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1 Introduction

1.1 Radiation pressure

Light has some truly amazing properties which has puzzled scientists for many centuries. Nothing can move faster than the speed of light and light can be considered both as a wave and a particle. As a particle, light has zero rest mass, while when reflecting off a surface it does exert a force. The concept of this force or radiation pressure, is already centuries old. In 1619 Keppler, based on observations by Brahe, suggested the existence of radiation pressure from observing the tail of a comet [1]. Keppler observed that a comet has two tails, of which one always points away from the sun. It took, however, more than 200 years for theory to catch up with observations. Maxwell's theory of electromagnetism [2] showed that electromagnetic waves carry momentum and can therefore exert a force. In 1901, Lebedev [3] and Nicholas and Hull [4] used a torsion balance to confirm Maxwell's theory, while carefully accounting for any thermal effects. This is perhaps the first optomechanical experiment.

Meanwhile, measurements of black body radiation let Planck to suggest in 1901 that the energy in electromagnetic waves might be released in packets of energy [5]. In 1905, Einstein supported this idea and named such package a "light quantum" [6]. The theory of quantum mechanics was soon developed afterwards.

1.2 Macroscopic superposition

To highlight the peculiar nature of quantum mechanics, Schrödinger proposed a thought experiment involving a cat whose fate was tied to the state of a radioactive atom [7]. Both the cat and the atom are placed together in a box. When the atom decays, a Geiger counter registers this decay upon which a deadly toxin is released and the cat dies. When the box is closed, we do not know the state of the atom and therefore also not the state of the cat. The cat is in a superposition between alive and dead. Such a superposition state is common in quantum mechanics, but certainly

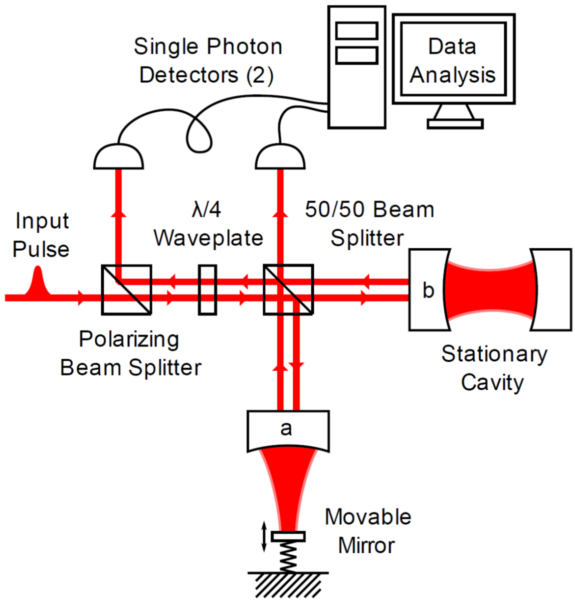

Figure 1.1: Schematic overview of the experiment proposed by Marshall et al.[8]. Figure is adapted from [9].

not in the everyday world. It is of course tempting, but not really ethical, to perform such an experiment with animals to find out where the border lies between quantum and classical. Fortunately several analogous experiments are possible to investigate the quantum to classical transition.

In 2003, Marshall et al. [8] proposed an optomechanical equivalent to this experiment. A schematic overview of the proposal is shown in Fig. 1.1. Ignoring for now the polarizing beam splitter and $\lambda/4$ waveplate, an input pulse consisting of a single photon is sent to a 50/50 beam splitter. After the 50/50 beam splitter, the photon ends up simultaneously in cavity A and cavity B. In cavity A, the photon will hit a movable mirror, which, due to the radiation pressure exerted by the photon, starts to move a little bit. Since beforehand the path of the photon is not known, the state of the movable mirror, namely standing still or moving a little, is also not known. Similar to Schrödinger's cat, the path the photon takes (the atom) is entangled with the state of the mirror (the cat).

This is where the analogy ends between the experiment proposed in Fig. 1.1 and Schrödinger's thought experiment. With the cat in the box, the only way to check if the cat is still alive is to open the box and look. No information about the state of the cat leaves the box as long as the box is closed. This is not true for the photon and the movable mirror, since the photon, which is simultaneously in cavity A and B, will leak out of the cavities back onto the 50/50 beam splitter. Depending on the state of the movable mirror, this photon is detected on either one of the single photon detectors. The precise details regarding the photon detection will not be discussed now, but the crucial part is that the experiment can be repeated many times to build up statistics on the state of the mirror as function of time. This will reveal in the end the lifetime of the superposition state.

The creation of such a macroscopic superposition state is in itself already interesting to explore, irrespectively of whether there are limits to quantum mechanics. The experiment, however, looks also beyond the known theories of quantum mechanics. Several ideas have been proposed, such as continuous spontaneous localization (CSL) and gravitationally induced decoherence [10, 11, 12, 13], suggesting that a superposition state involving a macroscopically sized object will be short lived. These theories can in principle be tested using the scheme depicted in Fig. 1.1.

1.3 Overview of this thesis

Although the scheme depicted in Fig. 1.1 is highly simplified, and more elaborate versions are already proposed [14, 15], an essential requirement for all proposals is the state of the movable mirror at the start of the experiment. In order for the interaction with a single photon to have maximal effect, the movable mirror should stand as still as possible. This is only achieved by cooling down the mirror to ultra low temperatures (below 10 microKelvin). In this thesis, a combination of optical and cryogenic cooling is investigated to reach these temperatures.

First in chapter 2 the necessary theory to describe an optical cavity with movable mirror (cavity A in Fig. 1.1) is presented. In chapter 2 also some of the experimental details are discussed, for example the movable mirror, which in this work is a trampoline resonator.

Chapters 3 and 4 deal with the dynamics of such an optomechanical cavity. In particular, the mechanical motion of the movable mirror can not only be cooled, but also driven, either using a single laser (chapter 3) or multiple lasers (chapter 4). In chapter 5 the core method of optical cooling is demonstrated. This method is also used in Chapter 6 to highlight how the polarization of light can play an important role in optomechanical systems in general.

In chapter 7 a full numerical simulation is presented to investigate how mechanical noise can influence our experiment. To isolate the movable mirror better from unwanted vibrations, a new type of trampoline resonator, the nested resonator, was designed. The first measurements using this new type of resonator are reported in chapter 8. In chapter 9, additional control for the nested trampoline resonator was implemented, improving the overall performance.

In chapter 10, all experimental techniques are combined, together with an improved vibration isolation system to perform optical cooling at cryogenic temperatures. Finally, chapter 11 presents initial measurements of a new method to create a macroscopic superposition state and discusses which optomechanical system is based suited to demonstrate this method in the quantum regime.