Enabling quantum optomechanics for phononic crystals and superfluid helium films

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Chapter 1

Introduction

1.1 Towards macroscopic quantum superpositions

Quantum Mechanics has revolutionized technology and our understanding of the universe for the past 120 years. Some of the basic concepts, such as nonlocal correlations and the quantum measurement postulate that places probabilistic predictions at a fundamental level of the theory, are however not well understood. We have learned to accept them and work with them. For example, the field of quantum cryptography and quantum computation is completely based on the concepts of quantum superpositions and projection measurements. Concerning the quantum measurement postulate, also referred to as the collapse of the quantum wave function upon a measurement, there is a pragmatic theory that explains the loss of quantum features of a specific quantum system due to coupling to degrees of freedom in the environment that are beyond experimental control. The resulting predictions made about measurements outcomes for the specific quantum system become naturally probabilistic because information got lost to the environment. If this is all there is to say about the nature of quantum measurements, it means that quantum superpositions of macroscopic systems can exists but they are simply hard to make because of the extreme isolation that is needed [1, 2].

Alternative approaches to explain the measurement postulate are based on including new physics that causes a quantum wave function to reduce during its evolution. For example, nonlinear terms in the equation of motion of the wave function (e.g. light propagating inside a nonlinear crystal) can lead to self-localizing dynamics of the wave. This approach has led to the field of nonlinear Schrödinger equations. See references [3–5] for an overview of such nonlinear models and several other alternative approaches. One of those other approaches involves an interplay between quantum mechanics and general relativity. Currently those two fundamental pillars of our modern understanding of nature do apply in opposite regimes of the physical parameter space. In other words, our understanding of quantum field theory and the structure of atoms and molecules does ignore gravitational interactions, and general relativity calculations ignores the quantum structure of matter [6]. When we are in the "middle-ground", i.e., the arena of macroscopic quantum superpositions, we have to deal with both theories in a unified way. Such a unified theory has not been developed to date, and no clear predictions can be made. What can be done, as advocated by Prof. R. Penrose, is to estimate the "error" that is made by ignoring gravity when macroscopic quantum superpositions are being considered [7]. By placing a lump of matter in a superposition of two locations we are dealing with two distinct space time structures. A simple calculation based on the difference between the two resulting Newtonian gravitational forces fields ($f_i(\vec{x}) = -\nabla\Phi_i(\vec{x})$, with Φ_i the Newtonian gravitational potential for the particle centered on location $i = 1, 2$) squared (to obtain a positive number that quantifies the difference), and integrated over space, provides a measure of the "error". We can express this measure of error as an energy by dividing the force squared integral by the gravitational constant G. Calling this energy expression the self-energy of the macroscopic superposition, we obtain the following expression, first introduced by Roger Penrose [7]:

$$E_{self} = \frac{1}{4\pi G} \int \left(f_1(\vec{x}) - f_2(\vec{x})\right)^2 d\vec{x}. \tag{1.1}$$

If we now consider this "measure of error" in the form of a self-energy of the superposition as an uncertainty in energy needed to sustain the superposition $E_{self} = \Delta E$, we can use the uncertainty relation for energy and time, $\Delta E \Delta t \sim \hbar$, to estimate the time Δt during which the superposition is allowed to persist. The bottom line is that Penrose predicts that macroscopic quantum superpositions will only be allowed to exist for a certain period of time, even in pure isolation from the environment. In order to get an idea of the times scale of Δt we analyze the largest controlled macroscopic superposition that has been reported to date. This is a superposition of a Sodium nanocluster containing about 7000 atoms (total mass $M = 2.82 \times 10^{-22}$ kg) in an optical grating interferometer as pioneered by the research group of prof. Arndt [8]. When performing the calculation in Eq.(1.1) based on the experimental parameters in [8] we find $E_{self} = 3.99 \times 10^{-47} J$ and the time that such a superposition is allowed to persist is $\Delta t = 84,000$ years! This Δt is about 14 orders of magnitude larger than the time scale of each experimental run (about 10 ms)! Therefore current experiments are still very far away from reaching the macroscopic quantum superposition regime of interest for observing gravitational induced decoherence. It might well be that the only viable route for such experiments is to work in space where clusters of particles could be sustained in quantum superpositions for very long times.

