

## Contents

**Preface** *XIII*

**Abbreviations and Notations** *XIX*

<b>1</b>	<b>The Failure of Classical Physics</b>	<b>1</b>
1.1	Blackbody Radiation	1
1.2	Heat Capacity	4
1.3	The Photoelectric Effect	9
1.4	Atoms and Their Spectra	12
1.5	The Double-Slit Experiment	14
	Problem	19
	References	19
<b>2</b>	<b>The First Steps into the Unknown</b>	<b>21</b>
2.1	The BBR and Planck's Formula	21
2.2	Einstein's Light Quanta and BBR	24
2.2.1	Discussion	27
2.3	PEE Revisited	30
2.4	The Third Breakthrough: de Broglie Waves	31
2.4.1	Exercise	33
	Problems	35
	References	35
<b>3</b>	<b>Embryonic Quantum Mechanics: Basic Features</b>	<b>37</b>
3.1	A Glimpse of the New Realm	37
3.2	Quantum-Mechanical Superposition of States	39
3.3	What Is Waving There (the Meaning of the $\Psi$ -Function)?	42
3.4	Observables and Their Operators	47
3.5	Quantum-Mechanical Indeterminacy	49
3.6	Indeterminacy and the World	53
3.7	Quantum Entanglement and Nonlocality	58
3.8	Quantum-Mechanical Phase Space	62
3.9	Determinism and Causality in Quantum World	63

3.9.1	Discussion	63
	Problems	66
	References	66
<b>4</b>	<b>Playing with the Amplitudes</b>	<b>69</b>
4.1	Composition of Amplitudes	69
4.2	Double Slit Revised I	74
4.3	Double Slit Revised II	77
4.4	Neutron Scattering in Crystals	78
4.5	Bosonic and Fermionic States	81
4.6	Path Integrals	89
	Problems	93
	References	93
<b>5</b>	<b>Basic Features and Mathematical Structure of QM</b>	<b>95</b>
5.1	Observables: the Domain of Classical and Quantum Mechanics	95
5.2	Quantum-Mechanical Operators	97
5.3	Algebra of Operators	100
5.4	Eigenvalues and Eigenstates	102
5.5	Orthogonality of Eigenstates	107
5.6	The Robertson–Schrödinger Relation	110
5.7	The Wave Function and Measurements (Discussion)	112
	Problems	116
	References	117
<b>6</b>	<b>Representations and the Hilbert Space</b>	<b>119</b>
6.1	Various Faces of a State Function	119
6.2	Unitary Transformations	121
6.3	Operators in the Matrix Form	125
6.4	The Hilbert Space	129
6.5	Operations in the Hilbert Space	135
6.6	Nonorthogonal States	142
	Problems	147
	References	148
<b>7</b>	<b>Angular Momentum</b>	<b>149</b>
7.1	Orbital and Spin Angular Momenta	149
7.2	The Eigenstates and Eigenvalues of $\hat{L}$	151
7.3	Operator $\hat{L}$ and Its Commutation Properties	154
7.4	Spin as an Intrinsic Angular Momentum	164
7.5	Angular Momentum of a Compound System	183
7.6	Spherical Harmonics	188
	Problems	196
	References	197

<b>8</b>	<b>The Schrödinger Equation</b>	199
8.1	The Schrödinger Equation	199
8.2	State Function and the Continuity Equation	200
8.3	Separation of Temporal and Spatial Variables: Stationary States	203
8.4	The Helmholtz Equation and Dispersion Equation for a Free Particle	205
8.5	Separation of Spatial Variables and the Radial Schrödinger Equation	207
8.6	Superposition of Degenerate States	209
8.7	Phase Velocity and Group Velocity	212
8.8	de Broglie's Waves Revised	218
8.9	The Schrödinger Equation in an Arbitrary Basis	222
	Problems	226
	References	226
<b>9</b>	<b>Applications to Simple Systems: One Dimension</b>	227
9.1	A Quasi-Free Particle	227
9.2	Potential Threshold	232
9.3	Tunneling through a Potential Barrier	236
9.4	Cold Emission	241
9.5	Potential Well	244
9.6	Quantum Oscillator	249
9.7	Oscillator in the $E$ -Representation	254
9.8	The Origin of Energy Bands	257
9.9	Periodic Structures	260
	Problems	269
	References	271
<b>10</b>	<b>Three-Dimensional Systems</b>	273
10.1	A Particle in a 3D Box	273
10.2	A Free Particle in 3D (Spherical Coordinates)	274
10.2.1	Discussion	277
10.3	Some Properties of Solutions in Spherically Symmetric Potential	277
10.4	Spherical Potential Well	278
10.5	States in the Coulomb Field and a Hydrogen Atom	281
10.6	Atomic Currents	287
10.7	Periodic Table	290
	Problems	293
	References	294
<b>11</b>	<b>Evolution of Quantum States</b>	295
11.1	The Time Evolution Operator	295
11.2	Evolution of Operators	299

