

Contents

Preface to the Second Edition	xiii
Preface to the First Edition	xv
Note to the Student	xvi
1 Origins of Quantum Physics	1
1.1 Historical Note	1
1.2 Particle Aspect of Radiation	4
1.2.1 Blackbody Radiation	4
1.2.2 Photoelectric Effect	10
1.2.3 Compton Effect	13
1.2.4 Pair Production	16
1.3 Wave Aspect of Particles	18
1.3.1 de Broglie's Hypothesis: Matter Waves	18
1.3.2 Experimental Confirmation of de Broglie's Hypothesis	18
1.3.3 Matter Waves for Macroscopic Objects	20
1.4 Particles versus Waves	22
1.4.1 Classical View of Particles and Waves	22
1.4.2 Quantum View of Particles and Waves	23
1.4.3 Wave-Particle Duality: Complementarity	26
1.4.4 Principle of Linear Superposition	27
1.5 Indeterministic Nature of the Microphysical World	27
1.5.1 Heisenberg's Uncertainty Principle	28
1.5.2 Probabilistic Interpretation	30
1.6 Atomic Transitions and Spectroscopy	30
1.6.1 Rutherford Planetary Model of the Atom	30
1.6.2 Bohr Model of the Hydrogen Atom	31
1.7 Quantization Rules	36
1.8 Wave Packets	38
1.8.1 Localized Wave Packets	39
1.8.2 Wave Packets and the Uncertainty Relations	42
1.8.3 Motion of Wave Packets	43
1.9 Concluding Remarks	54
1.10 Solved Problems	54
1.11 Exercises	71

2	Mathematical Tools of Quantum Mechanics	79
2.1	Introduction	79
2.2	The Hilbert Space and Wave Functions	79
2.2.1	The Linear Vector Space	79
2.2.2	The Hilbert Space	80
2.2.3	Dimension and Basis of a Vector Space	81
2.2.4	Square-Integrable Functions: Wave Functions	84
2.3	Dirac Notation	84
2.4	Operators	89
2.4.1	General Definitions	89
2.4.2	Hermitian Adjoint	91
2.4.3	Projection Operators	92
2.4.4	Commutator Algebra	93
2.4.5	Uncertainty Relation between Two Operators	95
2.4.6	Functions of Operators	97
2.4.7	Inverse and Unitary Operators	98
2.4.8	Eigenvalues and Eigenvectors of an Operator	99
2.4.9	Infinitesimal and Finite Unitary Transformations	101
2.5	Representation in Discrete Bases	104
2.5.1	Matrix Representation of Kets, Bras, and Operators	105
2.5.2	Change of Bases and Unitary Transformations	114
2.5.3	Matrix Representation of the Eigenvalue Problem	117
2.6	Representation in Continuous Bases	121
2.6.1	General Treatment	121
2.6.2	Position Representation	123
2.6.3	Momentum Representation	124
2.6.4	Connecting the Position and Momentum Representations	124
2.6.5	Parity Operator	128
2.7	Matrix and Wave Mechanics	130
2.7.1	Matrix Mechanics	130
2.7.2	Wave Mechanics	131
2.8	Concluding Remarks	132
2.9	Solved Problems	133
2.10	Exercises	155
3	Postulates of Quantum Mechanics	165
3.1	Introduction	165
3.2	The Basic Postulates of Quantum Mechanics	165
3.3	The State of a System	167
3.3.1	Probability Density	167
3.3.2	The Superposition Principle	168
3.4	Observables and Operators	170
3.5	Measurement in Quantum Mechanics	172
3.5.1	How Measurements Disturb Systems	172
3.5.2	Expectation Values	173
3.5.3	Complete Sets of Commuting Operators (CSCO)	175
3.5.4	Measurement and the Uncertainty Relations	177