The research group of Dirk Bouwmeester together with Roger Penrose worked out the details of an optomechanical experiments (possibly in space) that would be able to push superpositions to a macroscopic level, see Ref [9], with the ultimate goal of testing the prediction by Penrose that there is an intrinsic physical mechanism that causes the collapse of a quantum wave-function. Quantum states of a tiny mirror on top of a thin-film silicon nitride trampoline resonator have been pursued, and several interesting optomechanical experiments in the classical regime have been demonstrated with that system [10–13]. However, reaching the quantum regime with the mirror on a trampoline system remained very challenging because the combination of a Bragg mirror (approximately 30 micrometer in diameter and 62 alternating material layers) on top of a thin film trampoline caused energy dissipation at the edges of the mirror because there the bending of the thin film is concentrated. This prevented reaching sufficient isolation from the environment and motivated the shift to a membrane in the middle of an optical cavity configuration where the reflecting material is the thin film itself that makes up the mechanical resonator. Impressive progress has been on phononic crystal membrane optomechanical systems [14] and we adopted this technology to included such membranes in our cryogenic optical cavity system. The shift to the phononic crystal membrane structures marked the beginning of the research presented in **Part I: Membrane cavity optomechanics**. Crucial elements of the planned research on quantum dynamics of membrane optomechanics are close to unity detection efficiency and low dark count single photon detectors, and optical filter cavity systems.

After two years into the planned thesis research program an unfortunate event happened during building renovations. Cement dust entered our clean room research lab and dilution refrigeration system, degrading the optics, including the phononic crystal membrane and cryogenic optical cavity system. It was decided to shift the PhD research to an alternative optomechanical system, namely superfluid Helium on top of an optical ring resonator.

In **Part II: Superfluid optomechanics**, we investigate a closely related approach to the study of macroscopic quantum superpositions, acoustic excitations in superfluid Helium. Here we make use of the fact that superfluid Helium is a macroscopic quantum state in itself that has in principle zero viscosity. Similar to superpositions of currents in superconducting circuits, we can in principle consider superpositions of Helium flow. To interact with superfluid Helium in an efficient and well controlled manner, we decided to explore light-superfluid interactions via an optical ring resonator. This thesis reports some of the first results on this system and illustrates that very interesting nonlinear dynamics, from mode hoping of superfluid phonon lasing to chaotic superfluid dynamics, sets in. This in it's own right is of scientific interest, but at the same time guides us towards experiments in which we can explore quantum superposition states of superfluid Helium. Many of the experimental techniques developed for Part I, from laser locking schemes to millikelvin low-vibration technology, are crucial also for Part II, and new results on superfluid film non-linear dynamics were obtained. We now discuss the background of both parts in more detail.

1.2 Part I: Membrane cavity optomechanics

Optomechanics is based on the energy and/or momentum transfer between light and matter. Performing optomechnical interactions inside an optical cavity strongly enhances the coupling between light and matter. The exceptional control of light, down to the single photon level, makes cavity optomechanics an interesting platform to transfer quantum states of light to quantum states of mechanical motion, see Ref. [15] for a review.

The effect of light on the system depends on the underlying coupling mechanism, such as radiation pressure or photothermal coupling, and the resulting dynamical behavior varies accordingly. In regimes where the response remains close to linear, optical driving changes the effective mechanical damping and can produce cooling or amplification through the imbalance of anti-Stokes and Stokes scattering. Stokes (anti-stokes) scattering means that a photon scatters to a photon with a slightly lower (higher) frequency while creating (annihilating) a mechanical excitation (a phonon). Beyond this linear regime, the feedback induced by the optical field becomes intrinsically nonlinear and may drive the system into self-sustained oscillation, bifurcation, or more complex behavior, including chaos [16–18].

In the past two decades, rapid progress has been made on various cavity optomechanical platforms, demonstrating their relevance for quantum sensing, quantum transduction, and macroscopic quantum state engineering [15, 19]. A central goal of cavity optomechanics is to bring mechanical motion into the quantum regime. In thermal equilibrium, a mechanical resonator generally contains a large thermal phonon population that obscures quantum effects. Near ground-state cooling suppresses thermal excitations and drives the resonator towards a low mean phonon ($\bar{n}$) occupation. Reaching $\bar{n} < 1$ is an essential step towards creating quantum mechanical behavior of mechanical systems.

Ground-state cooling is typically realized using radiation-pressure sideband cooling in the resolved-sideband regime, where the optical cavity linewidth is smaller than the mechanical resonance frequency. Under a red-detuned optical drive, anti-Stokes scattering is enhanced while Stokes scattering is suppressed. In this process, cavity photons preferentially remove phonons from the mechanical resonator, leading to cooling of the mechanical mode. This technique has achieved near-ground-state cooling in a broad range of optomechanical platforms, including membranes, nanobeams, and microwave electromechanical devices [20–22].

