Levitated Cavity Optomechanics

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The ability to trap and to manipulate individual atoms is one of the central elements of modern day quantum optics. Controlling the motion of larger particles opens up new avenues for quantum science, both for the study of fundamental quantum phenomena in the context of matter wave interference, and for unique sensing and transduction applications in the context of quantum optomechanics. Specifically, it has been suggested that cavity cooling of a single submicron particle in high vacuum allows for the generation of quantum states of motion in a room-temperature environment [1–3], for unprecedented force sensitivity [4], and also for novel studies in non-equilibrium statistical physics [5, 6].

Research with levitated nanoparticles requires the development of new experiments. However, this development benefits strongly from the concepts, methods and technologies encountered in quantum optics experiments with atoms and the more recently developed field of cavity-optomechanics. I will sketch basic concepts used in cavity-optomechanics in general and discuss specific aspects that are unique to optical leviation. I will also use this opportunity to present recent experiments on optimal state estimation in a clamped cryogenic optomechanical system [7] and pulsed precision measurements in a photonic crystal structure performed in the Aspelmeyer labs in Vienna.

Then, we briefly review the current experimental developments in the optical control of levitated dielectrics with diameters on the order of 100 nm. For example, mechanical quality factors of $Q \approx 10^8$ have already been achieved with optically trapped nanoparticles [8], competing with the best mechanical quality factors achieved in clamped optomechanical systems. Also, cavity cooling of levitated nanoparticles has successfully been demonstrated [9, 10]. However, at this point no experiment could yet catch up with more conventional devices used in cavity optomechanics or reach the point where ground state cooling and the implementation of quantum protocols is possible. The important figure of merit in this context is the optomechanical cooperativity $C = \frac{g^2}{\kappa\Gamma}$ [11]. We discuss requirements and trade-offs to achieve $C > 1$ in an experiment.

Finally, I will present details and results on our experimental approach towards achieving this goal. It currently consists mainly of two experiments:

First, clean transport and optical control of submicron particles in hollow-core photonic crystal fibers (HCPCF). Here, an optical conveyor belt enables transport of optically trapped particles between two vacuum chambers. This will be used to separate a wet source of particles for loading the optical trap from the ultra-high vacuum environment envisioned for a science chamber, where the actual cavity-optomechanics experiment will be performed. Further, we demonstrate passive cooling of a 170 nm particle optically trapped in a Fabry-Perot cavity (see Fig.1). We show how this setup can be extended to allow 3-dimensional position readout and cooling of the nanoparticles center-of-mass motion using higher order cavity modes.

Combining these approaches should allow continuous trapping of a single submicron particle in ultra-high vacuum and operation in the quantum regime.

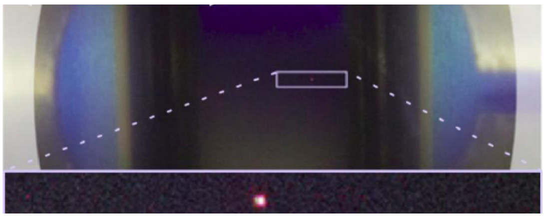

FIG. 1. Photograph of a submicron particle trapped in the intracavity field of a near-confocal, 11 mm long Fabry-Perot cavity with a finesse of 78000 [9].

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