H. Haken
H. C. Wolf

THE PHYSICS OF ATOMS AND QUANTA

INTRODUCTION TO EXPERIMENTS AND THEORY

Seventh Edition

原子和量子物理学 第7版

Springer

世界图书出版公司
www.wpcbj.com.cn

Hermann Haken Hans Christoph Wolf

The Physics of Atoms and Quanta

Introduction to Experiments and Theory

Translated by William D. Brewer

Seventh Revised and Enlarged Edition

With 300 Figures,
30 Tables, 177 Problems and Solutions

Springer

图书在版编目（CIP）数据

原子和量子物理学 = The physics of atoms and quanta：第 7 版：英文/（德）哈肯（Haken, H.）著．—影印本．—北京：世界图书出版公司北京公司，2014.8
ISBN 978-7-5100-8452-2

Ⅰ.①原… Ⅱ.①哈… Ⅲ.①原子物理学—英文 ②量子论—英文
Ⅳ.①O562 ②O413

中国版本图书馆 CIP 数据核字（2014）第 185688 号

书　　名：The Physics of Atoms and Quanta：Introduction to Experiments and Theory 7th ed.
作　　者：Hermann Haken，Hans Christoph Wolf
中 译 名：原子和量子物理学 第 7 版
责任编辑：高蓉　刘慧

出 版 者：世界图书出版公司北京公司
印 刷 者：三河市国英印务有限公司
发　　行：世界图书出版公司北京公司（北京朝内大街 137 号 100010）
联系电话：010-64021602，010-64015659
电子信箱：kjb@wpcbj.com.cn

开　　本：16 开
印　　张：34
版　　次：2015 年 1 月
版权登记：图字：01-2014-1028

书　　号：978-7-5100-8452-2　　　　定　　价：139.00 元

Fundamental Constants of Atomic Physics in the International System of Units (SI)

Permeability Constant of Vacuum	μ_0	$= 4\pi \cdot 10^{-7} \mathrm{Vs A^{-1} m^{-1}}$ $= 1.256637 \ldots \cdot 10^{-6} \mathrm{Vs A^{-1} m^{-1}}$
Permittivity Constant of Vacuum	ε_0	$= (\mu_0 c^2)^{-1}$ $= 8.8541878 \ldots \cdot 10^{-12} \mathrm{As V^{-1} m^{-1}}$
Velocity of Light in Vacuum	c	$= 2.99792458 \cdot 10^8 \mathrm{ms^{-1}}$
Boltzmann's Constant	k	$= 1.380658 \cdot 10^{-23} \mathrm{JK^{-1}}$
Faraday Constant	F	$= 9.6485309 \cdot 10^4 \mathrm{C mol^{-1}}$
Elementary Charge	e	$= 1.6021773 \cdot 10^{-19} \mathrm{C}$
Rest Mass of the Electron	m_0	$= 9.1093897 \cdot 10^{-31} \mathrm{kg}$
Specific Charge of the Electron	e/m_0	$= 1.75881962 \cdot 10^{11} \mathrm{C kg^{-1}}$
Rest Mass of the Proton	m_p	$= 1.6726231 \cdot 10^{-27} \mathrm{kg}$
Planck's Constant	h	$= 6.626755 \cdot 10^{-34} \mathrm{Js}$
	$\hbar$	$= h/2\pi = 1.0545887 \cdot 10^{-34} \mathrm{Js}$
Rydberg Constant	R_∞	$= 1.0973731534 \cdot 10^7 \mathrm{m^{-1}}$
Bohr Radius	a_0	$= 0.529177249 \cdot 10^{-10} \mathrm{m}$
Bohr Magneton	μ_B	$= 9.2740154 \cdot 10^{-24} \mathrm{Am^2} (= \mathrm{J/T})$
Nuclear Magneton	μ_N	$= 5.0507866 \cdot 10^{-27} \mathrm{Am^2}$
Compton Wavelength of the Electron	λ_c	$= 2.42631058 \cdot 10^{-12} \mathrm{m}$
Fine Structure Constant	α	$= 7.29735308 \cdot 10^{-3}$
Avogadro's number	N_A	$= 6.022045 \cdot 10^{23} \mathrm{mol^{-1}}$

Energy Conversion Table see inside back cover

The Physics of Atoms and Quanta

Advanced Texts in Physics

This program of advanced texts covers a broad spectrum of topics which are of current and emerging interest in physics. Each book provides a comprehensive and yet accessible introduction to a field at the forefront of modern research. As such, these texts are intended for senior undergraduate and graduate students at the MS and PhD level; however, research scientists seeking an introduction to particular areas of physics will also benefit from the titles in this collection.

