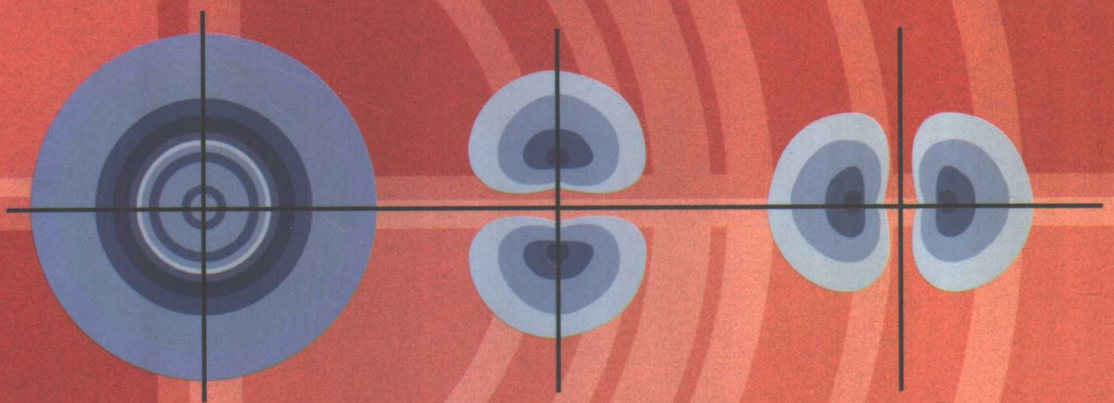
H.Haken
H.C.Wolf

The Physics of Atoms and Quanta

Introduction to Experiments and Theory

Sixth Edition

原子和量子物理学　第6版



Springer-Verlag
世界图书出版公司

Hermann Haken Hans Christoph Wolf

The Physics of Atoms and Quanta

Introduction to Experiments and Theory

Translated by William D. Brewer

Sixth Revised and Enlarged Edition
With 287 Figures,
29 Tables, 173 Problems and Solutions

Springer

书　　名：The Physics of Atoms and Quanta: Introduction to Experiments and Theory 6th ed.
作　　者：H. Haken, H. C. Wolf
中 译 名：原子和量子物理学
出 版 者：世界图书出版公司北京公司
印 刷 者：北京世图印刷厂
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：010-64015659, 64038347
电子信箱：kjsk@vip.sina.com
开　　本：16　　印　张：33
出版年代：2003 年 6 月
书　　号：7-5062-5954-0 / O • 373
版权登记：图字:01-2003-3606
定　　价：98.00 元

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
(Siebte, aktualisierte und erweiterte Auflage)

