A Student’s Guide to Atomic Physics

This concise and accessible book provides a detailed introduction to the fundamental principles of atomic physics at an undergraduate level. Concepts are explained in an intuitive way, and the book assumes only a basic knowledge of quantum mechanics and electromagnetism. With a compact format specifically designed for students, the first part of the book covers the key principles of the subject, including quantum theory of the hydrogen atom, radiative transitions, the shell model of multi-electron atoms, spin–orbit coupling, and the effects of external fields. The second part provides an introduction to four key applications of atomic physics: lasers, cold atoms, solid-state spectroscopy, and astrophysics. This highly pedagogical text includes worked examples and end-of-chapter problems to allow students to test their knowledge, as well as numerous diagrams of key concepts, making it perfect for undergraduate students looking for a succinct primer on the concepts and applications of atomic physics.

M A R K  F O X is Professor of Physics at the University of Sheffield. He is also a fellow of the Optical Society of America and the Institute of Physics. His research focuses on optics and photonics, and he specializes in solid-state atoms and quantum dots. He has authored two highly successful books: *Optical Properties of Solids* (2nd edition, 2010) and *Quantum Optics: An Introduction* (2005).
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A Student’s Guide to Atomic Physics

MARK FOX

University of Sheffield
## Contents

- **Preface**  page xi
- **Symbols**  xiv
- **Quantum Numbers**  xvii

### Part I Fundamental Principles  1

1 **Preliminary Concepts**  3
   1.1 Quantized Energy States in Atoms  3
   1.2 Ionization States and Spectroscopic Notation  5
   1.3 Ground States and Excited States  7
   1.4 Atomic Spectroscopy  10
   1.5 Spectroscopic Energy Units and Atomic Databases  14
   1.6 Energy Scales in Atoms  17
   Exercises  19

2 **Hydrogen**  20
   2.1 The Bohr Model of Hydrogen  20
   2.2 The Quantum Mechanics of the Hydrogen Atom  26
   2.3 Degeneracy and Spin  36
   2.4 Hydrogen-Like Atoms  37
   Exercises  38

3 **Radiative Transitions**  40
   3.1 Classical Theories of Radiating Dipoles  40
   3.2 Quantum Theory of Radiative Transitions  42
   3.3 Electric Dipole (E1) Transitions  43
   3.4 Selection Rules for E1 Transitions  45
   3.5 Higher-Order Transitions  48
   3.6 Radiative Lifetimes  49
## Contents

3.7 The Width and Shape of Spectral Lines 50  
3.8 Natural Broadening 51  
3.9 Collision (Pressure) Broadening 53  
3.10 Doppler Broadening 53  
3.11 Voigt Line Shapes 56  
3.12 Converting between Line Widths in Frequency and Wavelength Units 56  
Exercises 57  

4 The Shell Model and Alkali Spectra 60  
4.1 The Central-Field Approximation 60  
4.2 The Shell Model and the Periodic Table 64  
4.3 Justification of the Shell Model 70  
4.4 Experimental Evidence for the Shell Model 71  
4.5 Alkali Metals 77  
Exercises 82  

5 Angular Momentum 84  
5.1 Conservation of Angular Momentum 84  
5.2 Types of Angular Momentum 85  
5.3 Addition of Angular Momentum 92  
5.4 Spin-Orbit Coupling 93  
5.5 Angular Momentum Coupling in Single-Electron Atoms 93  
5.6 Angular Momentum Coupling in Multi-Electron Atoms 94  
5.7 LS Coupling 95  
5.8 Electric-Dipole Selection Rules in the LS Coupling Limit 97  
5.9 Hund’s Rules 99  
5.10 jj Coupling 102  
Exercises 103  

6 Helium and Exchange Symmetry 106  
6.1 Exchange Symmetry 106  
6.2 Helium Wave Functions 107  
6.3 The Pauli Exclusion Principle 110  
6.4 The Hamiltonian for Helium 111  
6.5 The Helium Term Diagram 114  
6.6 Optical Spectra of Divalent Metals 117  
Exercises 118  

7 Fine Structure and Nuclear Effects 119  
7.1 Orbital Magnetic Dipoles 119
Contents

7.2 Spin Magnetism 121
7.3 Spin-Orbit Coupling 122
7.4 Evaluation of the Spin-Orbit Energy for Hydrogen 127
7.5 Spin-Orbit Coupling in Alkali Atoms 129
7.6 Spin-Orbit Coupling in Many-Electron Atoms 132
7.7 Fine Structure in X-Ray Spectra 133
7.8 Nuclear Effects in Atoms 134
Exercises 138

8 External Fields: The Zeeman and Stark Effects 141
8.1 Magnetic Fields 141
8.2 The Concept of “Good” Quantum Numbers 152
8.3 Nuclear Effects 153
8.4 Electric Fields 154
Exercises 158

Part II Applications of Atomic Physics 161

9 Stimulated Emission and Lasers 163
9.1 Stimulated Emission 163
9.2 Population Inversion 166
9.3 Optical Amplification 168
9.4 Principles of Laser Oscillation 170
9.5 Four-Level Lasers 173
9.6 The Helium–Neon Laser 176
9.7 Three-Level Lasers 178
9.8 Classification of Lasers 180
Exercises 181