Professor Dr. Dr. h.c. Hermann Haken
Institut für Theoretische Physik
Universität Stuttgart
Pfaffenwaldring 57
70550 Stuttgart, Germany

Professor Dr. Hans Christoph Wolf
Physikalisches Institut
Universität Stuttgart
Pfaffenwaldring 57
70550 Stuttgart, Germany

Translator:
Professor Dr. William D. Brewer
Freie Universität Berlin
Fachbereich Physik
Arnimallee 14
14195 Berlin, Germany

Title of the German original edition:
H. Haken, H. C. Wolf: *Atom- und Quantenphysik*
Einführung in die experimentellen und theoretischen Grundlagen
(Achte, aktualisierte und erweiterte Auflage)

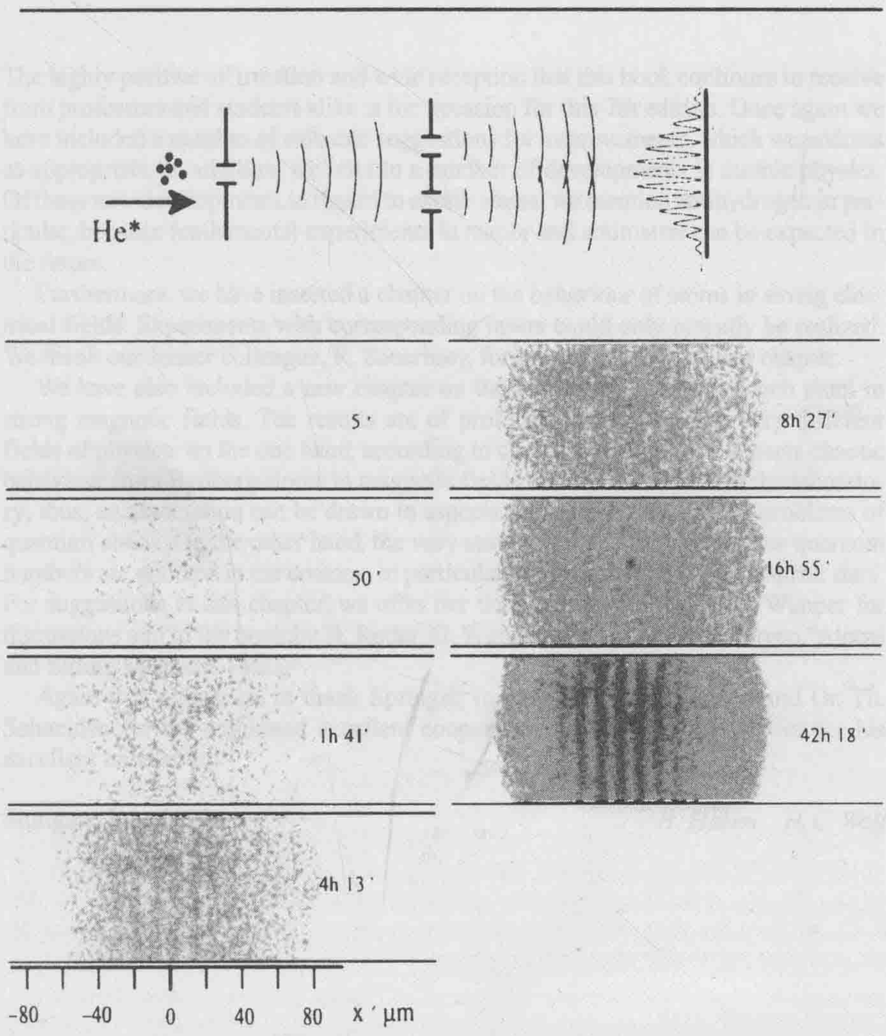
Library of Congress Control Number: 2005924537

ISSN 1439-2674
ISBN-10: 3-540-20807-0 7th Edition Springer Berlin Heidelberg New York
ISBN-13: 978-3-540-20807-5 7th Edition Springer Berlin Heidelberg New York

ISBN 3-540-67274-5 6th Edition Springer-Verlag Berlin Heidelberg New York

Reprint from English language edition:
The Physics of Atoms and Quanta: Introduction to Experiments and Theory 7th ed.
by Hermann Haken, Hans Christoph Wolf; translator W. D. Brewer

A Fundamental Experiment in Quantum Physics: *The Wave-Particle Dualism of Matter*



