1 Introduction

1.1 Historical perspective

Ever since the quantum interpretation of the black body radiation by M. Planck [Pla00], the discovery of the photoelectric effect by H. Hellwarth [Hel1898] and P. Lennard [Len02] and its interpretation by A. Einstein [Ein05] has the idea of photons been used to describe the origin of light. For the description of the generation of light a quantum model is essential. The emission of light by atoms, and equally the absorption of light, requires the assumption that light of a certain wavelength λ, or frequency ν, is made up of discrete units of energy each with the same energy $hc/\lambda = h\nu$.

This concept is closely linked to the quantum description of the atoms themselves. Several models have been developed to describe atoms as quantum systems, their properties can be described by the wave functions of the atom. The energy eigenstates of atoms lead directly to the spectra of light which they emit or absorb. The quantum theory of atoms has been developed extensively, it led to many practical applications [Tho00] and has played a crucial role in the formulation of quantum mechanics itself. Spectroscopy relies almost completely on the quantum nature of atoms. However, in this guide we will not be concerned with the quantum theory of atoms, but concentrate on the properties of the light, its propagation and its applications in optical measurements.

The description of optical phenomena, or physical optics, has developed largely independently from quantum theory. Almost all physical optics experiments can be explained on the basis of classical electromagnetic theory [Bow59]. An interpretation of light as a classical wave is perfectly adequate for the understanding of effects such as diffraction, interference or image formation. Even nonlinear optics, such as frequency doubling or wave mixing, are well described by classical theory. Even many properties of the laser, the key component of most modern optical instruments, can be described by classical means. Most of the present photonics and optical communication technologies are essentially applications of classical optics.

However, some experiments with extremely low intensities and those which are based on detecting individual photons raised new questions. For instance, the famous interference experiments by G.I. Taylor [Tay09] where the energy flux corresponds to the transit of individual photons. He repeated T. Young's double slit experiment [You1807] with typically less than one photon in the experiment at any one time. In this case the classical explanation of interference based on electromagnetic waves and the quantum explanation based on the interference of probability amplitudes can be made to coincide by the simple expedient of making the probability of counting a photon proportional to the intensity of the classical field. The experiment cannot distinguish between the two explanations. Similarly, the modern versions

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of these experiments, using the technologies of low noise current detection or, alternatively, photon counting, show the identity of the two interpretations.

The search for uniquely quantum optical effects continued through experiments concerned with intensity, rather than amplitude interferometry. The focus shifted to the measurement of fluctuations and the statistical analysis of light. Correlations between the arrival of photons were considered. It started with the famous experiment by R. Hanbury-Brown and R. Twiss [Bro56] who studied the correlation between the fluctuations of the two photocurrents from two different detectors illuminated by the same light source. They observed with a thermal light source an enhancement in the two-time intensity correlation function for short time delays. This was a consequence of the large intensity fluctuations of the thermal light and was called photon bunching. This phenomenon can be adequately explained using a classical theory which includes a fluctuating electro-magnetic field. Once laser light was available it was found that a strong laser beam, well above threshold shows no photon bunching, instead the light has a *Poissonian counting statistic*. One consequence is that laser beams cannot be perfectly quiet, they show noise in the intensity which is called *shot noise*, a name that reminds us of the arrival of many particles of light. This result can be derived from both classical and quantum models.

Next it was shown by R.J. Glauber in 1963 [Gla63] that additional, unique predictions could be made from his quantum formulation of optical coherence. One such prediction is *photon anti-bunching*, where the initial slope of the two-time correlation function is positive. This corresponds to greater than average separations between the arrival times of photons, the photon counting statistics may be sub-Poissonian and the fluctuations of the resulting photocurrent would be smaller than the shot noise. It was shown that a classical theory based on fluctuating field amplitudes would require negative probabilities in order to predict anti-bunching and this is clearly not a classical concept but a key feature of a quantum model. It was not until 1976, when H.J. Carmichael and D.F. Walls [Car76] predicted that light generated by resonance fluorescence from a two level atom would exhibit anti-bunching, that a physically accessible system was identified which exhibits non classical behaviour. This phenomenon was observed in experiments by H.J. Kimble, M. Dagenais and L. Mandel [Kim77], opening the era of quantum optics. More recently, the ability to trap and study individual ions allows the observation of both photon anti-bunching and sub-Poissonian statistics.

