Lasers in Applied and Fundamental Research

compiled and introduced by

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Foreword

Lasers have become central tools of physics investigations. Their use extends from purely technical applications to investigations into the basic principles of quantum mechanics. To collect a series of review articles exposing the range of applications of laser physics can hence be expected to be of interest to a wide range of readers.

In this book we have collected a series of four papers, which have been published in 'Reports on Progress in Physics'. They are:

1. S Feneuille: Interaction of laser radiation with free atoms

Rep.Prog.Phys. 40(1977) 1257-1304

2. E Abraham and S D Smith: Optical bistability and related devices

Rep.Prog.Phys. 45(1982) 815-885

3. R Loudon: Non-classical effects in the statistical properties of light

Rep.Prog.Phys. 43(1980) 913-949

4. J F Clauser and A Shimony: Bell's theorem: experimental tests and implications

Rep.Prog.Phys. 41(1978) 1881-1927

Of these paper #1 gives a general view of the use of lasers in spectroscopy. The basic theoretical tools are summarized in a manner detailed enough to serve as a pedagogical introduction. The complications appearing in real atomic systems are surveyed, and some fundamental experiments are discussed.

Paper #2 reviews the phenomenon of optical bistability, which has received a lot of interest recently. It has potential applications to optical computations, and it provided one of the roads into the very topical field of non-linear dynamics and chaotic behaviour of deterministic systems. The theory is based on that developed in paper #1, but usually realisations employ semiconductor materials.

In most problems concerned with the interaction between matter and laser light it suffices to use a classical description of the laser radiation, a semiclassical theory. In paper #3 the need for a quantum theory of light is discussed. The basic differences between the coherence properties of classical and quantum radiation are presented, and some experiments are discussed where the two types can be discerned.

Paper #4 gives a discussion of how lasers may be used to test the basic formulation of quantum mechanics itself. In spite of its tremendous success to describe experiments, many people feel that quantum mechanics is fundamentally an unsatisfactory theory. John Bell managed to derive certain relations which highlight the point where it appears offensive to our intuition. These relations are susceptible to experimental tests. Paper #4 presents the theoretical background and the experimental situation at the time of its writing. The work carried out later has only confirmed the picture obtained at that time; quantum mechanics predicts the correct experimental results and, when alternative theories differ, they are found to be wrong.

The aim of the present collection is two-fold. Firstly, it can act as a survey of the field of laser applications for physicists that work in other fields. Secondly its articles are detailed enough to present an introduction to the theory and observations of laser physics. Readers new to the field can penetrate into the details of the work and use the references to pursue interesting topics further.

The Introduction is written with both types of reader in mind. The basic theoretical questions are dealt with in the form of simple examples. These calculations are carried out in some detail and provide model examples for the more complicated cases in the reprinted papers. The discussions should enable the reader to consult the papers in any order desired, even if the subject matter appears to form a natural sequence as presented.

The Introduction also summarises the development in the field after the papers have been written. Newer reviews are referred to, and connections to other questions of topical interest are presented. In some cases there has been essential experimental progress, and then some key references are given. The authors have also been given the opportunity to add comments and references to their articles.

There is a problem of notation in this collection. The various articles use different symbols for the same quantities. I have chosen to handle this situation so that I use mainly the notation of paper #1 in my Introduction, and I provide a comparison of notations in table I.

In many applications the laser is but a glorious light source with a narrow spectral output and a high brightness. One interesting feature of laser spectroscopy is, however, that it has created many new methods and techniques for investigating the microscopic properties of atomic matter.

Many of these have developed from methods that were originally introduced in magnetic resonance spectroscopy and microwave spectroscopy. There are, however, some features of the interaction between matter and light that are new, and these lead to interesting phenomena. They are:

1. The wavelength is short. Any macroscopic sample extends over many waves. The atomic motion can take a particle through several wavelengths during the interaction period, and hence an appreciable Doppler shift appears.

2. The spontaneous emission at allowed transitions is fast because of the high frequency, and it contributes its own features to the spectra.

3. It is possible to detect a single quantum of the radiation using photon multipliers because of the high energy of the quanta. Then the information carried in the statistical properties of the photons is also accessible in contrast to the case for lower frequencies.

In this reprint collection we shall see examples of each of these features.

Table 1

Introduction: Paper	# 1	# 2	# 3
Lower-level frequency	ω_g	0 (2	0 (2
Upper-level frequency	ω_e	ω_0	ω_0
Laser frequency	ω	ω	ω
Detuning Δ	$\omega-(\omega_e-\omega_g)$	$\omega-\omega_0$	$\omega-\omega_0$
Dipole matrix element μ	$\langle e\vert\vec{\varepsilon}\cdot\vec{D}\vert g\rangle$ (1	μ	$\hbar g\sqrt{2\varepsilon_0 V/\hbar\omega}$ (3
Rabi frequency at resonance	2K	-	Ω
Rabi frequency with detuning	Ω	-	-
Decay rates	γ, Γ	γ, Γ	γ
Saturation parameter $\mu E/\hbar\gamma$	χ	-	-
Intensity parameter I	χ^2	I	-

1) $\vec{\varepsilon}$ = polarisation of radiation; $\vec{D}$ = dipole operator.

