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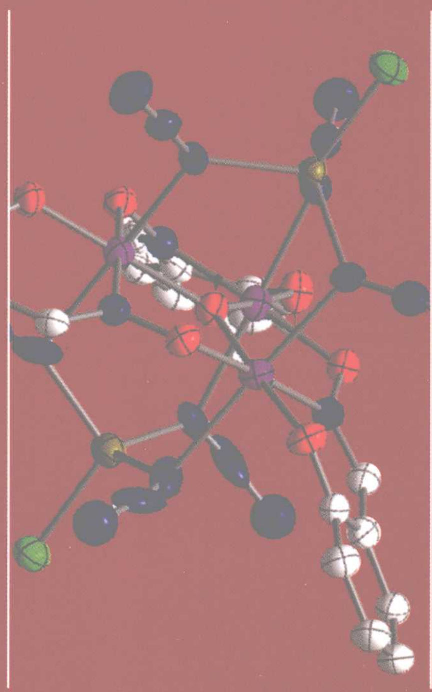
Atomic Physics
原子物理学



C. J. Foot

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Preface

This book is primarily intended to accompany an undergraduate course in atomic physics. It covers the core material and a selection of more advanced topics that illustrate current research in this field. The first six chapters describe the basic principles of atomic structure, starting in Chapter 1 with a review of the classical ideas. Inevitably the discussion of the structure of hydrogen and helium in these early chapters has considerable overlap with introductory quantum mechanics courses, but an understanding of these simple systems provides the basis for the treatment of more complex atoms in later chapters. Chapter 7 on the interaction of radiation with atoms marks the transition between the earlier chapters on structure and the second half of the book which covers laser spectroscopy, laser cooling, Bose–Einstein condensation of dilute atomic vapours, matter-wave interferometry and ion trapping. The exciting new developments in laser cooling and trapping of atoms and Bose–Einstein condensation led to Nobel prizes in 1997 and 2001, respectively. Some of the other selected topics show the incredible precision that has been achieved by measurements in atomic physics experiments. This theme is taken up in the final chapter that looks at quantum information processing from an atomic physics perspective; the techniques developed for precision measurements on atoms and ions give exquisite control over these quantum systems and enable elegant new ideas from quantum computation to be implemented.

The book assumes a knowledge of quantum mechanics equivalent to an introductory university course, e.g. the solution of the Schrödinger equation in three dimensions and perturbation theory. This initial knowledge will be reinforced by many examples in this book; topics generally regarded as difficult at the undergraduate level are explained in some detail, e.g. degenerate perturbation theory. The hierarchical structure of atoms is well described by perturbation theory since the different layers of structure within atoms have considerably different energies associated with them, and this is reflected in the names of the gross, fine and hyperfine structures. In the early chapters of this book, atomic physics may appear to be simply applied quantum mechanics, i.e. we write down the Hamiltonian for a given interaction and solve the Schrödinger equation with suitable approximations. I hope that the study of the more advanced material in the later chapters will lead to a more mature and deeper understanding of atomic physics. Throughout this book the experimental basis of atomic physics is emphasised and it is hoped that the reader will gain some factual knowledge of atomic spectra.

The selection of topics from the diversity of current atomic physics is necessarily subjective. I have concentrated on low-energy and high-precision experiments which, to some extent, reflects local research interests that are used as examples in undergraduate lectures at Oxford. One of the selection criteria was that the material is not readily available in other textbooks, at the time of writing, e.g. atomic collisions have not been treated in detail (only a brief summary of the scattering of ultracold atoms is included in Chapter 10). Other notable omissions include: X-ray spectra, which are discussed only briefly in connection with the historically important work of Moseley, although they form an important frontier of current research; atoms in strong laser fields and plasmas; Rydberg atoms and atoms in doubly- and multiply-excited states (e.g. excited by new synchrotron and free-electron laser sources); and the structure and spectra of molecules.

I would like to thank Geoffrey Brooker for invaluable advice on physics (in particular Appendix B) and on technical details of writing a textbook for the Oxford Master Series. Keith Burnett, Jonathan Jones and Andrew Steane have helped to clarify certain points, in my mind at least, and hopefully also in the text. The series of lectures on laser cooling given by William Phillips while he was a visiting professor in Oxford was extremely helpful in the writing of the chapter on that topic. The following people provided very useful comments on the draft manuscript: Rachel Godun, David Lucas, Mark Lee, Matthew McDonnell, Martin Shotter, Claes-Göran Wahlström (Lund University) and the (anonymous) reviewers. Without the encouragement of Sönke Adlung at OUP this project would not have been completed. Irmgard Smith drew some of the diagrams. I am very grateful for the diagrams and data supplied by colleagues, and reproduced with their permission, as acknowledged in the figure captions. Several of the exercises on atomic structure derive from Oxford University examination papers and it is not possible to identify the examiners individually—some of these exam questions may themselves have been adapted from some older sources of which I am not aware.