11.3	Spreading of a Gaussian Packet	301
11.4	The $B$ -Factor and Evolution of an Arbitrary State	303
11.5	The Fraudulent Life of an “Illegal” Spike	306
11.6	Jinnee Out of the Box	311
11.7	Inadequacy of Nonrelativistic Approximation in Description of Evolving Discontinuous States	315
11.7.1	Discussion	316
11.8	Quasi-Stationary States	317
11.8.1	Discussion	323
11.9	3D Barrier and Quasi-Stationary States	324
11.10	The Theory of Particle Decay	327
11.11	Particle–Antiparticle Oscillations	331
11.11.1	Discussion	337
11.12	A Watched Pot Never Boils (Quantum Zeno Effect)	339
11.13	A Watched Pot Boils Faster	344
	Problems	350
	References	352
<b>12</b>	<b>Quantum Ensembles</b>	<b>355</b>
12.1	Pure Ensembles	355
12.2	Mixtures	356
12.3	The Density Operator	358
12.4	Time Evolution of the Density Operator	366
12.5	Composite Systems	368
	Problems	376
	References	376
<b>13</b>	<b>Indeterminacy Revisited</b>	<b>377</b>
13.1	Indeterminacy Under Scrutiny	377
13.2	The Heisenberg Inequality Revised	380
13.3	The Indeterminacy of Angular Momentum	382
13.4	The Robertson–Schrödinger Relation Revised	384
13.5	The $N$ - $\phi$ Indeterminacy	388
13.6	Dispersed Indeterminacy	390
	Problems	394
	References	395
<b>14</b>	<b>Quantum Mechanics and Classical Mechanics</b>	<b>397</b>
14.1	Relationship between Quantum and Classical Mechanics	397
14.2	QM and Optics	400
14.3	The Quasi-Classical State Function	401
14.4	The WKB Approximation	404
14.5	The Bohr–Sommerfeld Quantization Rules	406
	Problems	409
	References	410

<b>15</b>	<b>Two-State Systems</b>	<b>411</b>
15.1	Double Potential Well	411
15.2	The Ammonium Molecule	415
15.3	Qubits Introduced	419
	Problem	422
	References	422
<b>16</b>	<b>Charge in Magnetic Field</b>	<b>423</b>
16.1	A Charged Particle in EM Field	423
16.2	The Continuity Equation in EM Field	425
16.3	Origin of the A-Momentum	427
16.4	Charge in Magnetic Field	429
16.5	Spin Precession	432
16.6	The Aharonov–Bohm Effect	437
16.6.1	Discussion	441
16.7	The Zeeman Effect	442
	Problems	444
	References	445
<b>17</b>	<b>Perturbations</b>	<b>447</b>
17.1	Stationary Perturbation Theory	447
17.1.1	Discussion	450
17.2	Asymptotic Perturbations	455
17.3	Perturbations and Degeneracy	457
17.4	Symmetry, Degeneracy, and Perturbations	460
17.5	The Stark Effect	462
17.6	Time-Dependent Perturbations	465
	Problems	471
	References	471
<b>18</b>	<b>Light–Matter Interactions</b>	<b>473</b>
18.1	Optical Transitions	473
18.2	Dipole Radiation	474
18.3	Selection Rules	477
18.3.1	Oscillator	478
18.3.2	Hydrogen-Like Atom	478
	Problems	480
	Reference	480
<b>19</b>	<b>Scattering</b>	<b>481</b>
19.1	QM Description of Scattering	481
19.2	Stationary Scattering	487
19.3	Scattering Matrix and the Optical Theorem	490
19.4	Diffraction Scattering	494
19.5	Resonant Scattering	498

