Autocorrelation and relaxation time measurements on metal oxide core – dielectric shell beads in an optical trap

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ABSTRACT

Optical Tweezers are capable of trapping individual particles of sizes that range from micrometers to sub micrometers. One can compute the trap strength experienced by a particle by analyzing the fluctuations in the position of the trapped particle with time. It is reported that the trap strength of a dielectric bead increases linearly with increase in the power of the trapping laser. The situation with metallic particles, however, is strongly dependent on the particle size. Available literature shows that metallic Rayleigh particles experience enhanced trap strengths when compared to dielectric particles of similar sizes due to a larger polarizability. On the contrary, micrometer sized metallic particles are poor candidates for trapping due to high reflectivity. We report here that commercially available micrometer sized metal oxide core - dielectric shell (core – shell) beads are trapped in a single beam optical tweezer in a manner similar to dielectric beads. However as the laser power is increased these core – shell beads are trapped with a reduced corner frequency, which represents a lowered trap strength, in contrast to the situation with ordinary dielectric beads. We attribute this anomaly to an increase in the temperature of the medium in the vicinity of the core – shell bead due to an enhanced dissipation of the laser power as heat. We have computed autocorrelation functions for both types of beads at various trapping laser powers and observe that the variation in the relaxation times with laser power for core - shell beads is opposite in trend to that of ordinary dielectric beads. This supports our claim of an enhanced medium temperature about the trapped core – shell bead. Since an increase in temperature should lead to a change in the local viscosity of the medium, we have estimated the ratio of viscosity to temperature for core – shell and dielectric beads of the same size. We observe that while for ordinary dielectric beads this ratio remains a constant with increasing laser power, there is a decrease for core – shell beads. We plan to extend this work towards studying the hydrodynamic correlations between a pair of trapped beads where one of the beads acts as a heat source.

Keywords: Optical Tweezers, Autocorrelation, Relaxation time, Microrheology

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1. INTRODUCTION

Optical tweezers, first developed and demonstrated by Arthur Ashkin, have revolutionized studies at the micron length scale. They have been used extensively as tools to apply well calibrated forces in the range of piconewtons to understand phenomena that range from micro rheology to cell mechanics. Conventional optical tweezers usually employ a laser with a Gaussian beam intensity profile. The principle of trapping is essentially a by-play between photon momentum, intensity gradient created by a high numerical aperture objective and the relative refractive index of the medium of the trapped object to that of the medium of suspension. The optical trap can be modeled as a Hookean system and one can compute the strength of the optical trap in terms of a spring constant. The governing equation of the motion of the trapped particle subject to Brownian fluctuations is the Langevin equation [1].

Optical tweezers have been used as tools to understand the viscoelastic properties of liquid crystals, gels and biological membranes. One monitors the Brownian fluctuations of an optically trapped microscopic particle suspended in the medium of interest. The Brownian trajectory of the trapped particle depends on the suspending medium as well as the strength of the optical trap. One can estimate various parameters such as viscosity, elasticity and refractive index which characterize the medium by analyzing the recorded Brownian fluctuations besides the trap strength [2].

Trapping of dielectric micro particles or beads and trap stiffness estimations from their Brownian displacements have established that the trap strength increases with increase in the laser power. With respect to metallic particles, it has been reported that while metallic Rayleigh particles have scattering similar to dielectric beads of the same size, micrometer sized metallic beads are trapped unstably or off center in conventional optical tweezers [3-6]. This may be attributed to high reflectivity of the metallic beads.

Certain commercially available magnetic beads consist of a core of iron oxide magnetic nanoparticles encapsulated in a polymer or inorganic matrix. These beads can therefore be considered to have a metal oxide core and a dielectric shell. These core – shell beads have been used extensively to tether and exert small, well calibrated forces at particular sites in certain biological samples of interest with the use of magnetic tweezers. Groups, working with such beads have commented on their unstable trapping in optical tweezers. It has also been remarked that the metal oxide core of these beads may be responsible for heating in the immediate vicinity of these beads [7-8].