3.6	Time Evolution of the System's State	178
3.6.1	Time Evolution Operator	178
3.6.2	Stationary States: Time-Independent Potentials	179
3.6.3	Schrödinger Equation and Wave Packets	180
3.6.4	The Conservation of Probability	181
3.6.5	Time Evolution of Expectation Values	182
3.7	Symmetries and Conservation Laws	183
3.7.1	Infinitesimal Unitary Transformations	184
3.7.2	Finite Unitary Transformations	185
3.7.3	Symmetries and Conservation Laws	185
3.8	Connecting Quantum to Classical Mechanics	187
3.8.1	Poisson Brackets and Commutators	187
3.8.2	The Ehrenfest Theorem	189
3.8.3	Quantum Mechanics and Classical Mechanics	190
3.9	Solved Problems	191
3.10	Exercises	209
4	One-Dimensional Problems	215
4.1	Introduction	215
4.2	Properties of One-Dimensional Motion	216
4.2.1	Discrete Spectrum (Bound States)	216
4.2.2	Continuous Spectrum (Unbound States)	217
4.2.3	Mixed Spectrum	217
4.2.4	Symmetric Potentials and Parity	218
4.3	The Free Particle: Continuous States	218
4.4	The Potential Step	220
4.5	The Potential Barrier and Well	224
4.5.1	The Case $E > V_0$	224
4.5.2	The Case $E < V_0$: Tunneling	227
4.5.3	The Tunneling Effect	229
4.6	The Infinite Square Well Potential	231
4.6.1	The Asymmetric Square Well	231
4.6.2	The Symmetric Potential Well	234
4.7	The Finite Square Well Potential	234
4.7.1	The Scattering Solutions ($E > V_0$)	235
4.7.2	The Bound State Solutions ($0 < E < V_0$)	235
4.8	The Harmonic Oscillator	239
4.8.1	Energy Eigenvalues	241
4.8.2	Energy Eigenstates	243
4.8.3	Energy Eigenstates in Position Space	244
4.8.4	The Matrix Representation of Various Operators	247
4.8.5	Expectation Values of Various Operators	248
4.9	Numerical Solution of the Schrödinger Equation	249
4.9.1	Numerical Procedure	249
4.9.2	Algorithm	251
4.10	Solved Problems	252
4.11	Exercises	276

5	Angular Momentum	283
5.1	Introduction	283
5.2	Orbital Angular Momentum	283
5.3	General Formalism of Angular Momentum	285
5.4	Matrix Representation of Angular Momentum	290
5.5	Geometrical Representation of Angular Momentum	293
5.6	Spin Angular Momentum	295
5.6.1	Experimental Evidence of the Spin	295
5.6.2	General Theory of Spin	297
5.6.3	Spin 1/2 and the Pauli Matrices	298
5.7	Eigenfunctions of Orbital Angular Momentum	301
5.7.1	Eigenfunctions and Eigenvalues of \hat{L}_z	302
5.7.2	Eigenfunctions of \hat{L}^2	303
5.7.3	Properties of the Spherical Harmonics	307
5.8	Solved Problems	310
5.9	Exercises	325
6	Three-Dimensional Problems	333
6.1	Introduction	333
6.2	3D Problems in Cartesian Coordinates	333
6.2.1	General Treatment: Separation of Variables	333
6.2.2	The Free Particle	335
6.2.3	The Box Potential	336
6.2.4	The Harmonic Oscillator	338
6.3	3D Problems in Spherical Coordinates	340
6.3.1	Central Potential: General Treatment	340
6.3.2	The Free Particle in Spherical Coordinates	343
6.3.3	The Spherical Square Well Potential	346
6.3.4	The Isotropic Harmonic Oscillator	347
6.3.5	The Hydrogen Atom	351
6.3.6	Effect of Magnetic Fields on Central Potentials	365
6.4	Concluding Remarks	368
6.5	Solved Problems	368
6.6	Exercises	385
7	Rotations and Addition of Angular Momenta	391
7.1	Rotations in Classical Physics	391
7.2	Rotations in Quantum Mechanics	393
7.2.1	Infinitesimal Rotations	393
7.2.2	Finite Rotations	395
7.2.3	Properties of the Rotation Operator	396
7.2.4	Euler Rotations	397
7.2.5	Representation of the Rotation Operator	398
7.2.6	Rotation Matrices and the Spherical Harmonics	400
7.3	Addition of Angular Momenta	403
7.3.1	Addition of Two Angular Momenta: General Formalism	403
7.3.2	Calculation of the Clebsch–Gordan Coefficients	409