19.6	The Born Approximation	501
	Problems	504
	References	505
<b>20</b>	<b>Submissive Quantum Mechanics</b>	<b>507</b>
20.1	The Inverse Problem	507
20.2	Playing with Quantum States	509
20.3	Playing with Evolution: Discussion	514
	Problems	522
	References	522
<b>21</b>	<b>Quantum Statistics</b>	<b>525</b>
21.1	Bosons and Fermions: The Exclusion Principle	525
21.1.1	Discussion	531
21.2	Planck and Einstein Again	540
21.3	BBR Again	542
21.4	Lasers and Masers	543
	Problems	545
	References	546
<b>22</b>	<b>Second Quantization</b>	<b>547</b>
22.1	Quantum Oscillator Revisited	547
22.2	Creation and Annihilation Operators: Bosons	548
22.3	Creation and Annihilation Operators: Fermions	552
	Problems	555
	References	555
<b>23</b>	<b>Quantum Mechanics and Measurements</b>	<b>557</b>
23.1	Collapse or Explosion?	557
23.2	“Schrödinger’s Cat” and Classical Limits of QM	563
23.3	Von Neumann’s Measurement Scheme	571
23.3.1	Discussion	575
23.4	Quantum Information and Measurements	578
23.5	Interaction-Free Measurements: Quantum Seeing in the Dark	586
23.6	QM and the Time Arrow	593
	Problems	595
	References	596
<b>24</b>	<b>Quantum Nonlocality</b>	<b>599</b>
24.1	Entangled Superpositions I	599
24.2	Entangled Superpositions II	601
24.2.1	Discussion	604
24.3	Quantum Teleportation	604
24.4	The “No-Cloning” Theorem	607

24.5	Hidden Variables and Bell's Theorem	613
24.6	Bell-State Measurements	619
24.7	QM and the Failure of FTL Proposals	627
24.8	Do Lasers Violate the No-Cloning Theorem?	628
24.9	Imperfect Cloning	636
24.10	The FLASH Proposal and Quantum Compounds	643
	Problems	649
	References	649
<b>25</b>	<b>Quantum Measurements and POVMs</b>	<b>651</b>
25.1	Projection Operator and Its Properties	651
25.2	Projective Measurements	655
25.3	POVMs	658
25.4	POVM as a Generalized Measurement	664
25.5	POVM Examples	666
25.6	Discrimination of Two Pure States	670
25.7	Neumark's Theorem	681
25.8	How to Implement a Given POVM	686
25.9	Comparison of States and Mixtures	695
25.10	Generalized Measurements	697
	Problems	700
	References	701
<b>26</b>	<b>Quantum Information</b>	<b>703</b>
26.1	Deterministic Information and Shannon Entropy	703
26.2	von Neumann Entropy	709
26.3	Conditional Probability and Bayes's Theorem	711
26.4	KL Divergence	716
26.5	Mutual Information	717
26.6	Rényi Entropy	719
26.7	Joint and Conditional Renyi Entropy	721
26.8	Universal Hashing	726
26.9	The Holevo Bound	731
26.10	Entropy of Entanglement	733
	Problems	734
	References	735
<b>27</b>	<b>Quantum Gates</b>	<b>737</b>
27.1	Truth Tables	737
27.2	Quantum Logic Gates	741
27.3	Shor's Algorithm	746
	Problems	751
	References	752

<b>28</b>	<b>Quantum Key Distribution</b>	<b>753</b>
28.1	Quantum Key Distribution (QKD) with EPR	753
28.2	BB84 Protocol	758
28.3	QKD as Communication Over a Channel	766
28.4	Postprocessing of the Key	769
28.5	B92 Protocol	776
28.6	Experimental Implementation of QKD Schemes	779
28.7	Advanced Eavesdropping Strategies	788
	Problems	793
	References	793
	<b>Appendix A: Classical Oscillator</b>	<b>795</b>
	Reference	799
	<b>Appendix B: Delta Function</b>	<b>801</b>
	Reference	807
	<b>Appendix C: Representation of Observables by Operators</b>	<b>809</b>
	<b>Appendix D: Elements of Matrix Algebra</b>	<b>813</b>
	<b>Appendix E: Eigenfunctions and Eigenvalues of the Orbital Angular Momentum Operator</b>	<b>817</b>
	<b>Appendix F: Hermite Polynomials</b>	<b>821</b>
	<b>Appendix G: Solutions of the Radial Schrödinger Equation in Free Space</b>	<b>825</b>
	<b>Appendix H: Bound States in the Coulomb Field</b>	<b>827</b>
	Reference	829
	<b>Index</b>	<b>831</b>