When helium atoms all having the same direction and velocity are passed through a double-slit apparatus, each atom produces a strictly localised *point* of impact on a screen behind the slits; the atoms appear to be essentially particles. If the experiment is allowed to run for a longer time, so that a large number of impact points is registered on the screen, then an interference pattern appears, analogous to that seen in Young's double-slit experiment with light; the helium atoms thus behave in this case as waves. The seven images show the measured intensity distribution on the screen as a function of time (5′ to 42h18′) after starting the experiment. This experiment demonstrates the wave-particle dualism of matter in an impressive fashion. How quantum theory bridges the apparent contradiction: pointlike particle on the one hand, extended wave on the other, is a subject treated in this book. These experiments on helium atoms were carried out by O. Carnal, J. Mlynek: Phys. Rev. Lett. *66*, 2689 (1991) and Ch. Kurtsiefer, T. Pfau, J. Mlynek: Nature *386*, 150 (1997). More details are given in Sect. 6.6.

Preface to the Seventh Edition

The highly positive affirmation and wide reception that this book continues to receive from professors and students alike is the occasion for this 7th edition. Once again we have included a number of valuable suggestions for improvements, which we address as appropriate. In addition, we refer to a number of developments in atomic physics. Of these new developments in regard to exotic atoms, we mention antihydrogen in particular, because fundamental experiments in matter and antimatter can be expected in the future.

Furthermore, we have inserted a chapter on the behaviour of atoms in strong electrical fields. Experiments with corresponding lasers could only recently be realized. We thank our Jenaer colleague, R. Sauerbrey, for his contribution of this chapter.

We have also included a new chapter on the behaviour of the hydrogen atom in strong magnetic fields. The results are of profound interest for two very different fields of physics: on the one hand, according to classical physics, one expects chaotic behaviour from Rydberg atoms in magnetic fields that can be created in the laboratory; thus, an association can be drawn to aspects of chaos theory and the problems of quantum chaos. On the other hand, the very strong fields necessary for low quantum numbers are realized in the cosmos, in particular with white dwarfs and neutron stars. For suggestions to this chapter, we offer our thanks to our colleague G. Wunner for discussions and to the book by H. Ruder, G. Wunner, H. Herold and F. Geyer, "Atoms and Strong Magnetic Fields".

Again it is a pleasure to thank Springer, in particular C.D. Bachem and Dr. Th. Schneider, for the continued excellent cooperation, and Prof. W.D. Brewer for his excellent translation.

Stuttgart, June 2005 *H. Haken H. C. Wolf*

Preface to the Sixth Edition

Since a new edition of our book has once again become necessary, we have as before taken the opportunity to include the latest developments in atomic and quantum physics. These areas continue to yield new and fascinating experimental and theoretical results which are of fundamental importance and are also extremely interesting to students of science. As a result of newly developed experimental methods and theoretical techniques, it has also become possible to find solutions to some long-established problems. In this spirit we have added an entire new chapter dealing with entangled wavefunctions, the Einstein-Podolsky-Rosen paradox, Bell's inequalities, the paradox of Schrödinger's cat and the concept of decoherence. In addition, we have treated new ideas relating to quantum computers and the numerous quantum-physical schemes for constructing them. These new concepts exemplify the rapidly-developing area of quantum information.

Finally, in this new chapter we have included the experimental realisation of the Bose-Einstein condensation and of the atom laser, which promise important new applications.

In Chap. 22, "Modern methods of optical spectroscopy", we have added a new section on nondestructive photon detection as an example of efficient methods for investigating the interactions between atoms and photons in resonant cavities. Considering the current importance of these areas, we emphasize references to the original literature. These can be found in the Bibliography.

In treating all of these subjects, we have as usual made an effort to give a readily understandable description, in line with the tradition of this book.

Once again, we express our gratitude to those students, colleagues and other readers of the book who have made a number of suggestions for its improvement. Our special thanks go to our colleagues Th. Hänsch, J. Mlynek and T. Pfau for providing us with coloured figures of their newest experimental results. We thank Ms. Irmgard Möller for her quick and careful preparation of the new parts of the manuscript. We are grateful to Springer-Verlag, in particular Dr. H.J. Kölsch and Mr. C.-D. Bachem for their efficient cooperation as always, and Prof. W.D. Brewer for his excellent translation of the new chapters.

Stuttgart, March 2000 *H. Haken H.C. Wolf*

Preface to the First Edition

A thorough knowledge of the physics of atoms and quanta is clearly a must for every student of physics but also for students of neighbouring disciplines such as chemistry and electrical engineering. What these students especially need is a coherent presentation of both the experimental and the theoretical aspects of atomic and quantum physics. Indeed, this field could evolve only through the intimate interaction between ingenious experiments and an equally ingenious development of bold new ideas.