In this study we report preliminary results on the autocorrelation of core-shell beads and compare them to that of regular dielectric beads of the same size made of the same material as the encapsulating matrix and trapped at identical powers. From the autocorrelation function variation with the lag time, we compute the relaxation time for the two varieties of beads. We observe that the relaxation times computed are vastly different between the two cases. We have estimated a ratio of the viscosity to temperature of the suspending medium in the presence of these optically trapped core –shell beads from the autocorrelation plots. The results validate our claim that there is indeed heat dissipation when the metal oxide core - dielectric shell beads are trapped in optical tweezers.

2. EXPERIMENTAL DETAILS

1μm sized Silica beads (Cospheric, USA) and metal oxide core – dielectric shell beads (Chemicell GmbH) are used in these experiments. The core-shell beads are essentially composed with a core of superparamagnetic maghemite (γ-

Fe_2O_3) nanoparticles, encapsulated in a shell of porous silica matrix. The silica beads used are of the same porous material. The experiment was carried out in a single beam optical gradient trap. The trapping laser has a wavelength of 830nm (Thor Labs, USA) which is passed through an objective having a numerical aperture of 1.25 (Olympus). The stochastic motion of the trapped beads is recorded using a Quadrant Cell Photodetector (Newport Inc., USA). The beads are imaged with a high resolution camera (Electrim Corporation). Figure 1 shows the schematic of the single beam optical trap. The experiment was carried out for varying laser powers. All the laser power measured and reported here have been measured after the aspheric lens.

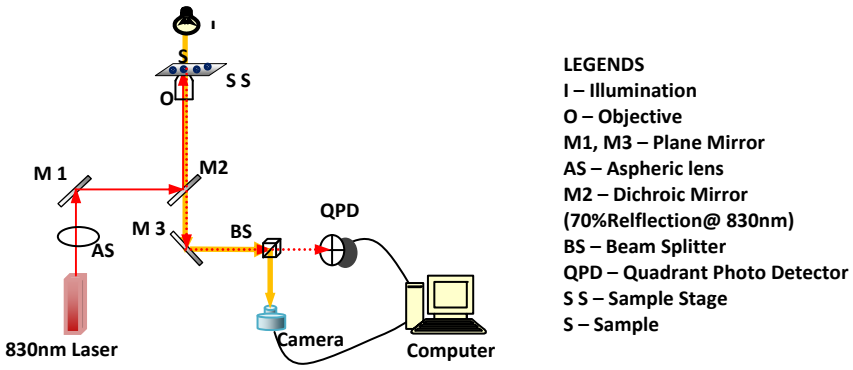

Figure 1: Schematic of the single tweezer setup

3. RESULTS AND DISCUSSION

3.1 Analysis of the Power Spectral Density

The porous silica beads were used to draw comparisons with the core - shell beads which differed from the former only in the composition of the core. From the analysis of the power spectral density (PSD), we were able to compute the corner frequency as a function of the laser power [1]. Figure 2 shows the PSD for both silica and core - shell beads at identical powers. We observe that while the trap stiffness for the ordinary silica beads increased with laser power, the trend is reversed in case of the core – shell beads. Figure 3 shows the plot of the corner frequency as a function of the laser power for both types of beads.