An equally important challenge is the verification of reaching a near quantum ground state in a mechanical system. Near the quantum ground state, conventional displacement-spectrum thermometry becomes increasingly challenging as the thermal motion signal approaches the noise floor set by quantum backaction and photon shot noise. A widely adopted approach relies on motional sideband asymmetry. In the quantum regime, the rates of Stokes and anti-Stokes scattering become intrinsically asymmetric due to the quantization of mechanical motion. The anti-Stokes process requires an initial phonon, whereas the Stokes process remains finite even in the mechanical ground state because of quantum vacuum fluctuations. The sideband asymmetry, quantified by $\Gamma_{\mathrm{AS}}/\Gamma_{\mathrm{S}} = n/(n+1)$, provides a direct measure of the mean phonon occupation n [23, 24].

Most previous experiments have measured sideband asymmetry using homodyne or heterodyne detection of the scattered optical field [25]. These techniques provide continuous-variable measurements with high signal-to-noise ratio and have played a central role in demonstrating quantum backaction and near-ground-state cooling. In contrast, photon-counting approaches offer direct access to the discrete nature of optomechanical scattering events. In the photon-counting regime, each detected sideband photon corresponds to an individual scattering process involving the mechanical resonator.

In this work, we aim to investigate sideband thermometry in a membrane optomechanical system using superconducting single-photon detectors combined with a high-suppression optical filtering stage. The filtering system strongly suppresses the pump field while preserving weak motional sidebands generated by optomechanical scattering. This enables direct photon-counting detection of the sideband photons associated with mechanical motion near the quantum ground state. By resolving the asymmetry between Stokes and anti-Stokes scattering rates, we aim to establish a stringent verification of the mechanical phonon occupation in the low-temperature regime.

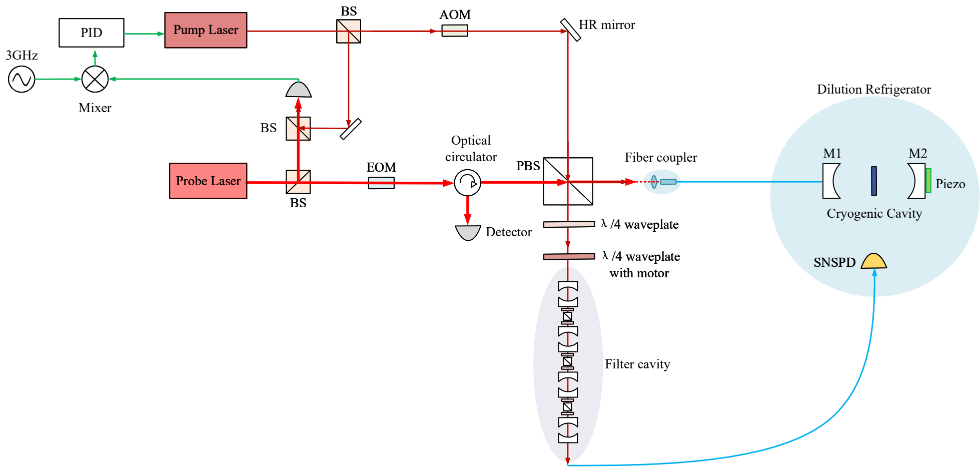

Figure 1.1: Schematic of the experimental setup for sideband thermometry. A pump beam and a probe beam are injected into the membrane-in-the-middle (MIM) optomechanical cavity located inside a dilution refrigerator. The frequencies of the two lasers are actively stabilized with respect to each other. The reflected cavity field is sent to a high-suppression filter-cavity system, which removes the strong carrier light and isolates the motional sidebands generated by the mechanical motion. The filtered signal is subsequently routed back to the dilution refrigerator and detected with a superconducting nanowire single-photon detector (SNSPD).

Figure 1.1 shows our experimental design for investigating quantum physics of a phononic crystal through cavity optomechanics. A phononic crystal membrane is placed in the middle of an optical cavity leading to the standard radiation-pressure interaction (see Sect.4.1). The experiments discussed in Part I of this thesis focus on the cooling regime, where red-detuned driving suppresses the membrane motion. More broadly, membrane cavity optomechanical platforms are of interest because they provide a path toward increasingly precise control of mechanical motion, with the long-term prospect of reaching regimes where quantum effects become dominant [26]. The present work is motivated not only by the observation of optical cooling as a dynamical phenomenon, but also by the goal of achieving control over mechanical motion at a level that enables preparation, manipulation, and measurement in the quantum regime. Important tools to achieve quantum state control are single photon detectors with ultra low dark counts and high quality filter cavity systems to extract individual photons from a background with photons that only slightly differ in frequency.

