Probing quantum puddles: nonlinear dynamics in superfluid film optomechanics

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Chapter 1

Introduction

Quantum mechanics has been one of the most successful theories of the 20th century, describing physics on the microscopic level to an astonishing accuracy [1]. While there are major differences between the predictions of quantum mechanics and macroscopic classical physics [2], large ensembles of electrons in a superconductor or ultracold atom clouds in Bose-Einstein condensates (BECs) have been found to be governed by the laws of quantum mechanics [3, 4]. Naturally, this leads to the question of the boundary of quantum mechanics and how the seemingly incompatible theories of microscopic quantum mechanics and macroscopic classical physics could be unified. In the past decade, there has been a surge of experiments and proposals to answer this question [5–8].

A suitable experimental system to address this research question should consist of a large number of particles that collectively occupy the same quantum state. One approach is to use the superfluid phase of helium, in which a macroscopic number of helium atoms can be described by one macroscopic wavefunction when helium is cooled below its so-called λ-Point of 1 to 2 Kelvin depending on the pressure [9]. In this phase Helium exhibits the macroscopic quantum phenomenon of zero viscosity, called superfluidity among many other exotic phenomena. In contrast to most ultracold atom BECs, there is a significant interaction between the individual helium atoms in the superfluid state, making for different dynamics and phenomena than in a weakly interacting system [10–13]. Superfluid Helium (especially the fermionic isotope Helium-3) could therefore also serve as a simulation platform for other systems with significant inter-particle interactions, such as the cores of neutron stars or development of the early universe [14–18]. Additionally, difficult modeling due to the strong internal interactions precluding the use of a mean-field approximation, make experimental simulations of the complex systems mentioned above even more attractive [19].

To probe and control these macroscopic quantum states, high precision technology with significant interaction strength is needed. Cavity optomechanics combines high-precision laser sensing with cavity enhanced interaction, making it a natural choice for a platform for macroscopic quantum experiments [2, 20, 21]. In fact, cavity optomechanical systems with effective masses of up to grams have been prepared in the motional ground state and superposition states [7, 22]. However, relatively small displacements have prevented these experiments from measuring a direct impact of gravity on the quantum state thus far.

1.1 Superfluid optomechanics

Although superfluid helium has a low susceptibility, combining it with cavity enhancement still allows for significant interaction strengths. In 2014 De Lorenzo and Schwab conducted a landmark experiment studying the interaction of bulk superfluid helium and electromagnetic waves in a microwave cavity [23]. This work was extended upon by Shkarin et al. by measuring quantum fluctuations of bulk superfluid Helium in an optical fiber cavity [24]. Instead of studying bulk superfluid Harris et al. condensed a thin film of superfluid Helium on optical ring resonators and achieved very high optomechanical coupling rates as well as demonstrating laser cooling of specific superfluid modes [25]. This work was later expanded upon by the same research group demonstrating Brioullin lasing [26] as well as laying the theoretical groundwork towards understanding of the interaction between thin films of superfluid helium, electromagnetic fields and photothermal driving [27–29].

1.2 Outline of this thesis

In chapter 2 we give a brief introduction to essential parts of the experiments presented in this thesis: the superfluid phase of helium, our optical experimental platform of ring resonators and evanescent coupling as a way to couple light into these optical systems, the field of cavity optomechanics and our dilution fridge.

In chapter 3 the two-fluid model of superfluid helium 4 and the resulting third sound in thin films of superfluid Helium is introduced. We present how the superfluid motion can be driven by radiation pressure and photothermal forces and compare these two forces. The mechanical lasing threshold due to photothermal driving is derived and we find a set of coupled differential equations that govern the dynamics of our system.

Chapter 4 introduces the experimental setup we use for superfluid cavity optomechanics experiments. We explain our in-house tapered fiber production and show calibrations at room temperature. We then detail our approach to keeping optical alignment during a cooldown and show critical coupling at 20 mK to a 6 mm wedge resonator.

In chapter 5 we present our results for the interaction of superfluid Helium with the optical field of the ring resonator, starting with a typical change in optical resonance frequency at the superfluid transition temperature and parametric oscillations when scanning over the optical resonance. We present third sound measurements to accurately determine the thickness of the superfluid film as well as network analysis measurements to determine the frequencies of the mechanical modes. We then report on mechanical lasing for 3 different film thicknesses and for different temperatures.

In chapter 6 we investigate mechanical multi-mode effects leading to mode-hopping and mode-locking of up to 17 mechanical modes. We present our observations for the systems evolution towards the mode-locked state and extract the shape of the resulting superfluid pulse. The underlying mode-locking mechanism is found to be caused by direct mode coupling due to the nonlinear restoring van der Waals force, which is supported by simulation results.

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