Finally, I would like to thank Professors Derek Stacey, Joshua Silver and Patrick Sandars who taught me atomic physics as an undergraduate and graduate student in Oxford. I also owe a considerable debt to the book on elementary atomic structure by Gordon Kemble Woodgate, who was my predecessor as physics tutor at St Peter's College, Oxford. In writing this new text, I have tried to achieve the same high standards of clarity and conciseness of expression whilst introducing new examples and techniques from the laser era.

Background reading

> It is not surprising that our language should be incapable of describing the processes occurring with the atoms, for it was invented to describe the experiences of daily life, and these consist only of processes involving exceeding large numbers

> of atoms. Furthermore, it is very difficult to modify our language so that it will be able to describe these atomic processes, for words can only describe things of which we can form mental pictures, and this ability, too, in the result of daily experience. Fortunately, mathematics is not subject to this limitation, and it has been possible to invent a mathematical scheme—the quantum theory—which seems entirely adequate for the treatment of atomic processes.
> From *The physical principles of the quantum theory*, Werner Heisenberg (1930).

The point of the excerpt is that quantum mechanics is essential for a proper description of atomic physics and there are many quantum mechanics textbooks that would serve as useful background reading for this book. The following short list includes those that the author found particularly relevant: Mandl (1992), Rae (1992) and Griffiths (1995). The book *Atomic spectra* by Softley (1994) provides a concise introduction to this field. The books Cohen-Tannoudji *et al.* (1977), Atkins (1983) and Basdevant and Dalibard (2000) are very useful for reference and contain many detailed examples of atomic physics. Angular-momentum theory is very important for dealing with complicated atomic structures, but it is beyond the intended level of this book. The classic book by Dirac (1981) still provides a very readable account of the addition of angular momenta in quantum mechanics. A more advanced treatment of atomic structure can be found in Condon and Odabasi (1980), Cowan (1981) and Sobelman (1996).

Oxford C. J. F.

Web site:

`http://www.physics.ox.ac.uk/users/foot`

This site has supplementary information and corrections found after going to press.

Fundamental constants

Bohr radius for hydrogen	$4\pi\epsilon_0\hbar^2/m_e e^2 =$	a_0	5.292×10^{-11} m
Velocity of light in free space		c	2.9979×10^8 m s^{-1}
Electronic charge		e	1.6022×10^{-19} C
Gravitational constant		G	6.673×10^{-11} N m^2 kg^{-2}
Planck's constant		h	6.626×10^{-34} J s
	$h/2\pi =$	$\hbar$	1.0546×10^{-34} J s
Boltzmann's constant		k_B	1.3807×10^{-23} J K^{-1}
Electron rest mass		m_e	9.109×10^{-31} kg
Pronton rest mass		M_p	1.6726×10^{-27} kg
Avogadro's number		N_A	6.022×10^{23} mol^{-1}
Molar gas constant		R	8.315 J mol^{-1} K^{-1}
Rydberg's constant	$\alpha^2 m_e c/2h =$	R_∞	1.0974×10^7 m^{-1}
		hcR_∞	13.606 eV
Standard molar volume		V_m	22.414×10^{-3} m^3 mol^{-1}
Fine structure constant	$e^2/4\pi\epsilon_0\hbar c =$	α	$(137.036)^{-1}$
Electric permittivity of free space		ϵ_0	8.854×10^{-12} F m^{-1}
Bohr magneton		μ_B	9.274×10^{-24} A m^2 *or* JT^{-1}
Nuclear magneton		μ_N	5.051×10^{-27} A m^2 *or* JT^{-1}
Magnetic flux quantum	$h/2e =$	Φ_0	2.0678×10^{-15} T m^2
Stefan's constant		σ	5.671×10^{-8} W m^{-2} K^{-4}
Magnetic permeability of free space		μ_0	$4\pi \times 10^{-7}$ H m^{-1}
Proton magnetic moment		μ_p	2.7928 μ_N
Neutron magnetic moment		μ_n	−1.9130 μ_N

Energy equivalents for photons $E = hf = k_B T = \dfrac{hc}{\lambda}$

E		f	T	λ	λ^{-1}	
(J)	(eV)	(Hz)	(K)	(m)	(m^{-1})	(cm^{-1})
1	6.242×10^{18}	1.509×10^{33}	7.243×10^{22}	1.486×10^{-25}	5.034×10^{24}	5.034×10^{22}
1.602×10^{-19}	1	2.418×10^{14}	1.160×10^4	1.240×10^{-6}	8.066×10^5	8.066×10^3
6.626×10^{-34}	4.136×10^{-15}	1	4.799×10^{-11}	2.998×10^8	3.336×10^{-9}	3.336×10^{-11}
1.381×10^{-23}	8.617×10^{-5}	2.084×10^{10}	1	1.439×10^{-2}	69.50	0.6950
1.987×10^{-25}	1.240×10^{-6}	2.998×10^8	1.439×10^{-2}	1	1.0	0.01
1.987×10^{-25}	1.240×10^{-6}	2.998×10^8	1.439×10^{-2}	1.0	1	0.01
1.987×10^{-23}	1.240×10^{-4}	2.998×10^{10}	1.439	0.01	100	1

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