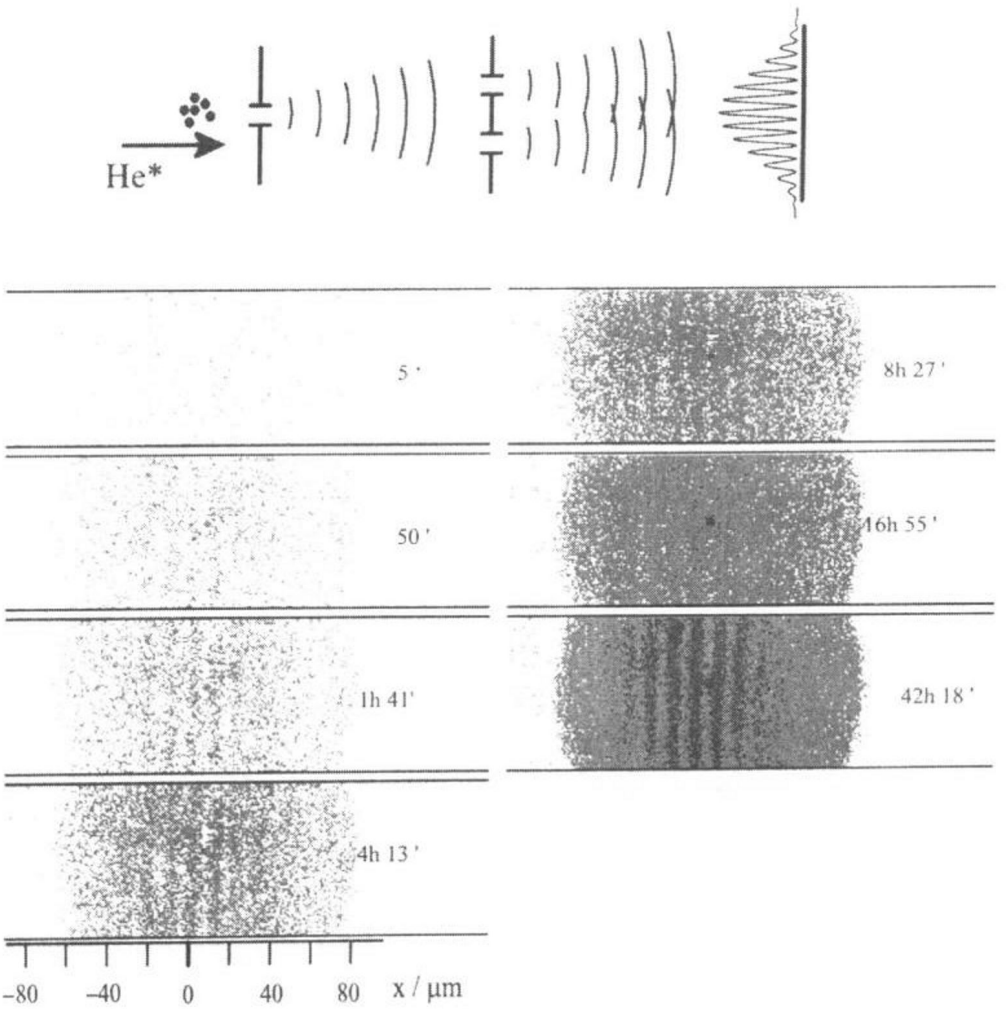
Library of Congress Cataloging-in-Publication Data. Haken, H. [Atom- und Quantenphysik. English] The physics of atoms and quanta : introduction to experiments and theory / Hermann Haken, Hans Christoph Wolf ; translated by William D. Brewer.–6th rev. and enl. ed. p.cm. Includes bibliographical references and index. ISBN 3540672745 (alk. paper) 1. Atoms. 2. Quantum theory. I. Wolf, H.C. (Hans Christoph), 1929– II. Title. QC 173.H175132000 539–dc21 00-038826

ISSN 1439-2674

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

ISBN 3-540-61555-5 5th Edition Springer-Verlag Berlin Heidelberg New York

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 42 h 18′) 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 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 Fourth Edition

This fourth edition contains a few additional figures. Otherwise only typographical errors have been removed.

The final chapter on Fundamentals of the Quantum Theory of Chemical Bonding is continued in an extended way in the textbook *Molecular Physics and Elements of Quantum Chemistry* by the same authors. This book contains, in particular, a profound presentation of group theory as applied to atoms and molecules. Furthermore, the interaction between atoms and molecules and light is treated in detail.

We thank again Springer-Verlag, in particular Dr. H. J. Kölsch and Mr. C.-D. Bachem for their excellent cooperation as always, and Prof. W. D. Brewer for his continuous support in translating our German text.

Stuttgart, February 1994 *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.