Initially these single particle effects were a pure curiosity. They showed the difference between the quantum and the classical world and were used to test quantum mechanics. In particular, the critique by A. Einstein and his collaborators B. Podolsky and N. Rosen and their EPR paradox [Ein35] required further investigation. Through the work of J.S. Bell [Bel64] it became possible to carry out quantitative tests. They are all based on the quantum concept of *entanglement*, that means pairs of particles or wave functions which have a common origin and have linked properties, such that the detection of one allows the perfect prediction of the other. Starting with the experiments by A. Aspect, P. Grangier and G. Roger [Asp82] with atomic sources, and later with the development of sources of *twin photon pairs* and experiments by A. Zeilinger [Zei00] and many others the quantum predictions have been extremely well tested. More recently, the peculiarities of single photon quantum processes have found technical applications, mainly in the area of communication. It was found that information sent by single photons can be made secure against eavesdropping, the unique quantum properties do not allow the copying of the information. Any eavesdropping will introduce noise and can therefore be detected. Quantum cryptography [Mil96] is now a viable technology, completely based on the weirdness of the concept of photons.

There is speculation of other future technological applications of photons. The superposition of different states of photons can be used to send more complex information, allowing the transfer not only of classical bits of information, such as 0 and 1, but of q-bits based on the superposition of states 0 and 1. The coherent evolution of several such quantum systems could lead to the development of quantum logic connections, quantum gates and eventually whole quantum computers which promise to solve certain classes of mathematical problems much more efficiently and rapidly [Mil98]. Even more astounding is the concept of *teleportation*, the perfect communication of the complete quantum information from one place to another. This is presently being tested in experiments, see Chapter 13. Optics is now a testing ground for future quantum technologies, for data communication and processing.

1.2 Motivation: Practical effects of quantum noise

Apart from their fundamental importance, quantum effects now increasingly play a role in the design and operation of modern optical devices. The 1960s saw a rapid development of new laser light sources and improvements in light detection techniques. This allowed the distinction between incoherent (thermal) and coherent (laser) light on the basis of photon statistics. The groups of A. Arecchi [Arr66], L. Mandel and R.E. Pike all demonstrated in their experiments that the photon counting statistic goes from super-Poissonian at threshold to Poissonian far above threshold. The corresponding theoretical work by R. Glauber [Gla63] was based on the concept that both the atomic variables and the light are quantised and showed that light can be described by a *coherent state*, the quantum analogy counterpart to a classical field. The results are essentially equivalent to a classical treatment of an oscillator. However, it is an important consequence of the quantum model, that any measurement of the properties of this state, intensity, amplitude or phase of the light, will be limited by *quantum noise*.

Quantum noise can impose a limit to the performance of lasers, sensors and communication systems and near the quantum limit the performance can be quite different. To illustrate this consider the result of a very simple and practical experiment: Use a laser, such as a laser printer with a few mW of power, detect all of the light with a photo-diode and measure the fluctuations of the photo-current with an electronic spectrum analyser, as shown in Fig. 1.1(a) This produces an electronic signal which represents the intensity noise at one single detection frequency. The fluctuations vary with the frequency, a plot of the noise power is called an *intensity noise spectrum* of the laser light. Such spectra will be discussed in detail in this book.

