Antenna-Coupled Light-Matter Interactions

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1. Program Scope

This project is focused on antenna-coupled photon emission from single quantum emitters. The properties of optical antennas are tailored to control different photophysical parameters, such as the excited state lifetime, the saturation intensity, and the quantum yield [3]. Using a single molecule coupled to an optical antenna whose position and properties can be controllably adjusted we established a detailed and quantitative understanding of light-matter interactions in nanoscale environments.

We have studied various quantum emitters: single molecules [11], quantum dots [7], rare-earth ions [2], and NV centers in diamond [19]. We have systematically studied the interaction of these emitters with optical antennas. The overall objective was to establish a high-level of control over the light-matter interaction. In order to eliminate the coupling to the environment, we have taken a step further and explored the possibility of levitating the quantum emitter in high vacuum. What started as a side-project soon became a main activity in our research program and led us to the demonstration of vacuum trapping and cooling of a nanoscale particle [14].

2. Recent Progress

The importance of trapping and cooling techniques is evidenced by the series of Nobel Prizes awarded to this theme (1989 ion trapping, 1997 atomic trapping, 2001 Bose-Einstein condensation, 2012 trapping of photons and ions). The trapping and cooling of *mesoscopic* objects, such as nanoparticles, is a new territory and lies at the boundary of classical and quantum physics. In this project we control the dynamics of a nanoscale object with high precision and study interactions on the mesoscopic length scale, - the grey zone between the discrete atomistic world and the continuous world of macroscopic systems.

As shown in Figure 1, we capture a dielectric nanoparticle by the gradient force of a focused laser beam in ultrahigh vacuum and control its center-of-mass motion by optical back-action. The classical equation of motion of the particle's x coordinate can be written as

$$\ddot{x}(t) \,+\, [\Gamma_0 + \delta\Gamma]\,\dot{x}(t) \,+\, [\Omega_0 + \delta\Omega]^2\,x(t) \;=\; F_{\rm fluct}(t)\,/\,m\;, \tag{1}$$

where $F_{\rm fluct}$ is a random Langevin force that satisfies $\langle F_{\rm fluct}(t)\,F_{\rm fluct}(t')\rangle = 2m\Gamma_0\,k_BT\,\delta(t-t')$. Γ_0 and Ω_0 are the particle's natural damping constant and oscillation frequency, respectively. Optical back-action gives rise to a modification of Γ_0 and Ω_0, which is accounted for by the terms $\delta\Gamma$ and $\delta\Omega$. The nature of the back-action force is in principle not relevant: it can be a force due to radiation pressure, a thermal force, or an optical force due to the modulation of laser power.

The heating of the center-of-mass motion is due to the random impact of air molecules inside the vacuum chamber, that is $\Gamma_0 \propto P_{\rm gas}$, where $P_{\rm gas}$ is the gas pressure. For ambient pressure we measure $\Gamma_0 \approx 3\,$MHz, which implies that in ultrahigh vacuum ($P_{\rm gas} = 10^{-9}$ mbar) the damping

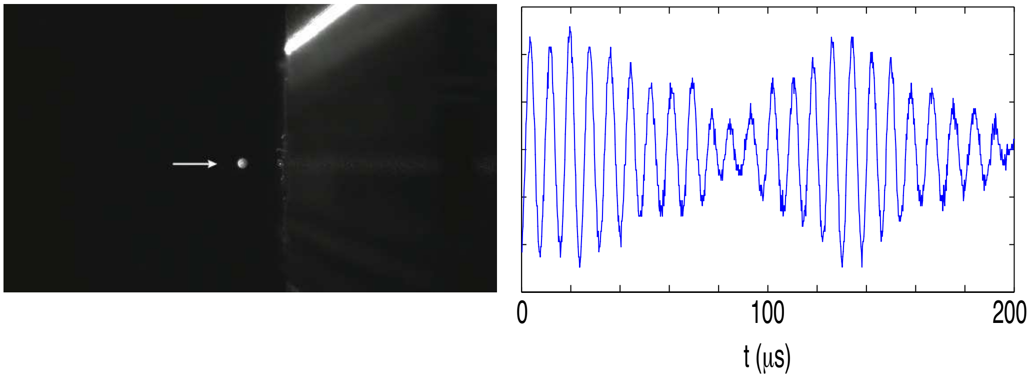

Figure 1: (a) Photograph of light scattered from a trapped silica nanoparticle (arrow). The object to the right is the outline of the objective that focuses the trapping laser. (b) Time trace of the particle's x coordinate (transverse to the optical axis) at 2 mBar pressure.

constant becomes $\Gamma_0 \approx 3\,\mu$Hz. This corresponds to a quality factor of $Q = 10^{11}$!

To increase $\delta\Gamma$ in Eq. (1) and hence to slow down the center-of-mass motion we employ parametric feedback cooling (see Fig. 2). The feedback hinders the particle's motion by increasing the trap stiffness whenever the particle moves away from the trap center and reducing it when the particle falls back toward the trap. In the frequency domain, this corresponds to a modulation at twice the trap frequency with an appropriate phase shift. Frequency doubling and phase shifting is done independently for each of the photodetector signals x, y and z. Since the three directions are spectrally separated, there is no cross-coupling between the three signals, that is, modulating one of the signals does not affect the other signals. Therefore, it is possible to sum up all three feedback signals and use the result to drive a single Pockels cell that modulates the power of the trapping laser. Thus, using a single beam we are able to effectively cool all spatial degrees of freedom.