10 Cold Atoms 184
10.1 Introduction 184
10.2 Gas Temperatures 185
10.3 Doppler Cooling 186
10.4 Optical Molasses and Magneto-Optical Traps 191
10.5 Experimental Considerations 192
10.6 Cooling below the Doppler Limit 193
10.7 Bose–Einstein Condensation 194
Exercises 200

11 Atomic Physics Applied to the Solid State 202
11.1 Solid-State Spectroscopy 203
11.2 Semiconductors 206
## Contents

11.3 Solid-State Hydrogenic Systems 214  
11.4 Quantum-Confined Semiconductor Structures 217  
11.5 Ions Doped in Crystals 220  
   Exercises 223

### 12 Atomic Physics in Astronomy 226
   12.1 Astrophysical Environments 226  
   12.2 Astrophysical Spectra 228  
   12.3 Information Gained from Analysis of Astrophysical Spectra 237  
   12.4 Hydrogen Spectra 240  
   12.5 Helium Spectra 244  
      Exercises 246

   *Appendix A* The Reduced Mass 248
   *Appendix B* Mathematical Solutions for the Hydrogen Schrödinger Equation 251
   *Appendix C* Helium Energy Integrals 256
   *Appendix D* Perturbation Theory of the Stark Effect 259
   *Appendix E* Laser Dynamics 264

References 267

Index 269
Preface

Undergraduate students come across the concepts of atomic physics at various stages during their degree programs. For example, the Bohr model is a central part of introductory courses on quantum physics, while the hydrogen atom is a key element in a first course on quantum mechanics. After that, the more advanced topics could either be a component of a second, broad quantum physics module, or a stand-alone unit. This book is designed for the latter approach, without necessarily excluding its usefulness for the former, where it might be used, for example, in conjunction with a text on nuclear physics.

The book evolved from a detailed set of lecture notes prepared for a third-year module at the University of Sheffield. The notes were prepared to respond to the lack of a short text at the right level. The subject material was either scattered across various chapters of large quantum physics texts, or was included in introductory sections of more advanced texts. Neither case was particularly suited to the needs of the students.

The range of topics included within the book aims to cover the core curriculum on atomic physics set out by the Institute of Physics, and might be useful either to second- or third-year students within the United Kingdom, depending on how a particular university subdivides the syllabus. For readers outside the United Kingdom, the text is pitched at intermediate-level students. It assumes basic familiarity with the techniques of quantum mechanics, but does not have the depth required for masters-level courses.

The course notes have been freely available on the Internet for several years, and I was approached by several publishers who thought they could form the basis for a textbook. Having already written two textbooks, I was well aware of the extra effort required to turn a set of lecture notes into a book and resisted the approaches I received. However, I then discovered the Cambridge Student’s Guide series, and realized that it is the right place for the material.
Its inclusion within the series makes it clear that the book does not claim to be an authoritative reference work, but rather an intermediate-level text aimed at explaining the basic concepts to undergraduate students.

The text is divided into two parts:

- Part I: Fundamental Principles (Chapters 1–8)
- Part II: Applications of Atomic Physics (Chapters 9–12)

The first part should be useful for undergraduate students at most universities, as it covers the core concepts of university-level atomic physics. The second part will find varied use, depending on how a particular university organizes its course. Chapter 9 covers most of the basic ideas required for the laser-physics component of Institute of Physics (IOP) curriculum. Chapter 10 gives a brief introduction to the techniques of laser cooling that underpin a large sector of modern atomic physics research. Chapter 11 reflects the author’s own background in semiconductor physics and solid-state lasers. The final chapter arose from the suggestions of the manuscript reviewers, and its writing involved a fascinating learning experience for the author.

Texts within the Cambridge Student’s Guide series are deliberately kept short. For this reason, some nonessential material that was in the first draft of the manuscript has been moved to an online supplement. The sections where additional notes are available online are identified by the symbol in the margin. Another key feature of the series is the inclusion of worked examples and exercises. Solutions to the exercises are available from the online resources.

I am very grateful to numerous people who have helped in various ways to bring the book to fruition. First, I would like to thank the generations of students at the University of Sheffield who have taken the course and provided feedback on the notes. I am also grateful to my colleagues at the University of Sheffield, on whom I have bounced ideas and with whom I have clarified concepts. Among these, I would like to single out Professor Paul Crowther, who provided invaluable help with Chapter 12. My knowledge of astrophysics was very limited before I wrote the chapter, and his critical reading of the manuscript has both greatly improved it and also ironed out deficiencies in my understanding. I would also like to thank people around the world who provided feedback on the Internet version of the notes, especially Dr. André Xuereb, from the University of Malta, for his comments on the 2013 version.

Second, I would like to thank the people who taught me atomic physics at the University of Oxford, especially my tutor, Professor Roger Cashmore, and my lecturers, Dr. Alan Corney and Dr. Kem Woodgate. I regard this book as an
Preface

introduction to their excellent texts, which are both still in print and included in the References. The structure of Part I broadly follows a set of lecture notes by Professors Paul Ewart and Derek Stacey at the University of Oxford, although the final ordering of material departs a little from their plan. Professor Stacey also provided comments on Part I of the manuscript, which have helped to iron out some potentially confusing statements.

