Enabling quantum optomechanics for phononic crystals and superfluid helium films

Wei, X.

Summary

The quantum measurement postulate is essential for quantum information science, for example enabling quantum cryptography and quantum error correction. In order to experimentally investigate the concept of a quantum measurement, which constitutes a transition from the quantum world to the classical world, we aim to investigate superpositions of macroscopic objects.

In particular, in this thesis we present two cavity optomechanical experiments in which light is used to measure and control motion of macroscopic mechanical systems. The first experiment couples a silicon nitride membrane to a Fabry–Pérot cavity and aims to bring a solid mechanical resonator towards the quantum regime. The second experiment couples an optical ring resonator to a thin film of superfluid helium and explores nonlinear collective dynamics. In both systems, mechanical motion shifts the resonance frequency of an optical cavity, while the intracavity field acts back on the mechanical degree of freedom.

Part I of the thesis describes the development of a cryogenic membrane-in-the-middle experiment. The aim was to cool a silicon nitride membrane close to its mechanical ground state and to verify its phonon occupation through the detection of individual Stokes and anti-Stokes scattering events. This required three key components: resolved-sideband cooling of the membrane, strong optical filtering of the driving field, and single-photon detection with high efficiency and low background noise.

After a general introduction in Chapter 1, Chapter 2 describes the installation and characterization of the single-photon detection system. Four tungsten silicide superconducting nanowire single-photon detectors were installed on the 1 K plate of the dilution refrigerator. Optical and electrical shielding reduced background counts and interference, and the highest measured system detection efficiency was approximately 94% at 1064 nm. These results showed that the detectors were suitable for measuring

the weak fields generated by optomechanical scattering.

Chapter 3 presents the optical filtering system developed to isolate the motional sidebands from the driving laser. Four Fabry–Pérot cavities were connected in sequence and stabilized using a reflection-based locking scheme. The complete system achieved a total optical transmission of approximately 40%, together with a calculated pump suppression of approximately 140 dB at a frequency offset of 1 MHz. The filter cavities and SNSPDs therefore provided the main infrastructure required for photon counting of the Stokes and anti-Stokes sidebands.

Chapter 4 describes the cryogenic membrane-in-the-middle experiment itself. A high-stress silicon nitride membrane with a phononic bandgap structure was placed inside a Fabry–Pérot cavity and cooled to 90 mK in a dilution refrigerator. The phononic structure confines the mechanical mode and reduces its coupling to the supporting frame, thereby suppressing mechanical dissipation. The cavity assembly was mounted on the mixing chamber and mechanically isolated from pulse-tube vibrations, providing stable optical access to a mechanical mode near 1 MHz.

The membrane displacement modulates the cavity resonance and generates motional sidebands around the driving laser. In the resolved-sideband regime, red-detuned driving enhances anti-Stokes scattering and cools the mechanical mode, while blue-detuned driving enhances Stokes scattering and amplifies the motion. Heterodyne measurements showed the expected cooling and heating behaviour as the laser detuning and optical power were varied. At the highest useful cooling power, the calibrated mechanical spectrum corresponded to a mean phonon occupation of approximately $\bar{n}_{\mathrm{m}} \approx 10$.

The final step was to combine the cooled membrane, the filter cavities, and the SNSPDs in a measurement of the Stokes and anti-Stokes photon rates. This would have provided an independent determination of the mechanical occupation and a direct test of the membrane's approach to the quantum regime. However, dust contamination associated with renovation work in a neighboring laboratory compromised the membrane sample and the cryogenic optical cavity. The individual components were therefore demonstrated separately, while the planned single-photon sideband measurement remains a natural next step.

Part II of the thesis studies a thin superfluid helium film on an optical ring resonator with a diameter of about 6 mm. Thickness oscillations of the film form third-sound modes, whose restoring force is mainly set by the helium–substrate interaction. Because the optical evanescent field overlaps with the film, these thickness changes shift the optical resonance and allow the collective motion of the film to be read out optically.

In contrast to the membrane experiment, the superfluid film was driven mainly through a photothermal response to intracavity optical power. This heating changes the thermodynamic equilibrium of the film and drives superfluid flow, redistributing the film thickness. The resulting thickness change shifts the cavity resonance, which modifies the intracavity power and hence the heating distribution. This feedback between optical power, temperature, film thickness, and detuning provides a natural route to nonlinear dynamics.

At low optical power, measurements at different film thicknesses revealed well-defined collective modes. As the power was increased, the dominant oscillation frequency decreased and then switched to a lower-frequency state. At stronger driving, subharmonic responses near half the original frequency appeared, indicating the onset of period-doubling behaviour. At still higher powers, the film entered a chaotic state with persistent irregular motion lasting several minutes. The experiment therefore demonstrates a progression from regular third-sound oscillations to frequency switching, period doubling, and chaos in an optically driven superfluid film.

The measurements do not identify a single mechanism for each transition. The observed dynamics likely arise from coupled optical, thermal, and hydrodynamic effects: optical heating modifies the film thickness, superfluid flow redistributes the film, delayed thermal relaxation provides feedback, and coupling between third-sound modes may introduce additional degrees of freedom. Large-amplitude thickness oscillations may also contribute through the intrinsic thickness dependence of the third-sound frequency.

For the membrane experiment, the next step is to repeat the cooling measurement with a clean membrane and combine it with the demonstrated filtering and photon-counting systems. Measuring Stokes and anti-Stokes scattering rates would independently calibrate the mechanical occupation and test single-phonon sensitivity. In this way, a well defined low phonon state can be prepared, which then can be manipulated to a macroscopic superposition state.

For the superfluid experiment, the measurements reveal rich nonlinear dynamics, including frequency switching, period doubling, and chaos. Future work could extend these observations into a more complete dynamical map, using finer control of optical power, detuning, temperature, and film thickness to separate the roles of optical heating, delayed thermal feedback, superfluid flow, and mode coupling. Together with quantitative modelling, this would connect the observed nonlinear dynamics to the broader potential of optically controlled superfluid helium films as a platform for studying macroscopic quantum-fluid phenomena, from third-sound excitations and vortex dynamics to precision optomechanical sensing.