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The physics of laser–atom interactions

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The physics of laser–atom interactions

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CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521462396

First published 1997
This digitally printed first paperback version 2005

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data
Suter, Dieter.
The physics of laser–atom interactions / Dieter Suter.
p. cm. – (Cambridge studies in modern optics)
Includes bibliographical references and index.
ISBN 0–521–46239–8
1. Laser manipulation (Nuclear physics) 2. Optical pumping.
3. Laser spectroscopy. I. Title. II. Series: Cambridge studies in
modern optics (Unnumbered)
OC689.5.L35S88 1997
539.7–DC21 96–52448
CIP

ISBN-13 978-0-521-46239-6 hardback
ISBN-10 0-521-46239-8 hardback

ISBN-13 978-0-521-01791-6 paperback
ISBN-10 0-521-01791-2 paperback

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Preface

Light interacting with material substances is one of the prerequisites for life on our planet. More recently, it has become important for many technological applications, from CD players and optical communication to gravitational-wave astronomy. Physicists have therefore always tried to improve their understanding of the observed effects. The ultimate goal of such a development is always a microscopic description of the relevant processes. For a long time, this description was identical with a perturbation analysis of the material system in the external fields. More than a hundred years ago, such a microscopic theory was developed in terms of oscillating dipoles. After the development of quantum mechanics, these dipoles were replaced by quantum mechanical two-level systems, and this is still the most frequently used description.

However, the physical situation has changed qualitatively in the last decades. The development of intense, narrowband or pulsed lasers as tunable light sources has provided not only a new tool that allows much more detailed investigation, but also the observation of qualitatively new phenomena. These effects can no longer be analysed in the form of a perturbation expansion. One consequence is that the actual number of quantum mechanical states involved in the interaction becomes relevant. It is therefore not surprising that many newly discovered effects are associated with the details of the level structure of the medium used in the experiment. Two popular examples are the discovery of sub-Doppler laser cooling and the development of magnetooptical traps, which rely on the presence of angular momentum substates.

Chapters 1 and 2 may be considered as a qualitative overview of the subjects relevant in this context and an introduction to the phenomena that can be analysed within the two-level model. Chapter 3 presents a mathematical analysis of effects that are incompatible with the two-level model, whereas Chapter 4 discusses the physical quantities associated with the more complicated level structures. Chapter 5 summarises optical pumping, the oldest technique that allows atomic systems to be driven far from thermal equilibrium. As shown in Chapter 6, such optically pumped vapours are optically anisotropic. Chapter 7 discusses coherent Raman processes, using atomic ions in a crystal matrix as the optical medium. Chapter 8 contains a summary of transient effects in the ground state sublevel system of atomic vapours driven by polarised light and magnetic fields, using laser light to probe the microscopic structure of the vapour. This can be done in much greater detail by using two-dimensional spectroscopy, a technique discussed in Chapter 9. As Chapter 10 shows, the system can be driven far from equilibrium by the interaction with laser light. As a result, the system can show spontaneous symmetry breaking and spontaneous structure formation. The final section summarises the recent development in the field of laser cooling and trapping, where the consideration of multilevel effects has significantly enhanced the possible experimental tools.

I am grateful to many colleagues who have helped me during the course of this work. In particular I should like to mention my former students Tilo Blasberg and Harald Klepel as well as my former supervisor Jürgen Mlynek. Among the people who helped to improve this manuscipt, I should like to mention specifically Rudi Grimm and Scott Holmstrom.

Symbols and abbreviations

Symbol	Explanation
a, $a^\dagger$	annihilation (or lowering), creation (or raising) operator
$\vec{B} = (B_x, B_y, B_z)$	magnetic induction
B_0	amplitude of static magnetic induction
β	Bohr magneton, $9.27 \cdot 10^{-24}$ J/T
c	velocity of light in vacuum, $2.9979 \cdot 10^8$ ms^{-1}
d	dipole moment
FID	free induction decay
γ_{eff}	damping rate
γ_F	gyromagnetic ratio of total angular momentum
γ_J	gyromagnetic ratio of total electronic angular momentum
γ_S	gyromagnetic ratio of electron spin
Γ_1	(optical) spontaneous emission rate
Γ_2	(optical) dephasing rate
Δ	optical detuning
$\bar{\Delta}$	normalised optical detuning
e	charge quantum, $1.60218 \cdot 10^{-19}$ C
ϵ_0	dielectric constant, $0.88542 \cdot 10^{-11}$ As/Vm
$\vec{E}$	electric field vector
$\mathscr{E}$	energy
EFG	electric field gradient
$\vec{F} = (F_x, F_y, F_z)$	total (nuclear + electronic) angular momentum operator
$\mathscr{F}$	Fourier transform operator
h, $\hbar$	Planck's constant, $\hbar = 1.05459 \cdot 10^{-34}$Js

$\vec{H} = (H_x, H_y, H_z)$	magnetic field
$\mathcal{H}$	Hamiltonian
$\vec{I} = (I_x, I_y, I_z)$	nuclear spin angular momentum operator
$\vec{J} = (J_x, J_y, J_z)$	total electronic angular momentum
$\vec{k}$	wave vector
k_B	Boltzmann constant, $1.38066 \cdot 10^{-23}$ JK^{-1}
$\vec{L} = (L_x, L_y, L_z)$	electron orbital angular momentum
l	sample length
λ	wavelength
$\vec{M}$	angular momentum of radiation field
$\vec{m} = (m_x, m_y, m_z)$	magnetisation
m_e	electron mass, $9.1094 \cdot 10^{-31}$ kg
μ_0	magnetic permeability, $4\pi \cdot 10^{-7}$VsA^{-1}m^{-1}
$\vec{\mu}_e$	electric dipole moment
$\vec{\mu}_m$	magnetic dipole moment
$P_R(z,\alpha)$	object rotation by α around z
$\vec{P}$	optical polarisation
$\vec{p}$	linear momentum
$R(z,\alpha)$	coordinate rotation by α around z
$R_E(\alpha, \beta, \gamma)$	Euler rotation
$\vec{r} = (x, y, z)$	position
ρ	density operator
$\dot{\rho}$	derivative of density operator
rf	radio time frequency
$\vec{S} = (S_x, S_y, S_z)$	electron spin angular momentum operator
$\sigma_x, \sigma_y, \sigma_z, \sigma_+, \sigma_-$	Pauli spin operators
$\sigma_i = li\rangle\langle il$	level shift operator
t	time
ω_0	atomic resonance frequency
ω_x	Rabi frequency
$\vec{\Omega}$	effective magnetic field
Ω_L	Larmor frequency
$\vec{\nabla}$	Nabla operator