Next, I would like to thank Dr. Nicholas Gibbons at Cambridge University Press for introducing me to the Student’s Guide series and supporting the project. I am especially grateful to him for finding a very helpful set of reviewers at the syndicate approval stage. These anonymous reviewers provided numerous helpful suggestions. In particular, the final chapter is included on their suggestion, while much of Chapter 1 is a response to one of the reviewers. This reviewer pointed out that my original notes took several basic concepts for granted, and this prompted me to rewrite the first three sections to provide fundamental definitions.

Finally, I would like to thank Dr. John Pantazis, from Amptek, Inc., for providing the data in Figure 4.6(a), and Róisín Munnelly at Cambridge University Press for her role as Content Manager. Her patience in seeing the project through to completion is much appreciated.
Symbols

The list gives the main symbols used in the text, excluding some that are used infrequently and are defined in situ. In some cases, it is necessary to use the same symbol to represent different quantities. Whenever this occurs, it should be obvious from the context which meaning is intended.

\[ a_0 \] Bohr radius
\[ a_H \] Bohr radius of hydrogen
\[ A \] area
\[ A_{ij} \] Einstein A coefficient
\[ B \] magnetic field (flux density)
\[ B_{ij} \] Einstein B coefficient
\[ d \] distance
\[ e \] magnitude of electron charge
\[ E \] energy
\[ \mathcal{E} \] electric field
\[ F \] force, total angular momentum
\[ g(E) \] density of states at energy \( E \)
\[ g(v) \] spectral line-shape function
\[ g \] degeneracy
\[ g_J \] Landé g-factor
\[ g_N \] nuclear g-factor
\[ g_s \] electron spin g-factor
\[ h \] Planck’s constant
\[ \hbar \] \( h/2\pi \)
\[ \hat{H} \] Hamiltonian
\[ H' \] perturbation
\[ i \] electrical current
Symbols

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<th>Symbol</th>
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<td>$I$</td>
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<td>$I$</td>
<td>nuclear angular momentum</td>
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<td>$I_z$</td>
<td>$z$ component of nuclear angular momentum</td>
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<td>$j$</td>
<td>angular momentum (single electron)</td>
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<tr>
<td>$J$</td>
<td>exchange constant</td>
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<td>total angular momentum</td>
</tr>
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<td>orbital angular momentum (single electron)</td>
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<td>$l_z$</td>
<td>$z$ component of orbital angular momentum (single electron)</td>
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<td>$L$</td>
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<td>$m$</td>
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<td>$m^*$</td>
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<td>mass of hydrogen atom</td>
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<td>$M_{ij}$</td>
<td>matrix element</td>
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<td>$N$</td>
<td>number of atoms per unit volume</td>
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<td>electric dipole moment, linear momentum</td>
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<td>$P$</td>
<td>power, pressure</td>
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<td>voltage, potential energy, volume</td>
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<td>$\hat{x}$</td>
<td>unit vector along the $x$-axis</td>
</tr>
<tr>
<td>$y$</td>
<td>position coordinate</td>
</tr>
<tr>
<td>$\hat{y}$</td>
<td>unit vector along the $y$-axis</td>
</tr>
<tr>
<td>$Y_{l,m_l}$</td>
<td>spherical harmonic function</td>
</tr>
<tr>
<td>$z$</td>
<td>position coordinate, Doppler redshift</td>
</tr>
</tbody>
</table>
xvi Symbols

\( \hat{z} \) unit vector along the \( z \)-axis
\( Z \) atomic number
\( \alpha \) fine-structure constant, absorption coefficient, polarizability
\( \gamma \) gyromagnetic ratio, gain coefficient
\( \Gamma \) torque
\( \delta \) frequency detuning
\( \delta_{i,k'} \) Kronecker delta function
\( \delta(x) \) Dirac delta function
\( \varepsilon_r \) relative permittivity
\( \theta \) polar angle
\( \lambda \) wavelength
\( \lambda_{\text{deB}} \) de Broglie wavelength
\( \mu \) magnetic dipole moment
\( \nu \) frequency
\( \nu \) wave number
\( \tau \) lifetime
\( \tau_c \) collision time
\( \phi \) azimuthal angle
\( \psi, \Psi \) wave function
\( \omega \) angular frequency
Quantum Numbers

In atomic physics, lower- and uppercase letters refer to individual electrons or whole atoms respectively.

- $F$: hyperfine total angular momentum
- $I$: nuclear spin
- $j, J$: total electron angular momentum
- $l, L$: orbital angular momentum
- $m$: magnetic
- $M_F$: $z$ component of hyperfine angular momentum
- $M_I$: $z$ component of nuclear spin
- $m_j, M_J$: $z$ component of electron total angular momentum
- $m_l, M_L$: $z$ component of orbital angular momentum
- $m_s, M_S$: $z$ component of spin angular momentum
- $n$: principal
- $s, S$: spin