Investigations of radiation pressure : optical side-band cooling of a trampoline resonator and the effect of superconductivity on the Casimir force

Eerkens, H.J.

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Introduction

The interaction between electromagnetic radiation and an object results in a pressure exerted on its surface. This is known as radiation pressure. The interaction can be (a combination of) reflection, absorption or emission of the electromagnetic radiation. Under normal, everyday circumstances, this pressure is too small to be detected. But when the amount of radiation is increased, or when the reflective or absorbing object is sufficiently small or well isolated, radiation pressure can become significant.

It was Kepler who first put forward the notion of radiation pressure [1], observing that a comet's tail always points away from the sun. It was later put in the frame of electromagnetism by Maxwell [2]. The first experiments detecting radiation pressure were conducted by Lebedev [3] and Nichols and Hull [4] around 1900. It took many years until radiation pressure could be used to influence the Brownian motion of a mechanical resonator [5–7]. Since then, research in radiation pressure has increased enormously, with applications reaching as far as gravitational wave detectors [8].

In this thesis we will investigate two separate manifestations of radiation pressure. The interaction of electromagnetic radiation with a micromechanical resonator is studied in the field of optomechanics. The possibility to couple quantum mechanical photon states to the motion of a macroscopic mirror allows the experimental investigation of macroscopic quantum superpositions and novel decoherence mechanisms. In this thesis we will investigate the first steps necessary to achieve a macroscopic superposition, namely optical cooling of the mirror. Our results will be discussed in the first three chapters of this thesis.

The radiation pressure exerted by vacuum fluctuations is more generally known as the Casimir force. As it is based on electromagnetism, which is well understood, the occurrence of new physics can be excluded as long as measurements of the Casimir force overlap with theoretical calculations. This has inspired Casimir force measurements as tests in the search of new physics [9–11]. But the Casimir force also finds applications, mainly in the design of nano- and microelectromechanical systems (NEMS and MEMS). These systems operate in the regime where the Casimir force is significant and good understanding of the force may lead to new possibilities to tune their properties. We will measure the Casimir force between superconducting materials, in order to better understand its dependency on the reflectivity of the surfaces. The last five chapters of this thesis are dedicated to the Casimir effect.

1.1 Cavity optomechanics

Macroscopic quantum states could be created via entanglement of a microscopic quantum state with a macroscopic state. A famous example of a macroscopic superposition created in such a way is Schrödinger's cat [12]. This thought experiment posed the question where the boundary between the quantum and classical world could be found, if such a boundary indeed exists.

A more realistic method of creating entanglement between micro- and macroscopic states, that does not endanger cats, is via radiation pressure. When light is trapped inside an optical cavity, it exerts an enhanced pressure on the end mirrors. Coupling between the cavity light and the macroscopic mirror motion can be obtained if one of the end mirrors is free to move. When the coupling is strong enough, even a single photon can exert enough pressure to significantly influence the mirror motion. This enables the transfer of the quantum mechanical properties of the photon to the macroscopic mirror [13, 14] and the investigation of the mechanism behind the decoherence of the macroscopic quantum state.

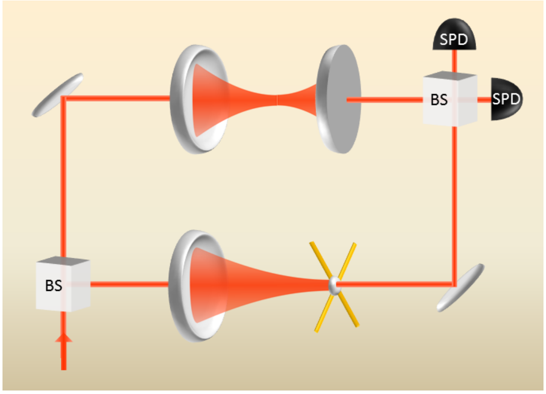

Figure 1.1: Artist impression of a set-up to create and investigate macroscopic superpositions. A single photon is brought into a superposition between two optical paths via a beam splitter (BS). In the lower path of the interferometer the photon interacts with a mechanical resonator that is represented by the yellow cross supporting a small mirror at its center. Note that this small mirror forms a cavity with a larger stable mirror to enhance the light-matter interaction. In the other arm a matching rigid cavity is inserted to make the two arms symmetric. If the radiation pressure exerted on the small mirror is strong enough, the photon can significantly displace the resonator. Entanglement between the photon and the resonator can be demonstrated by the interference signal at the single photon detectors (SPD).

