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Chapter 1

Introduction

1.1 What is quantum optics

The simplest 'definition' of quantum optics is the discipline that examines 'what is a photon'. A more detailed description would be a 'non-relativistic quantum field theory of atoms interacting with light'. The field grew out of the invention of the laser and the question of 'what is the difference between laser light and a light bulb'. The acronym LASER stands for 'light amplification by stimulated emission of radiation'. Often in textbooks it is stated that laser light is *directional, intense, and monochromatic.* Well I can make light directional via a fiber optic, I can turn up the power until the thing melts, and I can filter the output to limit the bandwidth. But what about stimulated emission? When a photon interacts with a detector, it does not announce its origin as stimulated or spontaneous, it is just an excitation of an electromagnetic field mode. My definition of a photon is a click in an absorptive detector, as we will detail later. It is not a particle, or a wave, but an excitation of a bosonic field. So, how DO you tell whether the light is coming from an incandescent bulb or a HeNe laser? Glauber [9] taught us that the difference is in *photon correlations*. One must look past expectation values and examine two-time correlations at the least. The fluctuations in the light field provide information that cannot be accessed by just examining averages. It will turn out that for laser light the statistics of the photo detection events are Poissonian, each one independent of the other. For light from an incandescent bulb, thermal light, we find that the photons are more likely to come in pairs than they would be for a random source. This is the origin of the Hanbury–Brown–Twiss effect [10], whereby one can detect correlations in intensity from two spatially separated detectors. We will find that light sources exist where the photons are less likely to come in pairs than from a laser, which is called photon anti-bunching. This type of light is quite interesting as it *cannot* be modeled by a deterministic random process. A cartoon of this concept is shown in figure 1.1.

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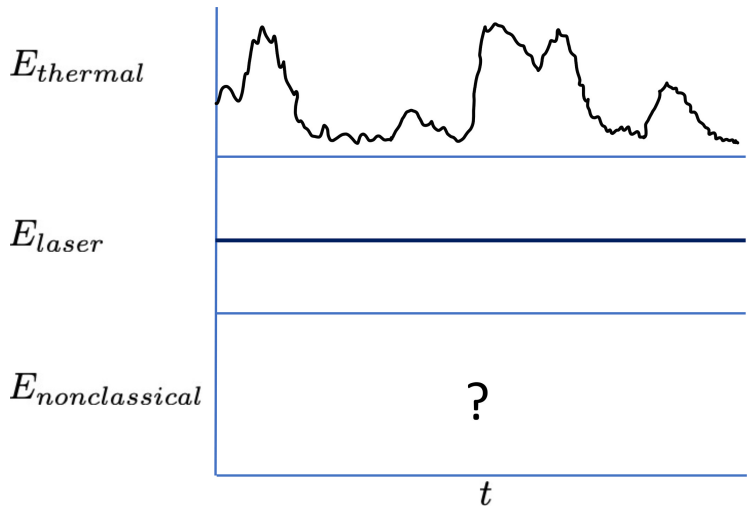

Figure 1.1. Electric field amplitude time evolution for (a) noisy, thermal source, (b) laser source, and (c) nonclassical or manifestly quantum light source.

In thermal light, there are large fluctuations, and during periods of higher intensity you are more likely to detect a photon. You are also more likely to get a second photon, simply because then there are more photons. For a laser, the output is described by a Poisson stochastic process, after detection of a photon you are no more or less likely to detect a second photon. A fully quantum theory of the laser due to Scully and Lamb [20] showed the Poissonian nature of the photon statistics and pointed out the key role of spontaneous emission in determining the non-zero linewidth of the laser output. What about anti-correlations? The simplest example of such a source is a single two-level atomic transition driven by a laser, and examining the fluorescence. To spontaneously emit, the atom must be excited. Upon emission the atom goes to the ground state and hence cannot emit a second photon. The photon statistics and spectra of this system of resonance fluorescence was the focus of intense work in the mid-1970s, and a fully quantum model of the electromagnetic field was found to be necessary to understand and predict results of experiments.

