Chapter 1

General introduction

Purpose of this book

The evolution of atomic physics during the last few decades has been spectacular. In the 1950's, many people believed that this discipline had already reached most of its objectives. The structure of atoms was well understood. Higher resolutions in atomic and molecular spectra were certainly possible, but no spectacular development was expected that could stimulate new ideas and open up new research directions. In fact, this pessimistic vision turned out to be completely wrong. Indeed, atomic physics has completely renewed itself during the last six decades, many times and in many directions. Here we mention a few of the developments that have occurred during this period in order to illustrate how impressive the renewal of this discipline has been: optical pumping methods, realization of laser light sources with unprecedented performances, nonlinear and time resolved spectroscopies, laser cooling and trapping, control of atomic systems at the single particle (electron, atom or photon) level, Bose-Einstein condensates and degenerate Fermi gases, cavity quantum electrodynamics, femtosecond and attosecond pulses, quantum information, detection of parity violation in atoms, etc. In parallel with these developments, interesting and fruitful connections have been established with many other fields of physics and chemistry, opening the way to new synergies and new possibilities of cross fertilizations.

It is clear that these spectacular advances of atomic, molecular and optical physics (AMO) require increasingly complex experimental and theoretical skills. In order to be competitive, a young researcher entering this field must often specialize in a narrow area of AMO. It is difficult for him or her to have a global view of the field, to understand how the evolution of ideas has allowed breakthroughs and opened totally new perspectives. The purpose of this book is to provide the reader with a better perception of the evolution of AMO by putting research performed at different times into perspective, and by trying to point out a few important and general concepts that can be frequently revisited from different points of view. Our hope is to give him or her a better confidence for exploring new problems where this global view of AMO can be fruitful.

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Organization of the book

The choice of topics covered in this book is necessarily biased by our better knowledge of the fields in which we have worked. It is impossible in a single book to cover all the advances of atomic physics during six decades! This does not mean that we establish any hierarchy between these topics. We only hope that our general interpretation of the impressive progress of atomic physics also applies to the fields that we do not address.

The book starts (Chap. 2) with a review of the general background that is needed for reading the other chapters. It introduces the atomic and field variables, the different possible classical and quantum descriptions of atom-field interactions, the basic conservation laws, which are a useful guideline for understanding how one can manipulate atoms with light, the basic ingredients of the description of magnetic resonance, including the Rabi oscillation, the Ramsey fringes and the Einstein coefficients describing the absorption and emission rates.

The other chapters of the book are grouped in 8 parts that can be read more or less independently and whose contents will be now briefly analyzed. A detailed index at the end of the book shall help the reader to easily locate topics of interest. Despite its length, the bibliography cannot be expected to be complete and we apologize for any omission of important references.

Part 1 - Advances in spectroscopy

We begin with a review of optical pumping methods (Chap. 3), which completely renewed radiofrequency and microwave spectroscopy in the middle of the last century. Large population differences between the Zeeman sublevels of atoms can be obtained by optical pumping, allowing a very sensitive optical detection of magnetic resonance in both excited and ground atomic states. Atoms can also be prepared by these methods in linear superpositions of Zeeman sublevels, and we show that this leads to interesting applications described in Chap. 4. Optical spectroscopy was revolutionized by the advent of lasers. In Chap. 5, we analyze the properties of the fluorescence light emitted by a two-level atom excited by a resonant laser beam. Finally, in Chap. 6, we describe several high resolution spectroscopic methods that use nonlinear effects (saturated absorption, two-photon transitions), confinement (Lamb-Dicke effect), or other schemes (shelving method), to get very narrow optical lines.

The field covered in this part 1 is a case study that allows us to introduce several new theoretical approaches that have proven to be very useful for atomic physics, including optical Bloch equations, the dressed atom approach and the quantum jump description of dissipative processes. Moreover, these approaches also establish a link between the concepts of magnetic resonance and those of quantum optics.

Part 2 - Perturbations of atomic levels by light

The light used in optical pumping experiments for polarizing atoms is also a source of perturbations for the atoms and the fields. In Chap. 7, we show that atomic levels are shifted and broadened by light, and that in turn, the propagation of the light is modified. In fact, light shifts, which are a source of perturbations for high resolution spectroscopy, were found to give rise to new interesting applications when laser sources became available. We show that they can be used to trap atoms in potential wells with different shapes and dimensionalities and to detect photons in a cavity without destroying them. In Chap. 8, we study how an atom is perturbed by a high frequency excitation whose frequency ω is much higher than the atomic resonant frequencies. We give a simple semiclassical interpretation of these perturbations in terms of the vibration of the atomic electron in the high frequency incident wave.