The strong coupling of the macroscopic state to its environment generally causes a rapid decay, an effect known as environment-induced decoherence [15]. When this coupling is reduced significantly, novel decoherence mechanisms may occur [16], such as gravitationally induced decoherence [17, 18]. Several proposals investigate the possibilities to explore the foundations of quantum mechanics [19] and these novel decoherence mechanisms [20–24]. These proposals form the long-term motivation of our research and the basic idea of some of them can be described using Figure 1.1. A Mach Zehnder interferometer contains an optical cavity in each arm. The end mirror of one of these cavities is free to oscillate and can interact with a single photon that has entered the interferometer. Since this photon is in a superposition of being in either arm of the interferometer, the mirror is in a superposition of being moved by the photon and still being in the unperturbed state. This macroscopic superposition can be detected by looking at the interference signal of the single photon leaving the interferometer.

The distinguishability of the macroscopic superposition is largest when the mirror is cooled to its quantum mechanical ground state. The ground state of a harmonic oscillator is defined as its lowest energy state. Its motion is then equal to the zero-point fluctuations, with amplitude given by

$$x_{\mathrm{zpf}} = \sqrt{\frac{\hbar}{2m_{\mathrm{eff}}\Omega_m}}, \tag{1.1}$$

with $\hbar$ the reduced Planck constant, m_{eff} the effective mass of the oscillator and Ω_m its angular resonance frequency. A classical resonator is in a thermal state, which is described by the Boltzmann distribution of the harmonic oscillator eigenstates. We therefore define that a resonator is in the quantum ground state when its thermal motion is less than the zero-point fluctuations defined for its mode.

Note that only the motion of a single mode of the resonator is addressed. The difference between optical cooling and changing the temperature of the bath (e.g. by placing the set-up in a cryostat), is that the other modes remain at the background temperature. It is therefore not correct to say that the resonator is cooled to a certain temperature, we can only say that the mode has an effective temperature, linked to the motion via the equipartition theorem.

The research field investigating the interaction between light in an optical cavity and the motion of a (nano- or microscopic) resonator is known as cavity optomechanics [25]. Apart from optical cooling a mechanical resonator to the quantum regime [26–30], optomechanical systems were proven to be useful for many more purposes, such as electromagnetically induced transparency (EIT) [31–33] and coherent state transfer [34, 35].

Our optomechanical system consist of an optical cavity with one large, fixed mirror with diameter $1.25\,\mathrm{cm}$ and radius of curvature $5\,\mathrm{cm}$ and one tiny mirror (diameter $60 - 130\,\mu\mathrm{m}$) attached to four silicon nitride wires, which enable it to oscillate. The mechanical mode can be cooled optically, but also driven. Our results on cooling and driving will be discussed in chapters 2 and 3 respectively. These trampoline resonators operate at relative low frequencies of order 10^5 Hz, which makes them susceptible to external mechanical vibrations. We have therefore surrounded the trampoline resonator with another mass-spring resonator that serves as a low-pass filter. The performance of these so-called nested resonators is discussed in chapter 4.

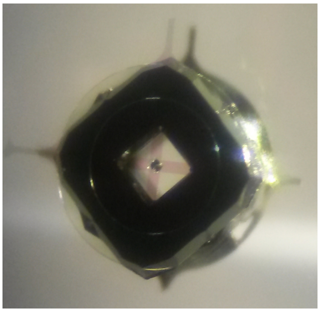

Figure 1.2: Photograph of a nested trampoline resonator that has been broken from its surrounding wafer. The small mirror is located in the center, suspended on four silicon nitride wires. The large silicon block forms the mass of the outer resonator, several of the silicon nitride arms connecting it to the wafer are still visible.

1.2 Casimir effect

Even when there is no light source available, radiation pressure can be exerted by the electromagnetic vacuum field. The vacuum is not empty, but filled with short-lived virtual particles. These particles can be of any type, depending on the vacuum field that they constitute. The electromagnetic vacuum field is made up of virtual photons, which can also be viewed as electromagnetic waves fluctuating around an expectation value of zero [36].

The vacuum state can also have an effect on macroscopic bodies. When two parallel plates are brought in each other's vicinity, the radiation pressure of the vacuum in between pushes them apart, while the vacuum outside the plates pushes them together. This is imaged in Figure 1.3 for the experimentally more accessible situation of a sphere near a plate. The surfaces set boundary conditions on the vacuum field, such that there are less modes possible between the plates than there are outside. This difference increases as the plates are brought closer together, since the density of states between the plates depends on their separation. Therefore the radiation pressure pushing the plates together is greater than the pressure exerted to keep them apart, which results in a attractive force between the plates, caused solely by the vacuum fluctuations and the boundary conditions of the plates. This effect was named after it's discoverer Hendrik Casimir [37]. Casimir was interested in the van der Waals interaction between particles and had already discovered, together with Polder, that the interaction between an atom and a plate at relative large distances is influenced by retardation effects caused by the finite speed of light. A different approach to the Casimir force is that it is caused by the van der Waals interaction between the atoms of the plates under the influence of retardation.