Figure 1.1(b) shows two different spectra. Trace (i) is the photo-current noise spectrum with light on the detector. Trace (ii) is the noise measured without light on the detector, the so called dark noise. It provides a noise background which contains all the electronic noise of the detector, the electronic amplifier, the spectrum analyser and any stray electrical signals picked up by the apparatus. It shows a strong, clearly identifiable spectral component at 5.5 [MHz] due to electric pickup, for example of a radio station, and a uniform, flat background noise slowly increasing with the frequency which is a property of the electronics used. The strong

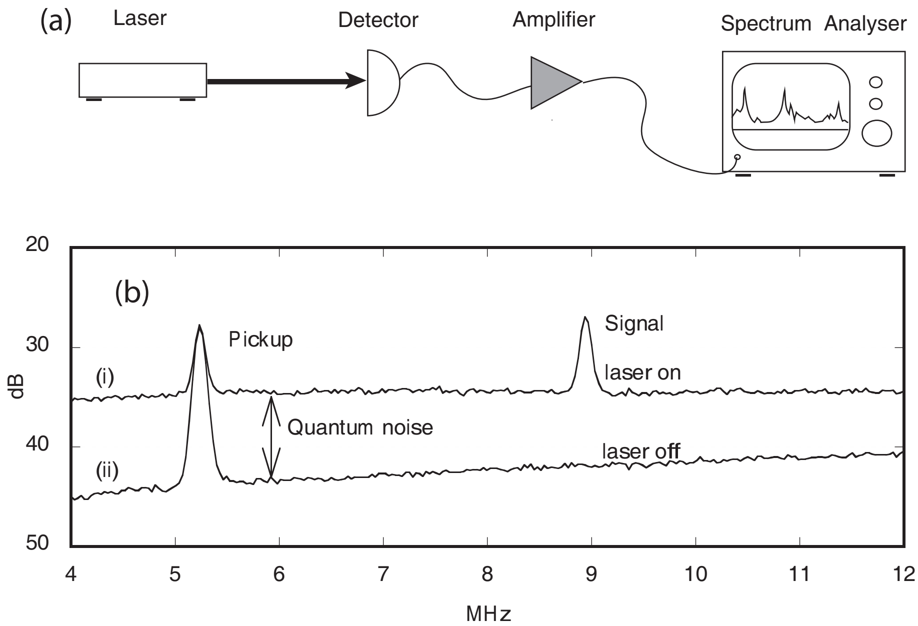

Figure 1.1: The intensity noise of a laser. (a) Schematical layout of the experiment. (b) The noise spectrum, for detection frequencies 4–12 [MHz]. The noise power is shown on a logarithmic scale. Two traces are shown: (i) laser on, (ii) laser off. Details of these measurements are discussed in Chapter 9.

individual components at 9 [MHz] are due to modulations of the light. This is the way information can be sent via a laser beam. The diagram shows that the quality of the information, given by the ratio between the size of the signal and the size of the noise, is limited.

The flat noise background in trace (i), which is frequency independent and thus classed as "white noise", is the feature of greatest interest in terms of quantum optics. This is *quantum noise* and represents a phenomenon which is not included in the classical electro-magnetic model of light. It is a direct consequence of the quantum theory of light and will be discussed in great detail in this book. This quantum noise represents some unavoidable fluctuations in the intensity, it forms the *quantum noise limit*, or *QNL*, for the intensity noise. It is an intrinsic property of the light and it appears for both laser and thermal light. The magnitude of the noise is directly linked to the intensity of the light detected, or the average of the photo-current, and is expressed by the shot noise formula.

Quantum noise can be interpreted in various ways. Firstly, it can be associated with the quantization of the light, can be regarded as a consequence of the Heisenberg uncertainty principle or of the properties of the operators used to describe the light field. Such a quantum model will be presented in detail and is used extensively in this book. This model is rigorous and will in all cases lead to the correct quantitative result. However, it is also very abstract and fits not directly to the concepts commonly used by many experimentalists. A related model is to view quantum noise as a consequence of the statistical property of a stream of photons.

These particles do not interact with each other and a certain degree of randomness, represented by a Poissonian distribution, is the natural state of this system. We will find that light tends to approach such a Poissonian distribution during the arrival times of the photons at the detector. As a consequence the photo-current, which is the quantity actually measured in the experiments, will display fluctuations of a magnitude dictated by the Poissonian distribution. Such a statistical model is very useful for the interpretation of intensity, but we will find that it has severe shortcomings whenever other properties of light, such as phase and interference, are investigated.