Even in the absence of exciting light, the atom is perturbed by its interaction with the radiation field which is then in the vacuum state. These perturbations (Lamb shift, spin anomaly $g-2$) are called radiative corrections. We show that the approach followed in part 2 provides new physical insights into radiative corrections produced by comparing the perturbations due to a non-zero applied field to those obtained when the electromagnetic field is in its vacuum state.

Part 3 - Multiphoton processes

An atom can make a transition between two states by absorbing several photons. In Chap. 9, we describe these multiphoton transitions between two discrete states, first in the radiofrequency domain, where they were first discovered in experiments using optically pumped atoms, then in the optical domain with laser sources. Particular attention is given to two-photon stimulated Raman processes, where the atom absorbs one photon and emits another photon in a stimulated way. Recent important applications of these processes will be described. When the multiphoton transition connects the ground state to a state in the continuum, the process is called multiphoton ionization. In Chap. 10, we describe the main features of multiphoton ionization and we show that interesting new effects appear when the light intensity is so high that the laser electric field becomes comparable to the Coulomb field binding the atomic electron. We show that the interpretation of these effects led to dramatic advances in our ability to produce ultrashort pulses of UV and X radiation, in the attosecond range (1 as $= 10^{-18}$ s).

The research field covered in this part 3 is a new example showing how physical processes discovered in the early days of optical methods have progressively evolved to be now at the heart of an important frontier of laser physics, which will be described in more detail in part 8.

Part 4 - Control of atomic motion. Cooling and trapping

The exchange of linear momentum between atoms and photons give rise to radiative forces acting on atoms and allows a control of their motion. In Chap. 11, we first present a calculation and a physical interpretation of these radiative forces based on different approaches. As a result of the Doppler shift, the radiative forces exerted by the laser waves on the atom acquire a velocity dependence which can, in certain conditions, act as a friction force which reduces the atomic velocity. In Chap. 12, we describe the Doppler laser cooling mechanism for two-level atoms, which was the first cooling scheme proposed for trapped ions as well as for neutral atoms. When the measurement of the temperatures of laser cooled atoms became more precise at the end of the 1980's thanks to time-of-flight techniques, it was discovered that other cooling mechanisms were taking place, or could be implemented, that lead to temperatures much lower than those obtained with Doppler cooling. In Chap. 13, we describe two of these mechanisms: low intensity Sisyphus cooling based on a combination of optical pumping and light shifts that leads to a situation in which the moving atom runs up potential hills more frequently than down; subrecoil cooling, which allows atoms to be cooled below the single photon recoil momentum. Finally, in Chap. 14, we discuss the problem of trapping charged particles as well as neutral atoms, which allows a full control of the external degrees of freedom, both in momentum and position space i.e. in phase space.

The research field covered in part 4 shows how the better understanding of atom-photon interactions progressively acquired during the last decades has allowed the emergence of a new very active research field, ultracold atom physics.

Part 5 - Ultracold interactions and their control

The developments described in part 4 raise the question of the description of interactions between ultracold atoms. In Chap. 15, we analyze this problem from both microscopic and macroscopic points of views. We first introduce the scattering length, a parameter which describes most of the properties of elastic collisions between ultracold atoms. We also introduce a few regularized delta potentials that lead to simpler calculations and show how the idea of a mean field can be derived by studying how the propagation of an atom can be modified by its interaction with a background ultracold gas. One of the most important developments of atomic physics in the field of ultracold atoms has been the discovery that atom-atom interactions can be controlled by using so-called Feshbach resonances. In Chap. 16, we present a detailed description of these resonances, their physical interpretation, and their use for producing ultracold molecules.

With Feshbach resonances, one can say that atomic physics has reached a full control of atomic parameters: spin polarization with optical pumping, velocity with laser cooling, position with trapping, atom-atom interactions with Feshbach resonances.