How can we differentiate different field states if we cannot measure the field directly? Let us consider a field inside a box and ask how many photons are in the box. We will open the box and let all the photons leak out and count how many we detect. Of course, we assume perfect photo detection for now. Then let us do that over and over, as our answer will be a random number generally. Different field states will have different statistics and different probability distributions for the number of photons we detect. Examples of such distributions are shown in figure 1.2. There are states of the field with a definite number of photons, called number, or Fock states. The coherent state that is output from a laser has a Poissonian distribution, and a thermal field has the decaying exponential distribution

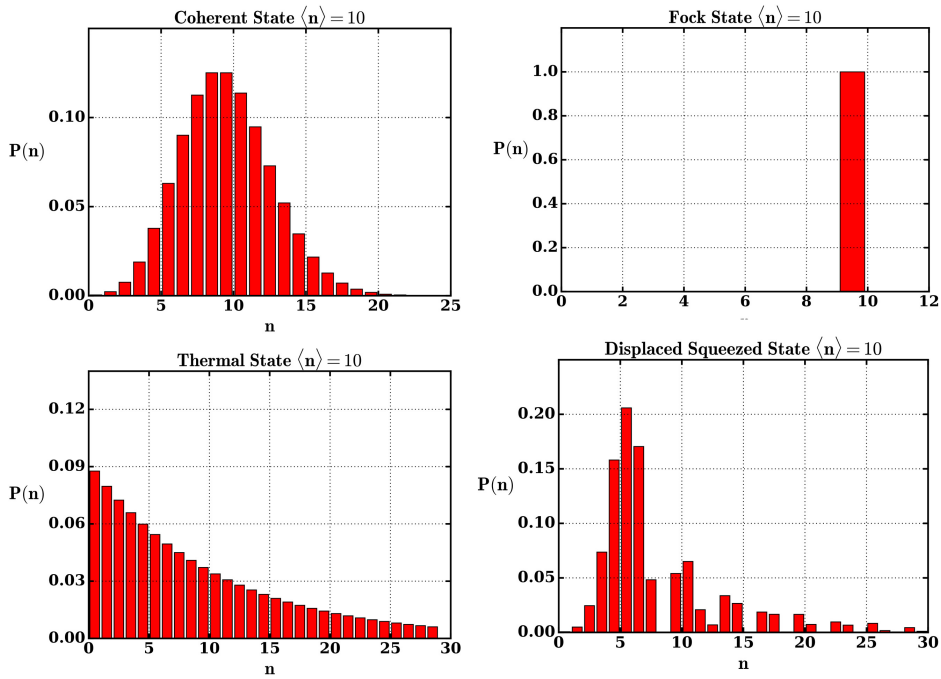

Figure 1.2. Probability distribution of photons $P(n)$ for the given field states.

characteristic of a Bose–Einstein distribution. More interesting distributions result from nonclassical states such as a displaced squeezed vacuum or squeezed state. How do we prepare such states in a box? Good question. What we are generally more interested in is a slightly leaky box, where we also inject photons. The result is often a steady state that is not in thermal equilibrium, a non-equilibrium steady state. The leaky box can be two mirrors forming an optical cavity, such as in a Fabry–Perot or a semiconductor wave guide with polished ends. We can use an essentially classical source, the output of a laser. We can put single atoms, a gas of many atoms, or crystals inside this slightly leaky box and create field states of our choice. Some are more difficult than others of course. We can infer what is inside the box by the statistical properties of what leaks out. This could be through a non-perfect mirror, or fluorescence out the sides of the cavity, perhaps via spontaneous emission. The leaky part is important, as we would like to create a field source, and the leak is essentially our output. A laser with two perfect mirrors would generate a large field inside the cavity, but if no light comes out, we cannot make laser pointers, blow holes in things, or do laser spectroscopy.

The focus of this book is to examine how to calculate the statistics of photo counts, as well as various spectral quantities in a variety of systems. We will mainly look at two-time correlations, but of course the probability distribution is determined in full by the entire set of n-time correlation functions, just as in quantum electrodynamics and other field theories.