Alternatively, quantum noise can be regarded as a consequence of the photo-detection process, as a randomness of the stream of electrons produced in the photo-detector. This view prevailed for a long time, particularly in engineering text books. But this view is misleading as we find in the recent *squeezing* experiments, described in this book. It cannot account for situations where nonlinear optical processes modify the quantum noise, while the detector remains unaffected. In the squeezing experiments the quantum noise is changed optically and consequently we have to assume it is a property of the light, not of the detector.

Finally, it is possible to expand the concept of classical waves and to expand the concepts of beat notes and modulation, which we already used in the description of the origin of the discrete components contained in the noise spectrum, see Fig. 1.1. Consider any noise detected as the outcome of a beat experiment. A signal at frequency Ω corresponds to the beat, or product, of at least two waves with optical frequencies ν and $\nu \pm \Omega$. Since there is only one dominant frequency component in the spectral distribution of a laser beam, which is at the centre frequency ν_L of the laser, the noise at Ω can be regarded as the consequence of randomly fluctuating fields at the laser sidebands $\nu_L + \Omega$ and $\nu_L - \Omega$ beating with the centre component at ν_L. The randomness of the field in the sidebands is not included in the classical wave model, where the amplitude is strictly zero away from the centre component. However, the quantum effect can be incorporated by adding fluctuations of a fixed size to the otherwise noiseless classical sidebands. This idea is very successful in interpreting experiments concerned with quantum noise, for example the description of the properties of beamsplitters and interferometers. It uses all of the components familiar from physical optics and electronics (monochromatic waves, sidebands, phase difference, interference and beat signals) and adds only one extra component, namely a randomly varying field. This model, which is rarely used in most of the research literature, has a prominent position in this book due to its simplicity and practicality.

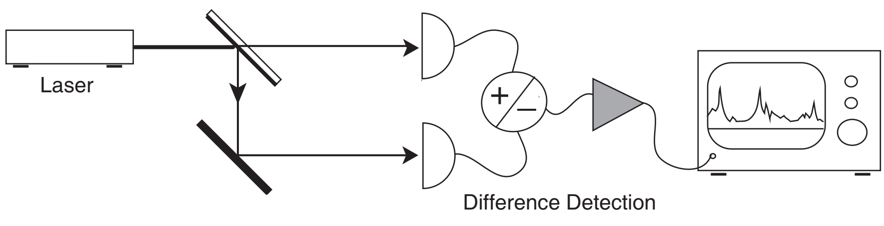

Figure 1.2: First attempt to eliminate noise by dual detection.

It is worthwhile to explore the properties of quantum noise somewhat further. It was found that, in clear distinction to classical noise, no technical trick can eliminate quantum noise. To illustrate the differences consider the following schemes for the suppression of the noise. The first scheme, see Fig. 1.2, involves difference detection, as it is frequently employed in absorption experiments. A beamsplitter after the laser is used to generate a second beam, which is detected on a second detector. Any intensity modulation of the intensity of the laser beam will appear on both beams and results in changes of the two photo-currents. The modulations of the currents will be strongly correlated. Using a difference amplifier the common fluctuations will be subtracted. When the gain of the two amplifiers has been chosen appropriately the resulting difference current will contain no modulation. This idea works not only for modulations but also for technical noise, which can be regarded as a random version of the modulations. Such technical noise can be subtracted. However, this scheme fails for the suppression of quantum noise. Both light beams contain quantum noise, which leads to white noise in the two photo-currents. Experiments show that these fluctuations are not subtracted by the difference amplifier. The noise of the difference is actually larger than the noise of the individual beams, it is the quadrature sum of the noise from the two individual currents. This result remains unchanged if the difference is replaced by a sum or if the two currents are added with an arbitrary phase difference. The resulting noise is always the quadrature sum independent of the sign, or phase, of the summation. This is equivalent to the statement that the noise in the two photo-currents is not correlated.