The Casimir force is best known as a result of the zero-point fluctuations of the electromagnetic field. But other quantized fields with a vacuum state, like the

Dirac field [36], can also give rise to a Casimir effect, as long as suitable mirrors exists for that field. According to some proposals, superconductors form mirrors for gravitational waves, such that two parallel superconducting plates may give rise to a Casimir force caused by quantum fluctuations in the gravitational field [38, 39]. Analogies of the Casimir force can also be found in the classical world, as the force between parallel plates in a liquid [40] or between beads on a string [41, 42].

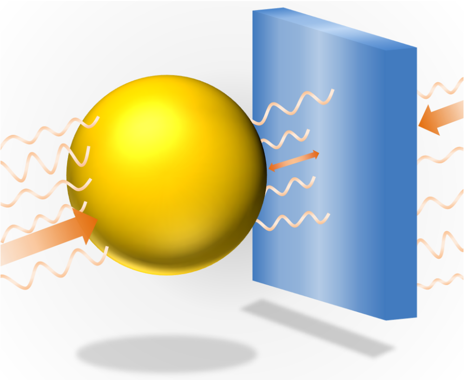

Figure 1.3: Artist impression of the Casimir force between a sphere and a plate. The electromagnetic waves of the vacuum exert radiation pressure on the surfaces. Since there are less waves between the sphere and plate, a result of their boundary conditions, the net pressure, as indicated by the arrows, is inwards.

The first experiments of the Casimir force were conducted soon after its discovery. Although they could not lead to a perfect comparison to theory due to a lack of optical data of the materials, they at least showed a qualitative agreement [43, 44] or even a good quantitative agreement [45, 46]. With the rise of nanotechnology, new methods for precision force measurements have become available, such that conclusive demonstration of the Casimir force became possible [47].

Casimir's calculation assumed that the plates were made of perfect conductors, which reflect all electromagnetic waves at all frequencies. The resulting force per area A for two plates at a distance d is given by

$$F_C = -\frac{\pi \hbar c A}{120 d^4}, \tag{1.2}$$

with $\hbar$ the reduced Planck constant and c the speed of light. Normal conductors, metals and dielectrics aren't perfect conductors, and their reflectivity is determined by the frequency dependent dielectric permittivity, which lowers the Casimir force compared to perfect conductors. Calculation of the force between real conductors is possible via the formulation developed by Lifshitz. But how exactly the dielectric permittivity affects the Casimir remains open to debate [48, 49]. The low frequency contribution needs to be extrapolated via models, but it is an open question whether to use to the Drude or the plasma model. The difference is that the Drude model accounts for dissipation in the material and the plasma model does not. Precision measurements of the Casimir force, both at room temperature and at low temperature [11, 50–54], so far have not given a satisfactory answer.

Since the dielectric permittivity is different in superconductors, comparison of the Casimir force between normal conductors and superconductors may give more insight in the exact influence of the dielectric permittivity [55]. In this thesis we investigate how the Casimir force between gold and niobium titanium nitride (NbTiN) changes as the NbTiN crosses the superconducting transition. Our set-up uses a microsphere (radius $100\,\mu$m) attached to an atomic force microscopy cantilever as a force sensor. A force gradient experienced by the cantilever changes its resonance frequency, which can be detected by a fiber-based interferometer. A photograph of the sphere, cantilever and fiber interferometer is shown in Figure 1.4. The plate is positioned underneath the sphere, on top of a translation stage used to set the distance.

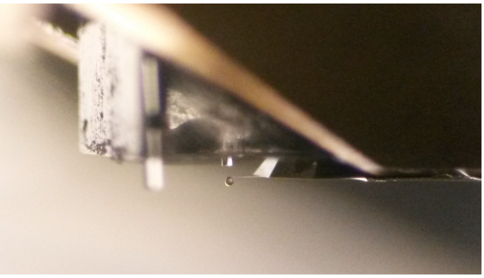

Figure 1.4: Photograph of the microsphere attached to a micromechanical cantilever. A single mode fiber is positioned above the cantilever for interferometric read-out of the cantilever motion. The plate (not shown in the image) is located below the sphere and can be positioned near it by a translation stage.

Measurements of the Casimir force are hindered by three technical aspects. The measurement apparatus needs to be calibrated, the actual distance between the surfaces has to be determined and compensation of the electrostatic force caused by the difference in work function of the materials is required. People therefore precede their force measurements by extensive calibrations. However, the system can drift between the calibrations and the measurements, causing discrepancies between the measured forces and calculations. Our set-up employs a real-time calibration scheme, based on modulation of the electrostatic force. Our Casimir force measurements now run simultaneously with our calibration, thereby practically eliminating the chance of discrepancies.

The second part of this thesis is dedicated to the Casimir effect. The theoretical background is described in chapter 5, chapter 6 gives details of some of the experimental techniques and the experimental set-up and method are explained in chapter 6. With this set-up we were able to measure the Casimir force between gold and a superconductor, the results will be discussed in chapter 8. The final chapter, chapter 9, contains some proposals to improve the force sensitivity.