7.3.3	Coupling of Orbital and Spin Angular Momenta	415
7.3.4	Addition of More Than Two Angular Momenta	419
7.3.5	Rotation Matrices for Coupling Two Angular Momenta	420
7.3.6	Isospin	422
7.4	Scalar, Vector, and Tensor Operators	425
7.4.1	Scalar Operators	426
7.4.2	Vector Operators	426
7.4.3	Tensor Operators: Reducible and Irreducible Tensors	428
7.4.4	Wigner–Eckart Theorem for Spherical Tensor Operators	430
7.5	Solved Problems	434
7.6	Exercises	450
8	Identical Particles	455
8.1	Many-Particle Systems	455
8.1.1	Schrödinger Equation	455
8.1.2	Interchange Symmetry	457
8.1.3	Systems of Distinguishable Noninteracting Particles	458
8.2	Systems of Identical Particles	460
8.2.1	Identical Particles in Classical and Quantum Mechanics	460
8.2.2	Exchange Degeneracy	462
8.2.3	Symmetrization Postulate	463
8.2.4	Constructing Symmetric and Antisymmetric Functions	464
8.2.5	Systems of Identical Noninteracting Particles	464
8.3	The Pauli Exclusion Principle	467
8.4	The Exclusion Principle and the Periodic Table	469
8.5	Solved Problems	475
8.6	Exercises	484
9	Approximation Methods for Stationary States	489
9.1	Introduction	489
9.2	Time-Independent Perturbation Theory	490
9.2.1	Nondegenerate Perturbation Theory	490
9.2.2	Degenerate Perturbation Theory	496
9.2.3	Fine Structure and the Anomalous Zeeman Effect	499
9.3	The Variational Method	507
9.4	The Wentzel–Kramers–Brillouin Method	515
9.4.1	General Formalism	515
9.4.2	Bound States for Potential Wells with No Rigid Walls	518
9.4.3	Bound States for Potential Wells with One Rigid Wall	524
9.4.4	Bound States for Potential Wells with Two Rigid Walls	525
9.4.5	Tunneling through a Potential Barrier	528
9.5	Concluding Remarks	530
9.6	Solved Problems	531
9.7	Exercises	562

10 Time-Dependent Perturbation Theory	571
10.1 Introduction	571
10.2 The Pictures of Quantum Mechanics	571
10.2.1 The Schrödinger Picture	572
10.2.2 The Heisenberg Picture	572
10.2.3 The Interaction Picture	573
10.3 Time-Dependent Perturbation Theory	574
10.3.1 Transition Probability	576
10.3.2 Transition Probability for a Constant Perturbation	577
10.3.3 Transition Probability for a Harmonic Perturbation	579
10.4 Adiabatic and Sudden Approximations	582
10.4.1 Adiabatic Approximation	582
10.4.2 Sudden Approximation	583
10.5 Interaction of Atoms with Radiation	586
10.5.1 Classical Treatment of the Incident Radiation	587
10.5.2 Quantization of the Electromagnetic Field	588
10.5.3 Transition Rates for Absorption and Emission of Radiation	591
10.5.4 Transition Rates within the Dipole Approximation	592
10.5.5 The Electric Dipole Selection Rules	593
10.5.6 Spontaneous Emission	594
10.6 Solved Problems	597
10.7 Exercises	613
11 Scattering Theory	617
11.1 Scattering and Cross Section	617
11.1.1 Connecting the Angles in the Lab and CM frames	618
11.1.2 Connecting the Lab and CM Cross Sections	620
11.2 Scattering Amplitude of Spinless Particles	621
11.2.1 Scattering Amplitude and Differential Cross Section	623
11.2.2 Scattering Amplitude	624
11.3 The Born Approximation	628
11.3.1 The First Born Approximation	628
11.3.2 Validity of the First Born Approximation	629
11.4 Partial Wave Analysis	631
11.4.1 Partial Wave Analysis for Elastic Scattering	631
11.4.2 Partial Wave Analysis for Inelastic Scattering	635
11.5 Scattering of Identical Particles	636
11.6 Solved Problems	639
11.7 Exercises	650
A The Delta Function	653
A.1 One-Dimensional Delta Function	653
A.1.1 Various Definitions of the Delta Function	653
A.1.2 Properties of the Delta Function	654
A.1.3 Derivative of the Delta Function	655
A.2 Three-Dimensional Delta Function	656

B Angular Momentum in Spherical Coordinates	657
B.1 Derivation of Some General Relations	657
B.2 Gradient and Laplacian in Spherical Coordinates	658
B.3 Angular Momentum in Spherical Coordinates	659
C C++ Code for Solving the Schrödinger Equation	661
Index	665