Probing quantum puddles: nonlinear dynamics in superfluid film optomechanics

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Summary

Helium is a fascinating element with unique properties. In our daily life we mainly encounter it as a gas to fill balloons or to make funny voices. Helium gas also plays an essential part in the manufacturing of computer chips. However, for physicists some of the most exciting phenomena occur when we cool the helium gas down to extremely low temperatures. Helium becomes liquid as the last element, only at about -269 °C or 4 °C above absolute zero, the temperature at which there is no more microscopic movement. Instead of forming ice or becoming a solid when you cool it down further helium enters a new liquid phase, called superfluid helium, where it flows without viscosity and towards heat sources. Helium never becomes solid because the balance of microscopic forces that attract and repel atoms is slightly different than for other elements.

Physicist use the properties of helium to cool experiments to extremely low temperatures that remain just a fraction of a degree above absolute zero. But if our control over superfluid helium is improved we could use it to simulate and better understand neutron stars and even parts of the development of the early universe.

One of the most precise tools of control that physicists have is laser light. Individual light particles carry a tiny amount of energy. When they reflect from a surface they can deposit or withdraw some energy from the material, but often times photons pass through the material without interacting. To increase the likelihood of interaction physicists trap the photons between two mirrors, called an optical cavity, and insert the material that we are interested in between the mirrors. In this way, the photons bounce back and forth between the mirrors and are more likely to interact with the material. The inserted material is often shaped like a trampolin or drumhead, such that the motion follows one or multiple periodic motions, called mechanical

modes. The periodicity of the motion is then imprinted on the photons inside the the optical cavity. The study of such an experimental setup is called cavity optomechanics.

Just like trapping photons between two mirrors, we can trap photons in a ring by letting them repeatedly bounce off of the outside of the ring. Instead of many mirrors, we can make the ring out of one material and use the principle of total internal reflection to make an optical ring resonator.

In this thesis, we have cooled an optical ring resonator to a fraction of a degree above absolute zero and condensed a very thin film of superfluid helium on top of it. With this setup we are able to measure the height of the superfluid film with an accuracy of the size of an atom. The superfluid film can move similar to trampoline or drumhead and supports different mechanical modes. Using a tiny fraction of the power produced by a light bulb, we investigated what happens when we drive the motion of the superfluid helium to large amplitudes. We observed a sudden jump in the amplitude of a superfluid mechanical mode, the mechanical lasing regime, and investigated the impact of the temperature and the thickness of this film on the mechanical lasing. Finally, we controlled the motion of multiple mechanical modes supported by the superfluid films, such that they together form separated pulses. This is called mode-locked lasing and is only possible through the direct interaction of the mechanical modes.

We have presented an exciting way to control the motion of superfluid helium by using light and have demonstrated the repeatability of our approach. This makes it possible to explore many different shapes and sizes of optical resonators and their interaction with superfluid helium. For example, we are developing better ways to confine the movement of superfluid helium to a certain area.