Quantum optomechanics for investigating the collapse of the quantum wave function

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Understanding the apparent collapse of the quantum wave function upon a measurement is still a challenge for modern science. Of course, environment induced decoherence is an important aspect of this problem, but leads to the notion of a multi-universe. Scientists, including Roger Penrose, have argued that the notion of a single universe is restored if there is an additional physical mechanism, possibly including gravity, that underlies the collapse process. This leads to experimentally testable predictions for large mass systems, and we proposed such an experiment many years ago [1].

We will present the experimental progress towards testing the collapse of macroscopic quantum superpositions. We make use of optomechanical systems in order to transfer photon superposition states into macroscopic mechanical superposition states. In multimode optomechanical systems, the mechanical modes can be coupled via the radiation pressure of the common optical mode, but the fidelity of the state transfer is limited by the optical cavity decay. We demonstrate stimulated Raman adiabatic passage (STIRAP) in optomechanics, where the optical mode is not populated during the coherent state transfer between the mechanical modes, thus avoiding this decay channel [2]. We show a state transfer of a coherent mechanical excitation between vibrational modes of a membrane in a high-finesse optical cavity with a transfer efficiency of 86%. Combined with high mechanical quality factors, STIRAP between mechanical modes can enable generation, storage, and manipulation of long-lived mechanical quantum states, which is important for quantum information science and for the investigation of macroscopic quantum superpositions. A crucial aspect of exploring the quantum regime in optomechanics is the ability to detect individual photons that have been up or down converted in frequency from the optical pump frequency by the absorption or emission of a phonon. This requires a narrow bandwidth optical frequency filter that passes the up or down converted photons while suppressing the pump beam well below the detection-rate of the converted photons. We demonstrate a four coupled cavity filter system that can filter out, with 40% overall detection efficiency, individual photons up or down converted by 1 MHz via optomechanics from a pump source.

[1] W. Marshall, C. Simon, R. Penrose, and D. Bouwmeester Phys. Rev. Lett. 91 (2003) 130401.

[2] V. Fedoseev, F. Luna, I. Hedgepeth, W. Löffler, and D. Bouwmeester Phys. Rev. Lett. 126 (2021) 113601