Part 6 - Atomic interferometry. Entangled states

The concept of linear superpositions of states, leading to quantum interference effects, is central in quantum mechanics. Many examples may be found in atomic physics. The pioneering experiments using optical methods involved only internal atomic states and are described in part 2. In part 6, we describe quantum interference effects that also involve external degrees of freedom (of the center of mass) and which become easier to observe with the large de Broglie wavelengths obtained by laser cooling. In Chap. 17, we show that several well known experiments in wave optics, like Young's double slit interferences, can be extended to atomic de Broglie waves. Furthermore, by playing with the atomic internal variables, one can realize atomic interferometers, where the two paths of the interferometer differ, not only by the external variables of the center of mass, but also by the atomic internal variables. In Chap. 18, we describe these interferometers and their important applications. Atomic clocks with ultracold atoms are presently the most accurate time frequency standards, and atomic interferometers provide the most precise measurements of inertial fields.

Finally, in Chap. 19, we consider linear superpositions of states of two subsystems 1 and 2. When such linear superpositions cannot be written as a product of a state of system 1 by a state of system 2, the two systems are in an *entangled state* that exhibits quantum correlations, impossible to understand with the concepts of classical physics. Different types of entangled states can now be prepared and are playing an important role in discussions concerning the quantum non-separability (violation of Bell's inequalities), the measurement process, the decoherence due to the coupling with the environment and the possibility to use quantum correlations to transmit and process information.

The topics covered in part 6 show that atomic physics is an ideal playground for deepening the understanding of quantum concepts. Important examples of linear superpositions of states have been analyzed in a long series of experiments of increasing complexity performed over the last six decades. These have given rise to a wealth of applications.

Part 7 - Quantum gases

Quantum gases presently receive a lot of attention. In part 7, we give a brief historical review of the developments which led to the emergence of this field and a description of a few important results that have been obtained. In Chap. 20, we begin by analyzing what is meant by quantum gas by comparing three characteristic lengths: the thermal de Broglie wavelength λ_{T} of the atoms of the gas, the mean distance between atoms d and the range r_0 of the atom-atom interactions. We review the various quantum regimes that can appear depending on the relative values of these three characteristic lengths.

We briefly describe the pioneering work of Albert Einstein who predicted in 1924 the phenomenon of *Bose-Einstein condensation* (BEC) appearing in this regime. In Chap. 21, we then discuss the long series of theoretical and experimental works that led to the observation of BEC in a gas, 70 years after Einstein's prediction. In this chapter, we restrict ourselves to the mean-field description of Bose-Einstein condensates where each bosonic atom in the condensate is considered to evolve in the mean field produced by the other atoms. In Chap. 22, we introduce the Gross-Pitaevskii equation, which describes this situation and which explains quantitatively most of the static and dynamic properties of weakly interacting condensates at very low temperatures. In Chap. 23, we introduce the correlation functions of the atomic field operators in quantum gases and show that they allow a clear understanding of the coherence properties of condensates. Finally, in Chap. 24, we analyze from an experimental point of view another spectacular quantum macroscopic property of quantum fluids, their superfluidity. We discuss the frictionless propagation of a probe particle in the condensate, due to the impossibility for this particle to create an elementary excitation in the fluid when its velocity is lower than a certain threshold. We also show how quantized vortices appear in the condensate when the trap containing this condensate is rotated at a high enough speed.

The history of gaseous BEC is a beautiful example of a long term fundamental research endeavor that required the combination of several experimental and theoretical contributions to make a major scientific discovery possible.

Part 8 - A few frontiers of atomic physics

Another important feature of atomic physics, which is well illustrated by the example of quantum gases, is its ability to stimulate fruitful connections with other fields, such as condensed matter physics, particle physics or laser physics. A few examples of these connections are given in the next part devoted to the frontiers of atomic physics:

- Tests of fundamental theories
  Several examples of such tests using the high precision of atomic physics experiments are already given in the previous parts. In Chap. 25, we focus on the tests of fundamental symmetries. We show how it has been possible to observe for the first time a parity violation in atoms and how the results obtained in this way for the parameters of the standard model complement the information deduced from high energy experiments.
- Strongly interacting many-body systems
  In Chap. 26, we describe a few effects that appear in quantum gases when interactions are too strong to allow a mean-field description, and which present interesting connections with other similar effects (Josephson effect, superfluid- Mott insulator transition, BEC-BCS crossover).
- Extreme light
  In Chap. 27, we focus on examples that show how the interplay between basic and applied research has allowed the realization, in table-top experimental set-ups, of laser sources with unprecedented performances. We first describe how the understanding of ionization of atoms in intense laser fields, described in Chap. 10, has led to the realization of ultrashort laser pulses, in the attosecond range. These developments would not have been possible without the development of intense femtosecond pulses based on several techniques, such as mode locking or chirped pulsed amplification, that are briefly described.

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