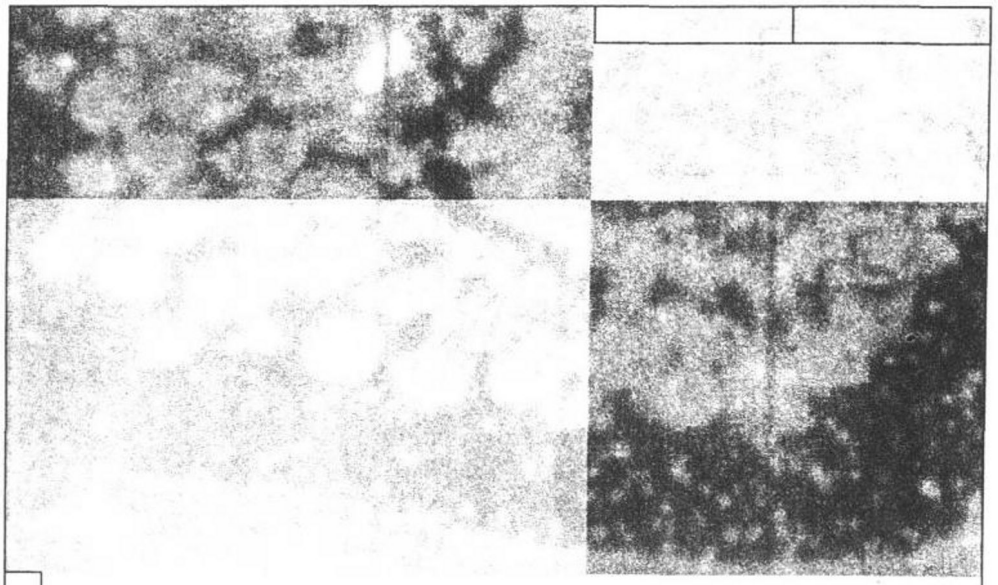
Stuttgart, February 1984 *H. Haken H.C. Wolf*

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.

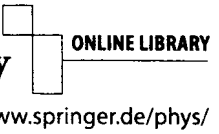
$\boldsymbol{A}$	Vector potential
A	Amplitude or constant
A	Mass number (2.2) or area
a	Interval factor or fine structure constant (12.28) and hyperfine splitting (20.10)
a_0	Bohr radius of the H atom in its ground state (8.8)
$\boldsymbol{B}$	Magnetic induction
b^+, b	Creation and annihilation operators 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 ($\mathrm{i} = \sqrt{-1}$)
$\boldsymbol{J}, J$	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
r Position coordinate (three-dimensional vector)
r Distance
S Resultant spin (17.4)
S Symbol for orbital angular momentum $L = 0$
s, s Electron spin and corresponding quantum number (12.15)
$\hat{s}$ 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
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]
μ, μ 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)
τ 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"



The Physics of Atoms and Quanta

Springer
Berlin
Heidelberg
New York
Barcelona
Hong Kong
London
Milan
Paris
Singapore
Tokyo



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.

Wilhelm Röck GmbH, Graphische Betriebe
74189 Weinsberg

Contents

List of the Most Important Symbols Used XIX

1. Introduction 1
1.1 Classical Physics and Quantum Mechanics 1
1.2 Short Historical Review 1

2. The Mass and Size of the Atom 5
2.1 What is an Atom? 5
2.2 Determination of the Mass 5
2.3 Methods for Determining Avogadro's Number 7
2.3.1 Electrolysis 7
2.3.2 The Gas Constant and Boltzmann's Constant 7
2.3.3 X-Ray Diffraction in Crystals 8
2.3.4 Determination Using Radioactive Decay 9
2.4 Determination of the Size of the Atom 10
2.4.1 Application of the Kinetic Theory of Gases 10
2.4.2 The Interaction Cross Section 11
2.4.3 Experimental Determination of Interaction Cross Sections 14
2.4.4 Determining the Atomic Size from the Covolume 15
2.4.5 Atomic Sizes from X-Ray Diffraction Measurements on Crystals 15
2.4.6 Can Individual Atoms Be Seen? 20
Problems 25

3. Isotopes 27
3.1 The Periodic System of the Elements 27
3.2 Mass Spectroscopy 29
3.2.1 Parabola Method 29
3.2.2 Improved Mass Spectrometers 32
3.2.3 Results of Mass Spectrometry 33
3.2.4 Modern Applications of the Mass Spectrometer 34
3.2.5 Isotope Separation 35
Problems 36

4. The Nucleus of the Atom 37
4.1 Passage of Electrons Through Matter 37
4.2 Passage of Alpha Particles Through Matter (Rutherford Scattering) .. 39
4.2.1 Some Properties of Alpha Particles 39
4.2.2 Scattering of Alpha Particles by a Foil 39
4.2.3 Derivation of the Rutherford Scattering Formula 41
4.2.4 Experimental Results 46
4.2.5 What is Meant by Nuclear Radius? 47
Problems 48