At this stage it is not easy to identify the point in the experiment where this uncorrelated noise is generated. One interpretation assumes that the noise in the currents is generated in the photo-detectors. Another interpretation assumes that the beamsplitter is a random selector for photons and consequently the intensities of the two beams are random and thus uncorrelated. A distinction can only be made by further experiments with squeezed light, which are discussed later in this book.

An alternative scheme for noise suppression is the use of feedback control, as shown in Fig. 1.3. It achieves equivalent results to difference detection. The intensity of the light can be controlled with a modulator, such as an acousto-optic modulator or an electro-optic modulator. Using a feedback amplifier with appropriately chosen gain and phase lag the intensity noise can be reduced, all the technical noise can be eliminated [Rob86]. It is possible to get very close to the quantum noise limit, but the quantum noise itself cannot be suppressed [Mer93], [Tau95]. This phenomenon can be understood by considering the properties of photons. As mentioned before, the quantum noise measured by the two detectors is not correlated, thus the feedback control, when operating only on quantum noise on one detector, will not be able to control the noise in the beam that reaches the other detector. This can be explained using a full quantum theory. Alternatively, it can be interpreted as a consequence of the properties of the beamsplitter. It will randomly select the photons going to the control detector and consequently the control system has no information about the quantum fluctuations of the light leaving the experiment.

Only recently has the role of the photon generation process been explored further. It was found that the noise of the light may be below the standard quantum limit if the pumping process exhibits sub-Poissonian statistics. This is particularly easy to achieve for light sources driven directly by electric currents, namely light emitting diodes (LEDs) or semiconductor lasers. The currents driving these devices are classical, at the level of fluctuations we are

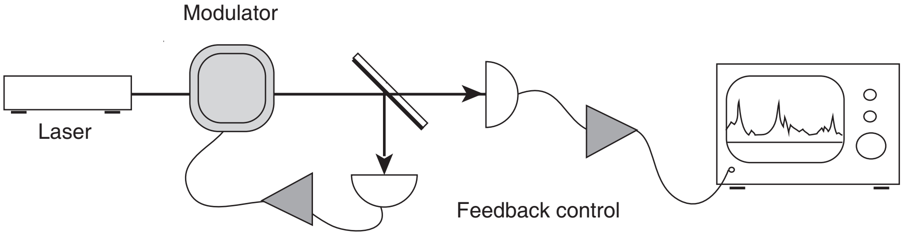

Figure 1.3: The second attempt to eliminate laser noise: An improved apparatus using a feedback controller, or 'noise eater'.

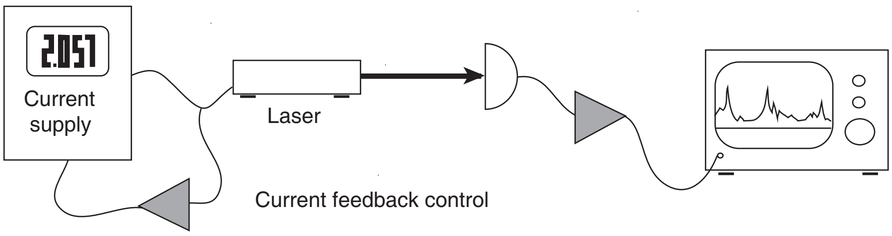

Figure 1.4: Feedback control of the current below the Poissonian limit. A laser with high quantum efficiency can convert the stabilised current into light with intensity noise suppressed below the quantum noise limit.

concerned with, and the fluctuations can be controlled with ease to levels well below the shot noise level. For sources with high quantum efficiencies the sub-Poissonian statistics of the drive current is transferred directly to the statistics of the light emitted. This is illustrated in the extension of our little experiment shown in Fig. 1.4. Such experiments were pioneered for the case of diode lasers by the group of Y. Yamamoto [Mac89]. They showed that intensity fluctuations can be suppressed in a high impedance semiconductor laser driven by a constant current and similar work was carried out with LEDs by several groups.

