Graduate Texts in Physics

Wolfgang Demtröder

Atoms, Molecules and Photons

An Introduction to Atomic-, Molecular- and Quantum Physics

原子、分子和光子 第2版

Second Edition

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With 677 Figures and 42 Tables

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Preface to the Second Edition

The first edition of this textbook had found a friendly acceptance. This second edition does not change the concept of the representation which combines the experimental techniques for the investigation of atoms and molecules and their results that have lead to the development of quantum physics. Some new developments in laser physics and quantum optics have been inserted in Chapter 12 in order to give the reader some ideas about the frontiers in these fields regarding experimental techniques and physical insight.

This second edition represents a thoroughly revised version of the first edition, which, unfortunately, contained a lot of errors and misprints. I am grateful to many readers who have informed me about such errors and who offered corrections and improvements of the representation for a better understanding. I am particularly indebted to Dr. Nico Dam, Raboud University Nijmegen, Netherland and Prof. Zamik Rosenwaks, Ben Gurion University, Israel, who have sent me an extensive correction list.

The author hopes, that this new edition will be well accepted and that critical readers will send their comments or ideas about possible improvements.

I thank Dr. Th. Schneider, Springer Verlag for his continuous interest and encouragement.

Kaiserslautern,
October 2010 *Wolfgang Demtröder*

Preface to the First Edition

The detailed understanding of matter, its phase transitions and its interaction with radiation could be only reached, after its microscopic structure determined by the kind of atoms or molecules as basic constituents of matter had been investigated. This knowledge allowed the controlled optimization of characteristic properties of matter. Atomic physics therefore represents not only an area of important fundamental research, but has furthermore many applications which have essentially formed our present technical world. The understanding of materials and their use in daily life, has major impact of our culture and our attitude towards nature and our environment.

This textbook is aimed as an introduction to the microscopic world of atoms, molecules and photons. It illustrates how our knowledge about the microscopic structure of matter and radiation came about and which crucial experiments forced an extension and refinement of existing classical theories, culminating in the development of quantum theory, which is now accepted as the basic theory of atomic and molecular physics.

The book therefore starts with a short historical review about the role of experiments for correcting erroneous ideas and proving the existence of atoms and molecules. The close interaction between experiments and theory has been one of the reasons for the rapid development of atomic physics in the 19^{th} and 20^{th} centuries. Examples are the kinetic theory of gases, which could be completely understood by the assumption of moving atoms in the gas, or the postulation of energy quanta in the radiation field, which could explain the discrepancy between measurements of the spectral energy distribution of thermal radiation fields and classical electrodynamics.

The new ideas of quantum physics and their corroboration by experiments are discussed in Chap. 3 while the fundamental equations of quantum mechanics and their applications to some simple examples are explained in Chap. 4.

A theory can be best understood by applications to a real situation. In Chap. 5 the quantum theory of the simplest real system, namely the hydrogen atom, is presented. Here it is again illustrated, that experiments enforced an extension of quantum mechanics to quantum electrodynamics in order to understand all experimental results. The description of larger atoms with many electrons is treated in Chap. 6, which also reduces the chemical properties of chemical elements to the structure of the electron shells and explains why all elements can be arranged in a periodic table.

The important subject of interaction of matter with radiation is discussed in Chap. 7. This prepares the ground for the explanation of lasers, treated in Chap. 8.

Molecules, consisting of two or more atoms, form the basis for the great variety of our world. They are discussed in Chaps. 9 and 10. In particular the question, why and how atoms can form stable molecules, and which kind of interaction occurs,

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is treated in more detail. In Chap. 11 the different experimental techniques for the investigation of atoms and molecules are presented, in order to give the reader a feeling for the inventive ideas and the necessary experimental skill for their realization. The last chapter presents a short overview on recent developments in atomic and molecular physics, which shall demonstrate that physics will be never a complete and finalized field. There is still much to explore and new ideas and scientific enthusiasm is needed, to push the border of our knowledge further ahead. Some examples in this chapter also illustrate possible important applications of new ideas such as the quantum computer or new techniques of frequency metrology used in the world wide global positioning system GPS.

Many people have helped to publish this book. First of all I would like to thank the team of LE-TeX, who have made the layout. In particular Uwe Matrisch, who has looked after the editing process and who has taken care of many handwritten remarks and corrections of the author with great patience. Dr. Schneider from Springer-Verlag has always supported this project, although it took longer as anticipated.

Many thanks go to all colleagues who have given their permission to reproduce figures or tables.

This book is an extended version of volume 3 of a German textbook consisting of 4 volumes. The authors hopes, that it will find a comparable good acceptance as the German version. He will be grateful for any reply of readers, giving corrections of possible errors or hints to improvements. Any of such replies will be answered as soon as possible. A textbook lives from the active collaboration of its readers and the author looks foreward to a lively correspondence with his readers. He hopes that this book can contribute to a better understanding of this fascinating field of atoms, molecules and photons.

Kaiserslautern,
August 2005 *Wolfgang Demtröder*

Contents

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1. Introduction

This book deals with the microscopic building blocks of matter: *atoms and molecules*. These are the smallest particles responsible for the characteristic properties of gases, liquids and solids. Although with modern techniques they can be split into still smaller particles, such as electrons, protons and neutrons, these latter "elementary particles" do not bear the characteristic features of the specific macroscopic body formed by atoms or molecules. We will discuss in detail in this textbook how the diversity of macroscopic bodies and their properties are related to their composition of atoms and molecules. We will, however, restrict the treatment to free atoms and molecules because a detailed discussion of the microscopic structure of solids would increase the size of this book beyond reason.