The initial plan for the thesis research was to study the quantum regime of phonons in a phononic crystal membrane in an optical cavity inside a vibration isolated dilution refrigerator connected to a dedicated optical clean room for the optical control of the system. This plan required several initial projects to be completed, including the installation, testing and optimization of customized superconducting single photon detectors, the design, fabrication, installation and testing of an exceptional filter cavity system, and the installation of an exceptional phononic crystal membrane (made at UCSB) inside an optical cavity inside a complex dilution refrigeration systems. Those three parts have been completed during the initial 2 years of the thesis research project resulting in chapters 2, 3 and 4 of the thesis.

Chapter 2 is devoted to superconducting single-photon detectors. Since efficient single-photon detection is essential for future experiments in the quantum regime, the chapter focuses on the installation and calibration of the commercial superconducting nanowire single-photon detectors. It describes the integration of the detectors into the cryogenic system, reports measurements of the dark count rate and system dark count rate, and presents the calibration of the detection efficiency, which reaches about 94%.

Chapter 3 develops the filter-cavity system required for photon counting in the cooling experiment. In these measurements, the scattered photons of interest are separated from the much stronger cooling light by only about 1 MHz in frequency, so very narrow low-frequency optical filtering is needed before they can be sent to the single-photon detector. This chapter therefore treats both the theoretical design of the filter cavity and the practical realization of the four-cavity system, including its construction and locking.

Chapter 4 turns to the membrane-in-the-middle optomechanical experiment. It introduces the basic theoretical picture relevant to radiation-pressure cooling, together with the cryogenic cavity platform used in the experiment. A central feature of this setup is its ability to maintain optical coupling efficiency at low temperature without adjustment during the cooldown of the dilution refrigerator. The chapter then presents clear experimental evidence of optomechanical cooling and discusses the corresponding measurements and their interpretation.

The next step would have been to combine all the components into a single system. But, as mentioned above, we had to make a transition to an alternative optomechanical system based on superfluid helium films.

1.3 Part II: Superfluid optomechanics

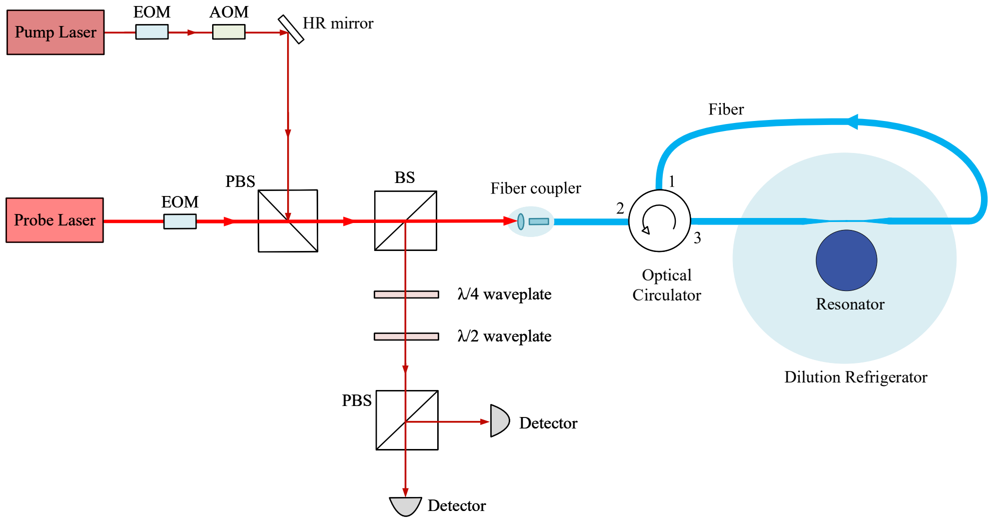

Figure 1.2: Schematic of the experimental setup. Two continuous-wave lasers are used: a pump laser to drive the cavity and a probe laser to monitor the cavity response. The pump beam passes through an EOM and an AOM, while the probe beam passes through a separate EOM. The two beams are combined and controlled by polarization optics, including PBSs and $\lambda/4$ and $\lambda/2$ waveplates, before being injected into the cryostat through a fiber coupler and an optical circulator. The returned signal is split and detected by photodetectors, allowing reconstruction of the in-phase and quadrature components.

