# Preface

At present, we are witnessing the dawn of an era of quantum technology. More and more money is invested in projects that make use of quantum phenomena to achieve new goals of practical applicability. Some people even talk about a *second quantum revolution* that applies the quantum rules to develop new technologies. The increasing ability to manipulate quantum effects is leading to new devices that are superior to traditional devices. It is very important to describe properly the quantum phenomena underlying the new technologies.

Quantum mechanics gives us new opportunities, but it also imposes some restrictions of a fundamental nature. For example, repeated measurement of one of the observable quantities leads to an average value around which there are quantum fluctuations or noise. The quantum noise is a fundamental property of all systems and persists even if all classical sources of error have been eliminated from the measurement process. Quantum fluctuations are present in all systems, including radiation fields in the vacuum state, and it has long been thought that they presented an insuperable barrier to accuracy. They limit the sensitivity achieved by detectors for spectral resolution and the signal-to-noise ratio and hence limit the accuracy to which measurements can be performed. All detection systems are subject to this limit, and it was long believed that this limit could not be suppressed. In the 1980s theoretical studies followed by experimental measurements showed that the quantum limit can be beaten using quantum technologies that employ quantum effects such as quantum interference, squeezing, and entanglement. The search for light fields and physical systems with reduced or even completely suppressed fluctuations has become a new subject in physics to study. The possibility to overcome the quantum limit with new sources of light allows one to perform experiments with greater precision than is possible with laser light. It also allows the transmission of information more accurately than with conventional light. This realm of physics is now known as precision quantum technology. However, some of these quantum technologies are still futuristic; for example, methods of creating and manipulating entanglement are still in their infancy.

The general field of quantum-limit spectroscopy is of importance in connection with the physical theories of noise-free measurements. The field of study of spectroscopic effects at the quantum noise limit is either explicit or implicit in almost all areas of physics and also in many areas of science such as chemistry and biology, and we explore the novel effects and recent developments in spectroscopy of atoms and quantum dots. Quantum effects in atomic radiation, which are distinct from semiclassical theories, arise when it is essential to quantize the electromagnetic field, and it is well known that they were central to the early discussions of the manifestation of the vacuum fluctuations characteristic of quantum fields. In the field of quantum optics the interest in quantum spectroscopic effects has been inspired in part by the work on the fluorescence and absorption spectra by Mollow and Eberly, photon antibunching and squeezing by Kimble, Mandel, Walls, Carmichael, and other workers in the seventies. In recent years quantum spectroscopy has become of interest not only for the basic understanding of complicated quantum structure of atomic systems, but also because it lies at the heart of such important applications as high-resolution spectroscopy, noise-free measurements, and atomic clocks. The latest applications are to quantum computation and to spectroscopy with Bose–Einstein condensates. It has also been demonstrated that quantum and precision spectroscopy methods provide an effective way of controlling quantum fluctuations and decoherence. Other rapidly developing modern topics, such as entanglement, enhanced spectral resolution, and controlled information transfers are, of course, intimately associated with quantum effects in the atom–field interaction. According to quantum mechanics, a coupled system of an atom and the radiation field is not merely an atom exchanging energy with the field: The atom and the radiation field become entangled. They form a composite entity, with superposition states that are entangled states.

Although this book is focused on a small collection of current research areas in atomic spectroscopy, it should nevertheless be evident how strongly atomic spectroscopy relates to basic quantum physics and quantum limits in particular. Quantum-limit spectroscopy lies at the frontier of current experimental and theoretical techniques, and is one of the areas of atomic spectroscopy where the quantization of the sources (atoms) and the field is essential to predict and interpret the existing experimental results. It was recognized as representing a radical departure from the traditional classical spectroscopy where the existing treatments turn out to be less than completely satisfactory. Currently, there is an increasing interest in quantum and precision spectroscopy both theoretically and experimentally, due to a significant progress in trapping and cooling of single atoms and ions. This progress allows us to explore in the most intimate detail the ways in which light interacts with atoms and to measure spectral properties and quantum effects with a large precision. Moreover, it allows us to perform subtle tests of quantum mechanics on the single atom and single photon scale which were hardly even imaginable as "thought experiments" a few years ago.

Some description of the mathematical tools for the study of quantum spectroscopy is required, and therefore we begin in Chap. 1 with an overview of the fundamental concepts relating to quantum fluctuations of the electromagnetic field and the spectroscopic methods of detecting them by means of photoelectron counting. Furthermore, the intensity spectrum, optical power spectrum, and quantum noise spectrum will be defined. The theories of the emission power spectrum, the absorption spectrum, and the phase-dependent spectrum and their relationship to radiating sources are developed in Chap. 2. This chapter also includes a discussion of the homodyne and balanced homodyne techniques for detection of the phase-dependent spectra and quantum fluctuations. In Chap. 3, we begin the analysis of quantum-limit spectroscopy with a consideration of the most fundamental models in atomic spectroscopy. We consider the optical spectra of a coherently driven two-level atom and discuss their properties with a particular attention on signatures of quantum fluctuations and their control. The effect of a tailored vacuum and coherent pumping on the spectral line narrowing is discussed in detail. The chapter concludes with a description of experimental studies of the spectral line narrowing. Chapter 4 is devoted to collective effects in atomic spectroscopy. The role of the collective behavior of the radiating atoms in the cancellation of spontaneous emission is discussed. This chapter also discusses techniques of a selective excitation of the collective states and experimental studies on the preparation of two atoms in a desired collective (entangled) state and the measurement of the subradiance from artificial atoms. The subject of spectroscopy with time-dependent fields is considered in Chap. 5. The theoretical techniques for calculating the fluorescence spectrum are explained in details and illustrated on examples of the excitation with bichromatic and amplitude-modulated fields. Experimental studies on the cancellation of spectral lines are also discussed. The theory of quantum spectroscopy with squeezed light is developed in Chap. 6. The main part of this chapter is devoted to applications of squeezed light in atomic spectroscopy with a particular attention on a class of applications which lead to features unique to quantum nature of squeezed light. Chapter 7 presents experimental studies on atomic spectroscopy with squeezed light. A full description of experiments which aimed to observe alterations in the radiative properties of atoms interacting with squeezed light is presented. A brief discussion of an experiment on ultrahigh frequency measurements, and frequency metrology, is also included. The subject of engineering collective and squeezed field interactions is considered in Chap. 8. The procedures of the adiabatic approximations are used to demonstrate that collective effects between distant atoms and a squeezed field type damping of an atom can be achieved. The chapter also includes experimental studies demonstrating collective behaves of distant atoms. Techniques of beating quantum limits in optical spectroscopy, called quantum strategies, are discussed in Chap. 9. The detailed discussion of different concepts of the fundamental limits in physics accompanies the presentation of experimental studies that demonstrated beating of the quantum limits and the improvement of the spectral resolution. The final chapter, Chap. 10, deals with various forms of squeezing of the fluctuations of the spin operators. The concepts of dipole, planar, and spin squeezing are introduced, and we demonstrate how to distinguish between these three forms of squeezing. The significance of spin squeezing in detection of entanglement is discussed.

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