A very important issue of atomic physics is the interaction of atoms and molecules with electromagnetic radiation, which can be absorbed or emitted by these particles. Photons, or "energy quanta," are the constituents of electromagnetic radiation and are created or annihilated by matter. They therefore form an essential part of the microscopic world.

"Classical physics" was already a well-established closed theory at the end of the 19th century and could explain nearly all aspects of fields such as mechanics, electrodynamics and optics. Only the theory of relativity and the physics of nonlinear phenomena, leading to the discovery of chaos, were later developed.

On the other side, most of the discoveries about atoms and molecules were made during the 20th century and even the last decade brought us still many surprises in atomic and molecular physics. The reasons for this relatively late development of atomic physics are manifold. First of all, the objects in this field are very small and cannot be viewed by the naked eye. Many sophisticated experimental techniques had to be invented first in order to gain reliable information on these microparticles. Furthermore it turned out that classical theories were not adequate to describe atoms and molecules and their interactions. After a new theory called "quantum theory" was developed in the first three decades of the 20th century, a rapid progress in atomic and molecular physics took place, and our knowledge on this field increased explosively. Nevertheless there are still a large number of open questions and poorly understood phenomena that await their solutions by future generations of researchers.

1.1 Contents and Importance of Atomic Physics

Atomic physics deals with the structure of atoms, their mutual interaction and their dynamics, i.e., their time-dependent properties. The goal of experimental and theoretical efforts in this field is the full understanding of macroscopic properties of matter on the basis of its microscopic composition of the constituent atoms and a quantitative description of the relations between microscopic and macroscopic features. We will later see that this goal has, besides its essential contribution to fundamental physics and a new concept of nature, an enormous influence on technical applications.

At the beginning of the 20th century, when atomic physics started to develop as an original field, it was regarded as pure fundamental science, with no practical application. *Lord Ernest Rutherford* (1871–1937), one of the pioneers of early atomic physics, wrote as early as 1927, after the discovery of possible transformations of atoms through impact by energetic particles, "Anyone who expects a source of power from transformation of atoms is talking moonshine." This point of view has radically changed. Besides the quite intensive

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fundamental research in atomic physics, the number of scientific and technical applications has increased enormously.

The methods developed in atomic physics are meanwhile used routinely in chemistry, biology, medicine and industry. In particular the instruments invented during research work in atomic physics, such as the X-ray tube, the electron microscope, the oscilloscope, spectrometers, tomographers, lasers etc., are now indispensable tools in other scientific fields or for the solution of technical problems.

The importance of atomic physics is therefore not restricted to physics. Atomic physics, together with molecular physics, forms the foundations of chemistry. It explains the chemical properties of atoms and the order of elements in the periodic table, the binding of molecules and the molecular structure. Chemical reactions are reduced to collisions between atoms and molecules. Because of its importance, a new branch of chemistry called "quantum chemistry" has been established, which deals with the theoretical foundation of chemistry based on quantum theory. The famous natural philosopher *Georg Christoph Lichtenberg* (1742–1799) wrote, "Someone who only knows chemistry does not really understand it either."

The complex reactions in the earth's atmosphere are started by the interaction of sunlight with atoms and molecules leading to energy deposition in molecules, their ionization and dissociation into fragments. Collisions between these particles can further increase the number of possible chemical reactions. The reaction probability depends not only on the temperature but also on the internal energy and structure of the collision partners. A more detailed understanding of these processes and the influence of man-made pollutant substances on such processes is of crucial importance for the survival of mankind [1.1–5].

During recent years the molecular basis of biological processes has been widely investigated. New experimental techniques of atomic physics have been applied to the studies of living cells and the reactions proceeding inside a cell. It is now possible to follow the paths of single molecules intruding a cell using spectroscopic methods of high spatial and spectral resolution [1.6–8].

Also in medicine, many diagnostic tools are borrowed from atomic physics and even therapeutic methods, such as specific laser treatment of cancer or irradiation with particle beams, are based on investigations in atomic physics.

The development of star models in astrophysics has gained important stimulation from laboratory experiments on absorption and emission of radiation by atoms or ions, on recombination processes between free electrons and ions or on lifetimes of excited atoms and on collision processes between electrons, ions and neutral atoms and molecules. Besides high-energy physics, atomic physics has considerably contributed to a better understanding of the formation of stars, on radiation transport and on the structure of star atmospheres [1.9–10].

Atomic physics has also played an essential role for the optimization of modern technical developments. One famous example is the rapidly increasing manifold of lasers and their various applications [1.11]. Modern illumination techniques with energy saving lamps, discharge tubes or light emitting diodes are essentially applied atomic physics [1.12–13]. New procedures for the nondestructive inspection of materials or for the enhancement of catalytic reactions on surfaces are based on results of research in atomic physics. For many technical developments in the production of semiconductor chips, such as the controlled diffusion of impurity atoms into the semiconductor or the interaction of gases and vapors with solid surfaces, which are processes studied in atomic physics, play an essential role [1.14, 15]. Without exaggeration, one may therefore say that atomic physics has an important share in the development of modern technology and this will certainly increase even more in the future.

For metrology the measuring techniques developed in atomic physics have increased the achievable accuracy by several orders of magnitude [1.16]. With laser spectroscopic methods, for example, the absolute values of fundamental physical constants, such as the Rydberg constant, the fine structure constant or the ratio m_e/m_p of electron mass to proton mass, could be measured with such high precision that the question of whether these "constants" are really constant or change slightly with time over millions of years can now be attacked experimentally with measurement times of a few years.

The central importance of atomic physics for many other fields is schematically illustrated by the block diagram in Fig. 1.1.

Besides its influence on the technological development, atomic physics and quantum theory have

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