According to the equipartition principle, the center-of-mass temperature $T_{\rm cm}$ follows from

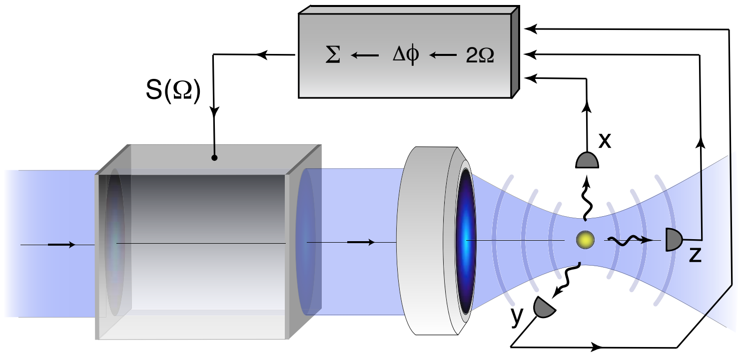

Figure 2: Principle of parametric feedback cooling. The center-of-mass motion of a laser-trapped nanoparticle in high vacuum is measured interferometrically with three detectors, labeled x, y, and z. Each detector signal is frequency doubled and phase shifted. The sum of these signals is used to modulate the intensity of the trapping beam.

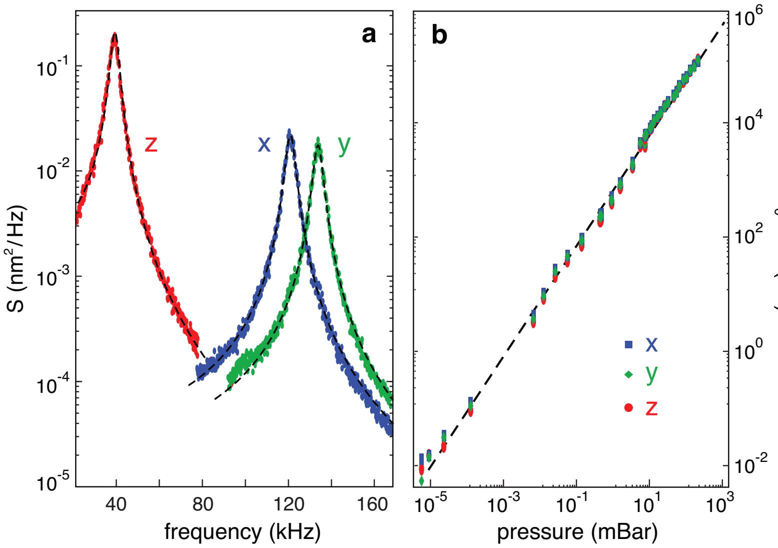

Figure 3: (a) Spectral densities of x, y and z at $P_{\rm gas} = 6.3\,$mbar. Because of the spectral separation of the individual resonances one can implement three independent feedback loops to cool all three degrees of freedom. (b) Measured linewidths as a function of pressure.

$k_{\rm B}\,T_{\rm cm} = m(\Omega_0{+}\delta\Omega)^2\langle x^2\rangle$. Considering that $\delta\Omega \ll \Omega_0$ we obtain

$$T_{\rm cm} \;=\; T\,\frac{\Gamma_0}{\Gamma_0+\delta\Gamma}\;, \tag{2}$$

where T is the equilibrium temperature in the absence of the parametric feedback ($\delta\Gamma = 0$). Thus, the temperature of the oscillator can be raised or lowered, depending on the sign of $\delta\Gamma$ in Eq. (2). With parametric feedback cooling we reach temperatures of a few milliKelvin.

A laser-trapped nanoparticle is physically decoupled from its environment, which guarantees extremely long coherence times and quality factors as high as 10^{11} at a pressure of 10^{-9} mbar. Force sensitivities of $10^{-20}\,{\rm N}/\sqrt{\rm Hz}$ can be achieved, which outperforms many other measurement techniques by orders of magnitude. Thus, a laser-trapped nanoparticle can be used as a local probe for measuring mesoscopic interactions, such as Casimir forces, vacuum friction, non-equilibrium dynamics and phase transitions, with ultrahigh accuracy.

3. Future Plans

In our future work we intend to explore the possibility of trapping particles that serve as hosts for molecules or ions whose states can be controlled by external laser fields. This will open up the attractive possibility to perform atomic spectroscopy in a host that is entirely isolated from its environment. Diamond NV centers are especially interesting because their paramagnetic ground state allows single electron spins to be controlled by external magnetic fields. We have experimentally verified that it is possible to trap single diamond nanocrystals and to monitor the photoluminescence from single NV centers in the levitated state [20].

In our first trapping and cooling experiments we levitated a single 70nm silica nanoparticle and cooled its center-of-mass temperature from room-temperature to 35 milli-Kelvin by means of a parametric feedback [14]. In these experiments we established the general trapping and cooling procedure and characterized all the important parameters in the system (laser power, vacuum pressure, feedback gain and phase, etc.). We are now well prepared for the next step, namely to vacuum trap and cool a single quantum emitter and to control its spin coherence by external fields.

4. Anticipated Unexpended Funds

None.

5. Number of Students and Postdocs Supported

This grant currently supports one graduate student (Steven Person) and one postdoctoral associate (Ryan Beams).

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