Superfluid helium provides a unique platform for exploring collective quantum phenomena in macroscopic systems. Owing to its vanishing viscosity, long coherence length, and extremely low intrinsic dissipation, superfluid helium has played a central role in the study of quantum hydrodynamics and many-body physics for several decades [27–29]. In confined geometries, superfluid helium films support a rich spectrum of collective excitations including third sound modes, surface waves, and quantized vortices [30, 31]. The exceptionally low mechanical dissipation of these excitations makes superfluid helium in principle attractive for precision measurements and quantum optomechanical applications.

Superfluid helium films condensed on optical microresonators provide a natural interface between quantum fluids and cavity photons. The film thickness modifies the optical resonance frequency through the evanescent field of the cavity, while optical forces can drive and control collective hydrodynamic motion. This interaction enables sensitive optical access to third-sound excitations and other collective modes of the superfluid film, as has been pioneered by the Bowen group [32–37] and the Harris group [38–41]. These properties establish superfluid helium films as a promising platform for exploring nonlinear optomechanics [33, 42] and macroscopic quantum fluid dynamics [29, 35].

The second experimental setup in this thesis focuses on a superfluid helium thin film formed on the surface of an optical micro-ring resonator. The dynamics of this system are driven and read out optically, but the physical picture differs fundamentally from that of a conventional solid-state mechanical resonator. The relevant excitations are collective surface modes of the helium film, most notably third sound, corresponding to oscillations of the film thickness. Because the film is formed directly on the resonator surface, its motion couples naturally to the optical cavity mode: fluctuations of the film modify the cavity resonance frequency, while optical forces and photothermal effects influence the film dynamics. The system therefore realizes cavity optomechanics in a setting where the mechanical degree of freedom belongs to a confined quantum fluid rather than a suspended solid structure.

In addition, third-sound modes in thin helium films possess a pronounced intrinsic nonlinearity arising from the van der Waals interaction between the film and the substrate. This nonlinearity becomes increasingly important as the mode volume is reduced, providing access to dynamical regimes that differ qualitatively from those typically explored in more conventional solid-state optomechanical resonators. As a result, superfluid-film optomechanics offers a unique setting in which optical driving, strong nonlinear dynamics, and quantum-fluid behaviour can be studied within a single experimental platform.

Motivated by these considerations, the work presented in Part II investigates the dynamical response of the coupled superfluid–optical system under optical driving. We observe the onset of strongly nonlinear behaviour, including irregular temporal dynamics and broadband spectral features consistent with optically induced chaotic motion. These observations suggest a complex interplay between optical forces, thermal effects, and superfluid hydrodynamics, and reveal a rich landscape of nonequilibrium phenomena in superfluid-film optomechanical systems.

Chapter 5 develops the theoretical framework used for the superfluid helium part of the thesis. The chapter first introduces the two-fluid description of He II and the thermomechanical effects that follow from it, including the fountain effect. It then reviews first, second, and third sound in superfluid helium, with particular emphasis on third sound in thin films. The final part of the chapter turns to nonlinear dynamics and chaos in superfluid helium films, including the logistic map as a simple model of chaotic behaviour and a preliminary model for the nonlinear dynamics of third sound. This model captures part of the physical picture relevant to the experiment, although a fully quantitative description that reproduces the measured behaviour is not yet available.

Chapter 6 presents the superfluid helium experiment. It describes the experimental setup and the formation of the superfluid helium film on the ring resonator, and then characterizes the system through its optical transmission response together with the eigen-frequencies and eigen-modes of the helium film. The chapter also examines the nonlinear dynamics that emerge under optical driving, in particular the power-dependent frequency-switching behaviour and the onset of chaotic dynamics. The chapter also includes a qualitative discussion of the thermal-photon mechanism as a possible contribution to the observed frequency switching and chaotic dynamics.

While the fundamental properties of superfluid helium have been studied extensively for many decades, its integration with cavity-optomechanical platforms has only recently been started. As a result, many aspects of superfluid-film optomechanics remain largely unexplored. The nonlinear and potentially chaotic dynamics observed in this work suggest that this emerging field offers a rich range of opportunities extending from nonequilibrium dynamics and nonlinear physics to quantum-limited measurements and future studies in the quantum regime.

More broadly, superfluid-film optomechanics brings together two areas of physics that have largely developed independently: the study of quantum fluids and the tools of modern cavity optomechanics. Although still at an early stage of development, this combination provides access to phenomena that are difficult to realize in either field alone. The experiments presented in this thesis represent steps toward exploring this intersection, where many open questions remain and where future advances may enable the study of increasingly complex nonlinear dynamics, quantum control of fluid excitations, and new forms of macroscopic quantum behaviour.