It is well known that the study of the microworld of atoms caused a revolution of physical thought, and that fundamental ideas of classical physics, such as those on measurability, had to be abandoned. But atomic and quantum physics is not only a fascinating field with respect to the development of far-reaching new physical ideas. It is also of enormous importance as a basis for other fields. For instance, it provides chemistry with a conceptual basis through the quantum theory of chemical bonding. Modern solid-state physics, with its numerous applications in communication and computer technology, rests on the fundamental concepts first developed in atomic and quantum physics. Among the many other important technical applications we mention just the laser, a now widely used light source which produces light whose physical nature is quite different from that of conventional lamps.

In this book we have tried to convey to the reader some of the fascination which atomic and quantum physics still gives a physicist studying this field. We have tried to elaborate on the fundamental facts and basic theoretical methods, leaving aside all superfluous material. The text emerged from lectures which the authors, an experimentalist and a theoretician, have given at the University of Stuttgart for many years. These lectures were matched with respect to their experimental and theoretical contents.

We have occasionally included in the text some more difficult theoretical sections, in order to give a student who wants to penetrate further into this field a self-contained presentation. The chapters which are more difficult to read are marked by an asterisk. They can be skipped on a first reading of this book. We have included chapters important for chemistry, such as the chapter on the quantum theory of the chemical bond, which may also serve as a starting point for studying solid-state physics. We have further included chapters on spin resonance. Though we explicitly deal with electron spins, similar ideas apply to nuclear spins. The methods of spin resonance play a fundamental role in modern physical, chemical and biological investigations as well as in medical diagnostics (nuclear spin tomography). Recent developments in atomic physics, such as studies on Rydberg atoms, are taken into account, and we elaborate the basic features of laser light and nonlinear spectroscopy. We hope that readers will find atomic and quantum physics just as fascinating as did the students of our lectures.

The present text is a translation of the second German edition *Atom- and Quantenphysik*. We wish to thank Prof. W.D. Brewer for the excellent translation and the most valuable suggestions he made for the improvement of the book. Our thanks also go to Dr. J. v. Schütz and Mr. K. Zeile for the critical reading of the manuscript, to Ms. S. Schmiech and Dr. H. Ohno for the drawings, and to Mr. G. Haubs for the careful proofreading. We would like to thank Mrs. U. Funke for her precious help in typing new chapters. Last, but not least, we wish to thank Springer-Verlag, and in particular H. Lotsch and G.M. Hayes, for their excellent cooperation.

Stuttgart, February 1984 *H. Haken H.C. Wolf*

List of the Most Important Symbols Used

The numbers of the equations in which the symbols are defined are given in parentheses; the numbers in square brackets refer to the section of the book. The Greek symbols are at the end of the list.

$\boldsymbol{A}$	Vector potential
A	Amplitude or constant
A	Mass number (2.2) or area
a	Interval factor or fine structure constant (12.28) and hyperfine splitting (20.10)
a_0	Bohr radius of the H atom in its ground state (8.8)
$\boldsymbol{B}$	Magnetic induction
b^+, b	Creation and annihilation operators for the harmonic oscillator
b	Constant, impact parameter
C	Constant
c	Velocity of light, series expansion coefficient
c.c.	Complex conjugate
$\boldsymbol{D}$	Dipole moment
d	Constant
dV	Infinitesimal volume element
$\boldsymbol{E}$	Electric field strength
E	Energy, total energy, energy eigenvalue
E_{kin}	Kinetic energy
E_{pot}	Potential energy
E_{tot}	Total energy
e	Proton charge
$-e$	Electron charge
e	Exponential function
$\boldsymbol{F}$	Electric field strength (14.1)
$\boldsymbol{F}, F$	Total angular momentum of an atom, including nuclear angular momentum and corresponding quantum number (20.6)
F	Amplitude of the magnetic induction [14.4, 14.5]
f	Spring constant
g	Landé g factor (12.10, 16, 21, 13.18, 20.13)
$\mathscr{H}$	Hamilton function, Hamiltonian operator
H_n	Hermite polynomial
h	Planck's constant
$\hbar$	$= h/2\pi$
$\boldsymbol{I}, I$	Nuclear angular momentum and corresponding quantum number (20.1)
I	Abbreviation for integrals [16.13] or intensity
i	Imaginary unit ($i = \sqrt{-1}$)
$\boldsymbol{J}, J$	Total angular momentum of an electron shell and corresponding quantum number (17.5)
$\boldsymbol{j}, j$	Total angular momentum of an electron and corresponding quantum number [12.7]
$\hat{j}$	Operator for the total angular momentum
k	Boltzmann's constant, force constant
$\boldsymbol{k}$	Wavevector
$\boldsymbol{L}, L$	Resultant orbital angular momentum and corresponding quantum number (17.3)
L_n	Laguerre polynomial (10.81)
$\boldsymbol{l}, l$	Orbital angular momentum of an electron and corresponding quantum number
$\hat{l}$	Angular momentum operator
m, m_0	Mass
m	Magnetic quantum number
m_l	– for angular momentum
m_s	– for spin
m_j	Magnetic quantum number for total angular momentum
m_0	Rest mass, especially that of the electron

