Ultra-sensitive force detection with optically-cooled and trapped nanospheres

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First studied by Ashkin and coworkers in the 1970s [1], there has recently been interest in extending the regime of optical trapping and cooling of dielectric particles in a high-vacuum environment [2]. In ultra-high vacuum, the center-of-mass motion of optically trapped sub-micron-sized dielectric spheres is well decoupled from its surroundings, making these systems excellent candidates for ground state cooling and studies of quantum coherence [3]. In addition, optically levitated and cooled mechanical systems have the potential to behave as sensitive force detectors.

High force sensitivity resonant sensors have typically consisted of solid-state micro-fabricated structures [4], for example cantilever beams or membranes. In these systems, the internal materials losses and clamping mechanisms are responsible for limiting the quality factor of the oscillator to typically below $Q \sim 10^7$. For force detection, it is desirable to have minimal dissipation, as the minimum detectable force due to thermal noise scales as $Q^{-1/2}$. It can be expressed as $F_{\text{min}} = \left[\frac{4k\kappa Tb}{\omega Q}\right]^{1/2}$, where $b$ is the bandwidth of the measurement, $T$ is the effective temperature of the mode under consideration, $\omega$ is its resonance frequency, and $k$ is the spring constant. In ultra-high vacuum, the center-of-mass motion of optically levitated micron-sized dielectric spheres and could exhibit $Q$ factors approaching $10^{12}$, leading to force sensitivity well below 1 aN/Hz$^{1/2}$. Such force sensors may be useful to characterize short range forces such as Casimir forces. In addition, they can be used to test for deviations from Newtonian gravity at micrometer length scales [5], as predicted by several recent theories.

We are constructing an apparatus to trap and cool silica spheres of diameter 300 nm in a combined dipole-cavity trap. The beads will be trapped in an anti-node of the cavity trapping light and cavity-cooled using a second laser. To evaluate their utility as resonant force sensors, the quality factor of the center of mass oscillations will be determined as a function of pressure from ambient pressure down to ultra-high vacuum. Cavity cooling of a nanobead towards its ground state will be explored. While the force sensitivity does not generally improve with cavity cooling or active feedback cooling, the cooling is necessary to mitigate the effects of heating due to the recoil of scattered trap laser photons. In addition, cooling is essential to damp the oscillator so that motion due to perturbations can ring-down on reasonably short time scales for experiments. By trapping a sphere in an anti-node close to an end-mirror of the cavity, Casimir forces due to the end-mirror can be measured as a frequency shift of the oscillator, and non-Newtonian gravity-like forces can be measured by monitoring the displacement of the sphere as a mass is brought behind the cavity mirror. The technique we describe could potentially extend the search for non-Newtonian gravity by several orders of magnitude at the micron length scale.

References