2) The lower level is given energy zero; the upper level energy $\omega_0 = (E_2-E_1)/\hbar$.

3) V = the quantisation volume of the cavity.

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Introduction

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1. COMMENTS ON PAPER #1

1.1 A two-level system in a strong field

In paper #1 the use of laser light for spectroscopic investigations is discussed, and hence we start by considering the utilisation of the strong field intensity. The basic ideas are presented in its section 2. Here, we present some aspects of this in a slightly simplified form to lead the reader into the subject. The archetype of a quantum atom is the two-level system of figure 1. The lower level $|g\rangle$ does not necessarily have to be the ground state. All other levels can be omitted from the discussion because, for atomic transitions, the energy differences are mostly such that laser light interacts resonantly with only one pair of levels at a time. In reality these would, of course, have fine structures, which we neglect here.

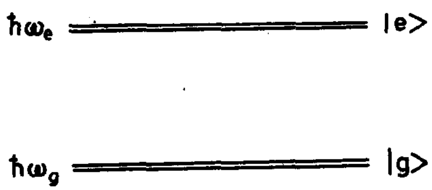

Fig.1. The simplest theoretical model in spectroscopy consists of two levels only. The lower one $|g\rangle$ has got the energy $\hbar\omega_g$ and the excited one $|e\rangle$ the energy $\hbar\omega_e$. The lower state may be the ground state, but it can be any state selected by a laser field nearly resonant with the frequency difference $\omega_e-\omega_g$.

If the laser light has frequency ω we introduce the quantum state in the form

$$|\psi\rangle = \alpha \exp(-i\omega_g t)|g\rangle + \beta \exp[-i(\omega+\omega_g t)]|e\rangle. \qquad (1)$$

The coupling between the levels is assumed to be given by the dipole operator μ, and the interaction Hamiltonian is

$$H = -\mu E \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \cos \omega t. \qquad (2)$$

Schrödinger's equation gives for the probability amplitudes of equation

(1) the time evolution

$$i\dot{\alpha} = -\frac{\mu E}{\hbar} \cos \omega t \; e^{-i\omega t} \beta \tag{3a}$$

$$i\dot{\beta} + (\omega+\omega_g)\beta = \omega_e \beta - \frac{\mu E}{\hbar} \cos \omega t \; e^{i\omega t} \alpha. \tag{3b}$$

In these we neglect rapidly oscillating components approximating

$$e^{\pm i\omega t} \cos \omega t \sim 1/2 \tag{4}$$

which by analogy with magnetic resonance theory is called the 'rotating wave approximation'. The equations to be solved are then

$$i\dot{\alpha} = -K\beta \tag{5a}$$

$$i\dot{\beta} = -\Delta\beta - K\alpha \tag{5b}$$

where we have set

$$\Delta = \omega - \omega_e + \omega_g \tag{6}$$

$$K = \frac{\mu E}{2\hbar} . \tag{7}$$

The eigenvalues of this set are

$$\lambda_{\pm} = i\left[\Delta \pm \sqrt{K^2+\Delta^2/4}\right] = i\left[\Delta \pm \Omega/2\right] \tag{8}$$

and with the initial conditions

$$\begin{aligned} \alpha(0) &= 1 \\ \beta(0) &= 0 \end{aligned} \tag{9}$$

we obtain the solution

$$\alpha(t) = e^{i\Delta t/2} \frac{2K^2}{\Omega} \left[\frac{e^{i\Omega t/2}}{\Omega + \Delta} - \frac{e^{-i\Omega t/2}}{\Omega - \Delta} \right] \tag{10a}$$

$$\beta(t) = i \; e^{i\Delta t/2} \frac{2K}{\Omega} \sin (\Omega t/2) . \tag{10b}$$

This is a simplified form of the solution in equation (2.8) of paper #1.

The probability for occupation of the upper level becomes

$$|\beta(t)|^2 = \frac{4K^2}{\Omega^2}\sin^2(\Omega t/2)$$

$$= \frac{2K^2}{\Omega^2}[1 - \cos\Omega t] \qquad (11)$$

and we see that it pulsates regularly between the upper and the lower level with the frequency

$$\Omega = (\Delta^2 + 4K^2)^{1/2} \qquad (12)$$

which is called the 'Rabi flipping frequency' after its original discoverer Rabi(1937).

In many spectroscopic applications it is impossible to control the interaction time t with the accuracy required to apply equation (11). The measurement takes place in a steady state situation, but the individual atoms begin their interactions and end them at random times. It leads us to consider an ensemble of atoms introduced into the interaction region and removed after a random period. This corresponds to incoherent pumping of the atoms into the interacting level pair and the random termination of interaction through radiative decay to unobserved levels or quenching collisions. In these cases the expected lifetime of an interacting atom is described by the exponental distribution

$$W(t) = \gamma e^{-\gamma t} \qquad (13)$$

and the observed signal becomes an average over an ensemble with this distribution.

Calculating the observed average from equation (11) we find that the upper state population becomes

$$P_e = \int \gamma e^{-\gamma t} |\beta(t)|^2 dt$$

$$= \frac{2K^2}{\Delta^2 + \gamma^2 + 4K^2} . \qquad (14)$$

As a function of the detuning we thus obtain a Lorentzian line shape, but