A two dimensional description of the light, with properties we will call *quadratures* will be necessary to explain this quantum effect. Noise can be characterized by the variance in both the amplitude and phase quadrature. This work shows one of the limits of the quantum models discussed above: they were restricted to one individual laser beam but should have included the entire apparatus. We will derive a simple formalism that allows us to predict the laser noise at any location within the instrument.

It took almost a decade after the observation of photon anti-bunching in atomic fluorescence to predict another quantum phenomenon of light – the suppression, or squeezing, of quantum fluctuations [Wal83]. For a coherent state the uncertainties in the quadratures are equal and minimise the product in Heisenberg's uncertainty principle. A consequence is that measurements of both the amplitude or the phase quadrature of the light show quantum noise. In a *squeezed state* the fluctuations in the quadratures are no longer identical. One quadrature may have reduced quantum fluctuations at the expense of increased fluctuations in the other quadrature. Such squeezed light could be used to beat the standard quantum limit. After the initial theoretical predictions, the race was on to find such a process. A number of nonlinear processes were tried simultaneously by several competing groups. The first observation of a squeezed state of light was achieved by the group of R.E. Slusher in 1985 in four-wave mixing in sodium atomic beam [Slu85]. This was soon followed by a demonstration of squeezing by four wave mixing in optical fibres by the group of M.D. Levenson and R. Shelby [She86] and in an optical parametric oscillator by the group of H.J. Kimble [Wu87]. In recent years a number of other nonlinear processes have been used to demonstrate the quantum noise suppression based on squeezing [Sp.Issues]. An generic layout is shown in Fig. 1.5. The experiments are now reliable and practical applications are feasible.

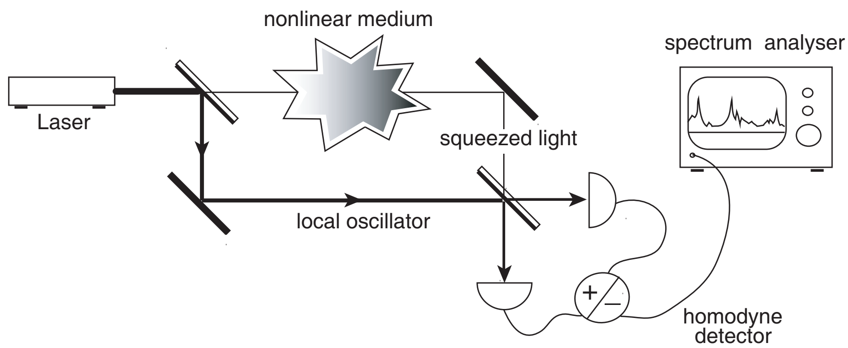

Figure 1.5: A typical squeezing experiment. The nonlinear medium generates the squeezed light which is detected by a homodyne detection scheme.

In the last few years the concept of *quantum information* has brought even more life to quantum optics. Plans for using the complexity of quantum states to code information, to transmit it without out losses, also known as teleportation, to use it for secure communication and cryptography, to store quantum information and possibly use it for complex logical processes and quantum computing have all been widely discussed. The concept of *entanglement* has emerged as one of the key qualities of quantum optics. As it will be shown in this guide, it is now possible to create entangled beams of light either from pairs of individual photons or from the combination of two squeezed beams and the demand and interest in non-classical states of light has sharply risen. We can see quantum optics playing a large role in future communication and computing technologies [Mil96, Mil98].

For this reason the guide covers both single photon and CW beam experiments parallel to each other. It provides a unified description and compares the achievements as well as tries to predict the future potential of these experiments.

1.3 How to use this guide

This guide leads through experiments in quantum optics, experiments which deal with light and which demonstrate, or use, the quantum nature of light. It shows the practicalities and challenges of these experiments and gives an interpretation of their results. One of the current difficulties in understanding the field of quantum optics is the diversity of the models used. On the one hand, the theory, and most of the publications in quantum optics, are based on a rigorous quantum model which is rather abstract. On the other hand, the teaching of physical optics and the experimental training in using devices such as modulators, detectors and spectrum analysers are based on classical wave ideas. This training is extremely useful, but frequently does not include the quantum processes. Actually, the language used by these two approaches can be very different and it is not always obvious how to relate a result from a theoretical model to a technical device designed and vice versa. As an example compare the schematical representation of a squeezing experiment, given in Fig. 1.6, both in terms of the theoretical treatments for photons and laser beams and in an experimental description. The purpose of this guide is to bridge the gap between theory and experiment. This is done by describing the different building blocks in separate chapters and combining them into complete experiments as described in recent literature.

