# Contents

*Preface*  
page xi

## I THEORY

### 1 The Wave Function

1.1 The Schrödinger Equation  
1.2 The Statistical Interpretation  
1.3 Probability  
1.3.1 Discrete Variables  
1.3.2 Continuous Variables  
1.4 Normalization  
1.5 Momentum  
1.6 The Uncertainty Principle  
Further Problems on Chapter 1  
page 20

### 2 Time-Independent Schrödinger Equation

2.1 Stationary States  
2.2 The Infinite Square Well  
2.3 The Harmonic Oscillator  
2.3.1 Algebraic Method  
2.3.2 Analytic Method  
2.4 The Free Particle  
2.5 The Delta-Function Potential  
2.5.1 Bound States and Scattering States  
2.5.2 The Delta-Function Well  
2.6 The Finite Square Well  
Further Problems on Chapter 2  
page 76

### 3 Formalism

3.1 Hilbert Space  
3.2 Observables  
3.2.1 Hermitian Operators  
3.2.2 Determinate States  
page 96
Contents

3.3 Eigenfunctions of a Hermitian Operator 97
  3.3.1 Discrete Spectra 98
  3.3.2 Continuous Spectra 99
  3.4 Generalized Statistical Interpretation 102
  3.5 The Uncertainty Principle 105
    3.5.1 Proof of the Generalized Uncertainty Principle 105
    3.5.2 The Minimum-Uncertainty Wave Packet 108
    3.5.3 The Energy-Time Uncertainty Principle 109
  3.6 Vectors and Operators 113
    3.6.1 Bases in Hilbert Space 113
    3.6.2 Dirac Notation 117
    3.6.3 Changing Bases in Dirac Notation 121
  Further Problems on Chapter 3 124

4 Quantum Mechanics in Three Dimensions 131
  4.1 The Schrödinger Equation 131
    4.1.1 Spherical Coordinates 132
    4.1.2 The Angular Equation 134
    4.1.3 The Radial Equation 138
    4.2 The Hydrogen Atom 143
    4.2.1 The Radial Wave Function 144
    4.2.2 The Spectrum of Hydrogen 155
    4.3 Angular Momentum 157
      4.3.1 Eigenvalues 157
      4.3.2 Eigenfunctions 162
    4.4 Spin 165
      4.4.1 Spin 1/2 167
      4.4.2 Electron in a Magnetic Field 172
    4.4.3 Addition of Angular Momenta 176
    4.5 Electromagnetic Interactions 181
      4.5.1 Minimal Coupling 181
      4.5.2 The Aharonov–Bohm Effect 182
  Further Problems on Chapter 4 187

5 Identical Particles 198
  5.1 Two-Particle Systems 198
    5.1.1 Bosons and Fermions 201
    5.1.2 Exchange Forces 203
5.1.3 Spin
5.1.4 Generalized Symmetrization Principle
5.2 Atoms
5.2.1 Helium
5.2.2 The Periodic Table
5.3 Solids
5.3.1 The Free Electron Gas
5.3.2 Band Structure

Further Problems on Chapter 5

6 Symmetries & Conservation Laws

6.1 Introduction
6.1.1 Transformations in Space
6.2 The Translation Operator
6.2.1 How Operators Transform
6.2.2 Translational Symmetry
6.3 Conservation Laws
6.4 Parity
6.4.1 Parity in One Dimension
6.4.2 Parity in Three Dimensions
6.4.3 Parity Selection Rules
6.5 Rotational Symmetry
6.5.1 Rotations About the $z$ Axis
6.5.2 Rotations in Three Dimensions
6.6 Degeneracy
6.7 Rotational Selection Rules
6.7.1 Selection Rules for Scalar Operators
6.7.2 Selection Rules for Vector Operators
6.8 Translations in Time
6.8.1 The Heisenberg Picture
6.8.2 Time-Translation Invariance

Further Problems on Chapter 6

II APPLICATIONS

7 Time-Independent Perturbation Theory

7.1 Nondegenerate Perturbation Theory
7.1.1 General Formulation
7.1.2 First-Order Theory
## Contents

7.1.3 Second-Order Energies 284
7.2 Degenerate Perturbation Theory 286
7.2.1 Two-Fold Degeneracy 286
7.2.2 “Good” States 291
7.2.3 Higher-Order Degeneracy 294
7.3 The Fine Structure of Hydrogen 295
7.3.1 The Relativistic Correction 296
7.3.2 Spin-Orbit Coupling 299
7.4 The Zeeman Effect 304
7.4.1 Weak-Field Zeeman Effect 305
7.4.2 Strong-Field Zeeman Effect 307
7.4.3 Intermediate-Field Zeeman Effect 309
7.5 Hyperfine Splitting in Hydrogen 311
Further Problems on Chapter 7 313

### 8 The Variational Principle 327
8.1 Theory 327
8.2 The Ground State of Helium 332
8.3 The Hydrogen Molecule Ion 337
8.4 The Hydrogen Molecule 341
Further Problems on Chapter 8 346

### 9 The WKB Approximation 354
9.1 The “Classical” Region 354
9.2 Tunneling 358
9.3 The Connection Formulas 362
Further Problems on Chapter 9 371

### 10 Scattering 376
10.1 Introduction 376
10.1.1 Classical Scattering Theory 376
10.1.2 Quantum Scattering Theory 379
10.2 Partial Wave Analysis 380
10.2.1 Formalism 380
10.2.2 Strategy 383
10.3 Phase Shifts 385
10.4 The Born Approximation 388
10.4.1 Integral Form of the Schrödinger Equation 388
10.4.2 The First Born Approximation 391
10.4.3 The Born Series 395
Further Problems on Chapter 10 397

11 Quantum Dynamics 402
11.1 Two-Level Systems 403
11.1.1 The Perturbed System 403
11.1.2 Time-Dependent Perturbation Theory 405
11.1.3 Sinusoidal Perturbations 408
11.2 Emission and Absorption of Radiation 411
11.2.1 Electromagnetic Waves 411
11.2.2 Absorption, Stimulated Emission, and Spontaneous Emission 412
11.2.3 Incoherent Perturbations 413
11.3 Spontaneous Emission 416
11.3.1 Einstein's $A$ and $B$ Coefficients 416
11.3.2 The Lifetime of an Excited State 418
11.3.3 Selection Rules 420
11.4 Fermi's Golden Rule 422
11.5 The Adiabatic Approximation 426
11.5.1 Adiabatic Processes 426
11.5.2 The Adiabatic Theorem 428
Further Problems on Chapter 11 433

12 Afterword 446
12.1 The EPR Paradox 447
12.2 Bell's Theorem 449
12.3 Mixed States and the Density Matrix 455
12.3.1 Pure States 455
12.3.2 Mixed States 456
12.3.3 Subsystems 458
12.4 The No-Clone Theorem 459
12.5 Schrödinger's Cat 461

Appendix Linear Algebra 464
A.1 Vectors 464
A.2 Inner Products 466
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.3</td>
<td>Matrices</td>
<td>468</td>
</tr>
<tr>
<td>A.4</td>
<td>Changing Bases</td>
<td>473</td>
</tr>
<tr>
<td>A.5</td>
<td>Eigenvectors and Eigenvalues</td>
<td>475</td>
</tr>
<tr>
<td>A.6</td>
<td>Hermitian Transformations</td>
<td>482</td>
</tr>
</tbody>
</table>

*Index*  
486