Decay Rates	580
16.4.3 Two-Body Hadronic Decays	582
16.5 CP Violation in B Mesons	588
16.5.1 B^0 – $\bar{B}^0$ Mixing	588
16.5.2 CP Asymmetries in Neutral B Meson Decays	594
Problems	598
Suggestions for Further Reading	599

17 Status and Perspectives of the Standard Model	601
17.1 Production and Decay of the Higgs Boson	602
17.2 Why Go Beyond the Standard Model?	605
17.3 The Standard Model as an Effective Theory	607
17.3.1 Problems with the Standard Model	608
17.3.2 Renormalization Group Equation Analysis	610
17.3.3 Supersymmetry and Technicolor	611
Problems	614
Suggestions for Further Reading	614
Selected Solutions	615
Appendix: Useful Formulas	645
A.1 Relativistic Quantum Mechanics	645
A.2 Cross-Sections and Decay Rates	649
A.3 Phase Space and Loop Integrals	650
A.4 Feynman Rules	653
A.5 Parameters of the Standard Model	656
Index	657