N, n	Particle number, particle number density
N	Normalisation factor
n	Principal quantum number or number of photons or an integer
P	Spectral radiation flux density (5.2) or probability
P_l^0	Legendre polynomial
P_l^m	($m \neq 0$) Associated Legendre function
$p, \bar{p}$	Momentum, expectation value of momentum
Q	Nuclear quadrupole moment (20.20)
Q, q	Charge
$R(r)$	Radial part of the hydrogen wavefunction
$\boldsymbol{r}$	Position coordinate (three-dimensional vector)
r	Distance
$\boldsymbol{S}$	Resultant spin (17.4)
S	Symbol for orbital angular momentum $L = 0$
$\boldsymbol{s}, s$	Electron spin and corresponding quantum number (12.15)
$\hat{\boldsymbol{s}}$	Spin operator $= (\hat{s}_x, \hat{s}_y, \hat{s}_z)$
T	Absolute temperature
T_1	Longitudinal relaxation time
T_2	Transverse relaxation time
t	Time
u	Spectral energy density (5.2), atomic mass unit [2.2]
V	Volume, potential, electric voltage
$\bar{V}$	Expectation value of the potential energy
$\boldsymbol{v}$	Velocity, particle velocity
x	Particle coordinate (one-dimensional)
$\bar{x}$	Expectation value of position
$Y_{l,m}(\theta, \phi)$	Spherical harmonic functions (10.10, 48 – 50)
Z	Nuclear charge
α	Fine structure constant [8.10] or absorption coefficient (2.22)
β	Constant
Γ	Decay constant
γ	Decay constant or linewidth gyromagnetic ratio (12.12)
∇^2	Laplace operator $= \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$
ΔE	Energy uncertainty
Δk	Wavenumber uncertainty
Δp	Momentum uncertainty
Δt	Time uncertainty (= finite measurement time)
ΔV	Finite volume element
$\Delta\omega$	Uncertainty in the angular frequency
Δx	Position uncertainty
$\delta(x)$	Dirac delta function (see mathematics appendix)
$\delta_{\mu,\nu}$	Kronecker delta symbol: $\delta_{\mu,\nu} = 1$ for $\mu = \nu$, $\delta_{\mu,\nu} = 0$ for $\mu \neq \nu$
ε	Dimensionless energy (9.83)
$\varepsilon^{(n)}$	Energy contributions to perturbation theory
ε_0	Permittivity constant of vacuum
θ	Angle coordinate (10.2)
κ	Defined in (10.54)
λ	Wavelength (exception: expansion parameter in [15.2.1, 2]) Mean free path [2.4.3]
$\boldsymbol{\mu}, \mu$	Magnetic moment (12.1)
μ	Reduced mass (8.15)
μ_B	Bohr magneton (12.8)
μ_N	Nuclear magneton (20.3)
ν	Frequency [8.1]
$\bar{\nu}$	Wavenumber [8.1]
ξ	Dimensionless coordinate (9.83)
ϱ	Charge density, density of states, mass density; or dimensionless distance
σ	Scattering coefficient, interaction cross section (2.16)
$\boldsymbol{\tau}$	Torque (12.2)
Φ	Phase
ϕ	Phase angle, angle coordinate
$\phi(x)$	Wavefunction of a particle
$\phi_\uparrow, \phi_\downarrow, \phi$	Spin wavefunctions
ψ	Wavefunction
Ψ	Wavefunction of several electrons
$\hat{\Omega}$	Generalised quantum mechanical operator
Ω	Frequency [14.4, 14.5, 15.3]
ω	Angular frequency $2\pi\nu$, or eigenvalue [9.3.6]
$\triangleq$	means "corresponds to"

Contents