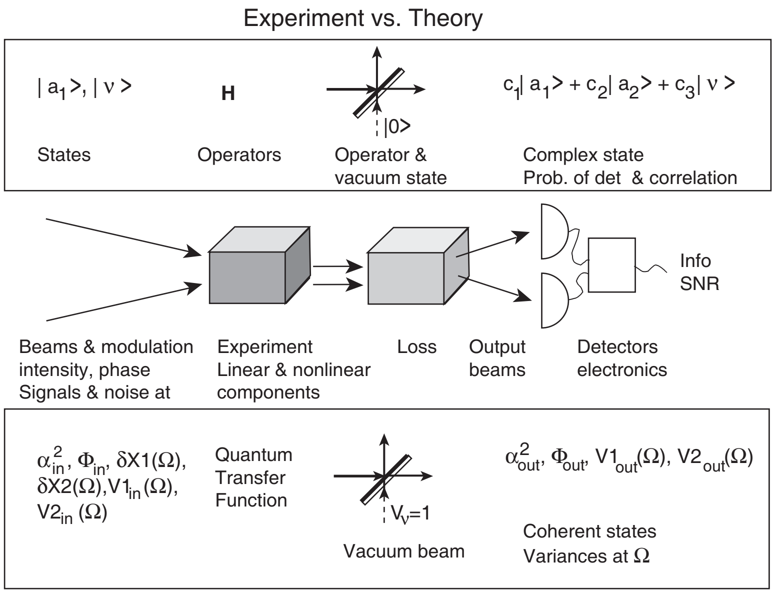

Figure 1.6: Comparison between an experiment (middle) and the theoretical description for few photon states (top) and laser beams (bottom)

We start with a classical model of light (Chapter 2). Experiments reveal that we require a concept of photons (Chapter 3), which is expanded into a quantum model of light (Chapter 4). The properties of optical components and devices (Chapter 5) and a detailed description of lasers (Chapter 6) are given. Next is a detailed discussion of photodetection for single photons and beams (Chapter 7). This is followed by a discussion of complete experiments. The technical details required for reliable experimentation with quantum noise, including techniques such as cavity locking and feedback controller, given in Chapter 8. The concept of squeezing is central to all attempts to improve optical devices beyond the standard quantum limit and is introduced and discussed in Chapter 9. It also describes the various squeezing experiments and their results are discussed, the different interpretations are compared. In a similar way Chapter 11 discusses quantum non-demolition experiments. Finally, the potential applications of squeezed light are described in Chapter 10. In Chapter 12 experiments which test the fundamental concepts of quantum mechanics are discussed. Finally, the concepts of quantum information and the present state of art of experiments using either single photon or CW beams are presented in Chapter 13.

This guide can be used in different ways. A reader who is primarily interested in learning about the ideas and concepts of quantum optics would best concentrate on Chapters 2, 3, 4, 9, 12, and 13 but may leave out many of the technical details. For these readers Chapter 5 would provide a useful exercise in applying the concepts introduced in Chapter 4. In contrast, a reader who wishes to find out the limitations of optical engineering or wants to learn about the intricacies of experimentation would concentrate more on Chapters 2, 6, 5, 8 and for an extension into experiments involving squeezed light Chapters 9, 10 can be added. A quick overview of the possibilities opened by quantum optics can be gained by reading Chapters 3, 4, 6, 9, 11, and 12. We hope that in this way our book provides a useful guide to the fascinating world of quantum optics.

This book is accompanied by a Web page
http://photonics.anu.edu.au/qoptics/people/bachor/book.html
which provides updates, exercises, links and, if required, errata.

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