1.2 Open quantum systems

In this example above, resonance fluorescence, the atom is not an isolated system. Energy is put into the system via the driving laser, and energy leaves the system via interaction with the field modes (all directions, frequencies, and polarizations) that are in the ground or vacuum state. It is via the latter interaction that quantum fluctuations, or vacuum fluctuations, enter the picture. Such a system that interacts with its environment is known as an *open quantum system*. Such a system is not described by a wave function, unless one considers the wave function of the atom and all of the field modes, an infinite number. So, such an approach is not tenable, and we must resort to approximations. If we want a description of our atom and its interaction with its environment, we must use a density operator, or density matrix. In the simplest models, the density operator evolves via the Schrödinger supplemented by corrections due to the environmental interactions. These corrections will depend only on gross properties of the environment, such as temperature and pressure. In this procedure, we reduce the number of equations by omitting the details of the environment, thereby losing information about the environment. A good example might be dropping an ice cube into the ocean. The ice cube will eventually melt, and the temperature of the ocean will not change very much, nor will any other properties of the ocean. The ocean can be considered a heat bath at a constant temperature. This is mainly due to the large volume of the ocean, an ice cube dropped into a glass of water will lower the temperature of the resulting water by a measurable amount, and as such thermodynamic properties of water can be measured via calorimetry. In the case of the quantum electromagnetic vacuum, we have an infinite number of modes. An infinite number of frequencies, each with an infinite number of propagation directions and two polarizations. Therefore, it seems reasonable that an approach based on an interaction of a closed quantum system with a type of heat bath will be useful.

We consider the coupling of the atom to a given field mode (g) as very small, that it scales with the inverse square root of the volume of the field mode (which is infinite). But the number of modes N is infinite. We will find that the spontaneous emission rate of the atom depends on the product Ng^2 which can take on a finite value, as in figure 1.3. The fancy title for what we are doing is quantum statistical mechanics.

1.3 This book

This book resulted from notes developed for teaching quantum optics to upper level undergraduates, and grad students starting out in the field, or anyone with a good grasp of quantum mechanics that wishes to know more. Quantum optics is one of the seminal fields for the revolution underway in quantum information processing, detection of gravitational waves, many-body quantum systems, nanophotonics, and others. As such, an audience beyond specialists will want/need to understand the basics of quantum optics. This book seeks to present the simplest non-trivial models that illustrate the principles and is not meant to be exhaustive. In the 1980s while in graduate school, the key books (at least for me) were those of Loudon [11]; Allen

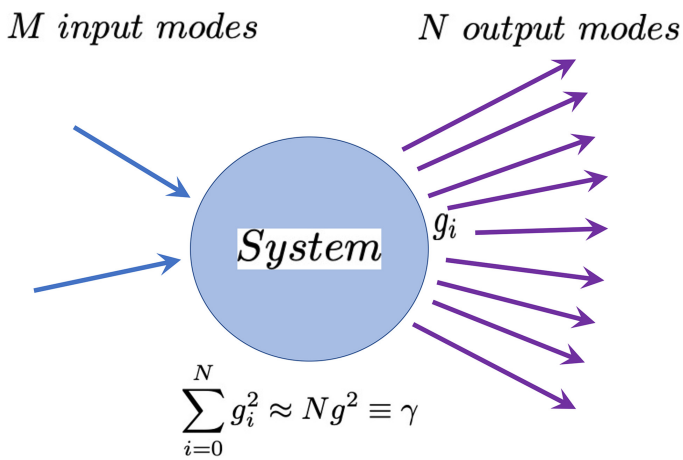

Figure 1.3. Sketch of an open quantum system with a (typically small) M number of input modes and a large number N of output modes. The coupling of the system to a given mode is g_i.

and Eberly [2]; and Sargent, Scully, and Lamb [19]. I would suggest that the modern trifecta would include the books by Orszag [18], Scully and Zubairy [21], and Mandel and Wolf [12]. I would also recommend the trilogy written by Carmichael [4–6] and the work of Milonni [14–17] for more details. My interactions with the latter two largely form the basis of my approach. A similar approach is that of Bruer and Pettrucione [3]. Other books I am familiar with enough to highly recommend are those of Walls and Milburn [23], Gardiner and Zoller [7], Gerry and Knight [8], Meystre and Sargent [13], and Agarwal [1]. I would be remiss not to direct the readers' attention to the set of notes on quantum and atom optics notes available online, provided by Steck [22]. There are many good texts on quantum optics these days, so why one more? The novelty hopefully is the accessibility of the material to a newcomer to the field, and it is more pedagogical than exhaustive.

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