

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

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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

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

Permeability Constant of Vacuum	$\mu_0 = 4\pi \cdot 10^{-7} \text{VsA}^{-1}\text{m}^{-1}$ $= 1.256637 \dots \cdot 10^{-6} \text{VsA}^{-1}\text{m}^{-1}$
Permittivity Constant of Vacuum	$\epsilon_0 = (\mu_0 c^2)^{-1}$ $= 8.8541878 \dots \cdot 10^{-12} \text{AsV}^{-1}\text{m}^{-1}$
Velocity of Light in Vacuum	$c = 2.99792458 \cdot 10^8 \text{ms}^{-1}$
Boltzmann's Constant	$k = 1.380658 \cdot 10^{-23} \text{JK}^{-1}$
Faraday Constant	$F = 9.6485309 \cdot 10^4 \text{Cmol}^{-1}$
Elementary Charge	$e = 1.6021773 \cdot 10^{-19} \text{C}$
Rest Mass of the Electron	$m_0 = 9.1093897 \cdot 10^{-31} \text{kg}$
Specific Charge of the Electron	$e/m_0 = 1.75881962 \cdot 10^{11} \text{Ckg}^{-1}$
Rest Mass of the Proton	$m_p = 1.6726231 \cdot 10^{-27} \text{kg}$
Planck's Constant	$h = 6.626755 \cdot 10^{-34} \text{Js}$ $\hbar = h/2\pi = 1.0545887 \cdot 10^{-34} \text{Js}$
Rydberg Constant	$R_\infty = 1.0973731534 \cdot 10^7 \text{m}^{-1}$
Bohr Radius	$a_0 = 0.529177249 \cdot 10^{-10} \text{m}$
Bohr Magneton	$\mu_B = 9.2740154 \cdot 10^{-24} \text{Am}^2 (= \text{J/T})$
Nuclear Magneton	$\mu_N = 5.0507866 \cdot 10^{-27} \text{Am}^2$
Compton Wavelength of the Electron	$\lambda_c = 2.42631058 \cdot 10^{-12} \text{m}$
Fine Structure Constant	$\alpha = 7.29735308 \cdot 10^{-3}$
Avogadro's number	$N_A = 6.022045 \cdot 10^{23} \text{mol}^{-1}$

Energy Conversion Table see inside back cover

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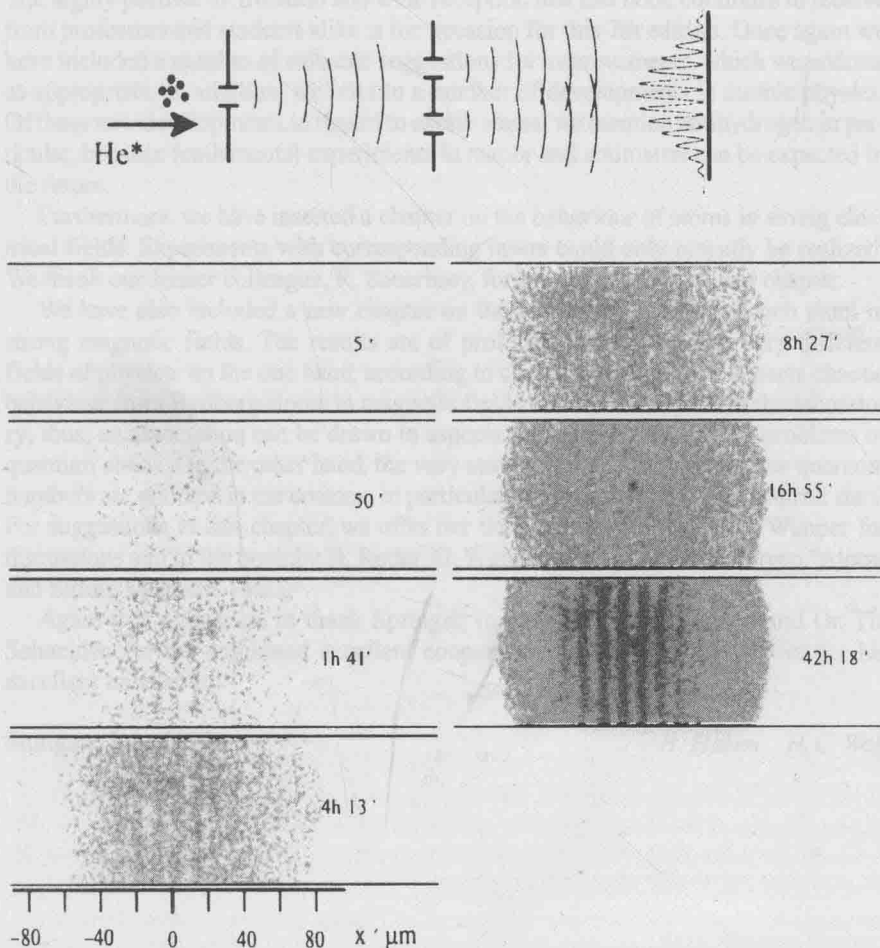
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A Fundamental Experiment in Quantum Physics: *The Wave-Particle Dualism of Matter*



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 42h 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 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- und 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.

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

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

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