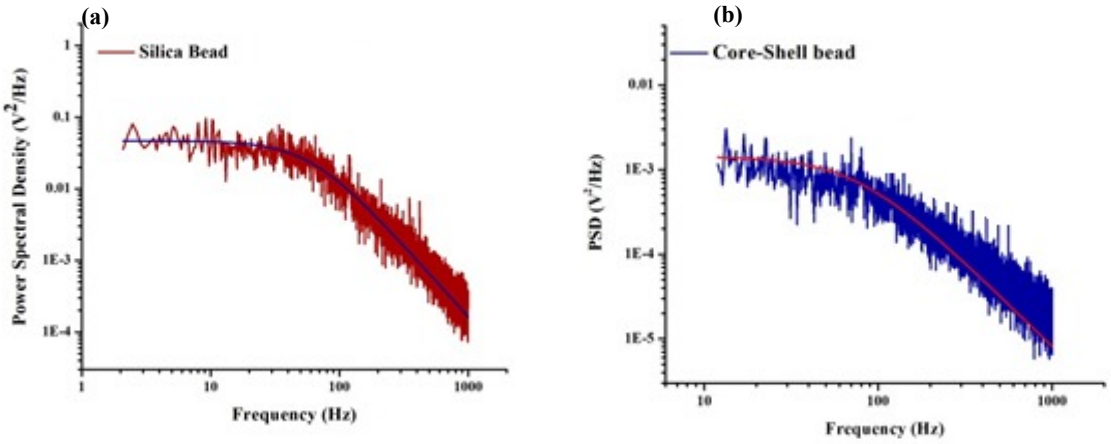

Figure 2: Power spectral density plots at a trapping laser power of 69.9mW for (a) silica bead, corner frequency = 55.59 Hz (b) Core - shell bead, corner frequency = 30.35 Hz

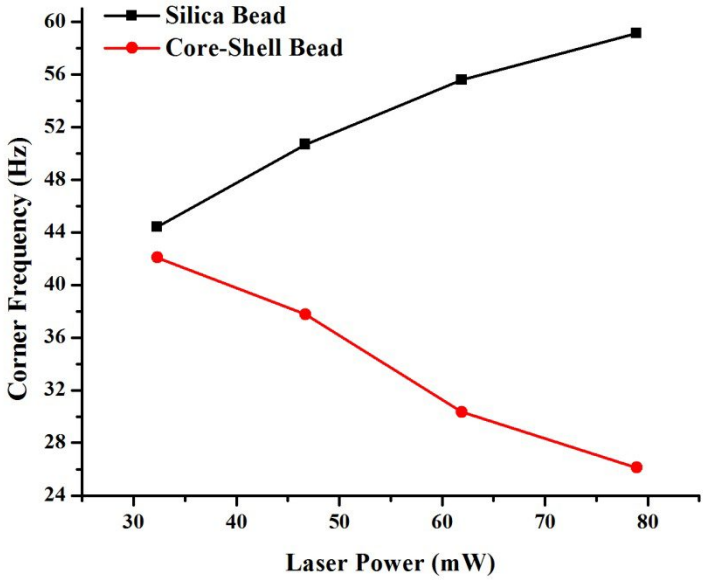

Figure 3: Variation of the corner frequency with increase in laser power for a trapped silica bead (black) and a trapped core -shell bead (red). (The lines joining the data points are a guide to the eye)

3.2 Autocorrelation function and the relaxation time measurements

A micro bead suspended in a fluid undergoes stochastic motion due to the thermal fluctuations in the suspension medium. However this random motion of the micro bead is constrained by the harmonic potential of the optical trap which exerts a restoring force on the bead. Therefore the trajectory of this Brownian particle is governed by both these factors.

The autocorrelation or serial correlation of a signal is the measure of the extent to which the signal correlates with itself. One can compute the relaxation time of the particle trapped in a harmonic optical trap. However there are two characteristic time scales to the problem – a fast relaxation time which is entirely the effect of the suspension medium and a slow relaxation time which is strongly dependent on the trap strength [9]. The autocorrelation function of a trapped micro bead assumes the form of an exponential decay [10-15]. Since we are limited by the detection speed (detection rate of the ADC card is 10,000 samples per second) [16], our measurements are not sensitive to the fast relaxation time of the trapped particle and henceforth, "relaxation time" refers to the slow relaxation time.

The autocorrelation function is computed for the two types of beads from the position fluctuations recorded using the QPD. Figure 4 shows the autocorrelation plots for the silica and core – shell beads trapped at 69.9mW of laser power. From the exponential fits we obtain the relaxation times of the two of beads. We observe that the relaxation time of the silica bead decreases as the laser power increases whereas in case of the core – shell beads, it increases with increase in laser power. The silica bead's relaxation time variation with laser power is in agreement with work showing that the trap strength is inversely proportional to the relaxation time [9]. On the other hand the core-shell bead displays anomalous behavior with the trap strength decreasing as the laser power is increased. This may be attributed to the increased thermal fluctuation in the medium surrounding the bead, as a result of heat transfer to the medium. Figure 5 shows the plot of the relaxation time as a function of the laser power.

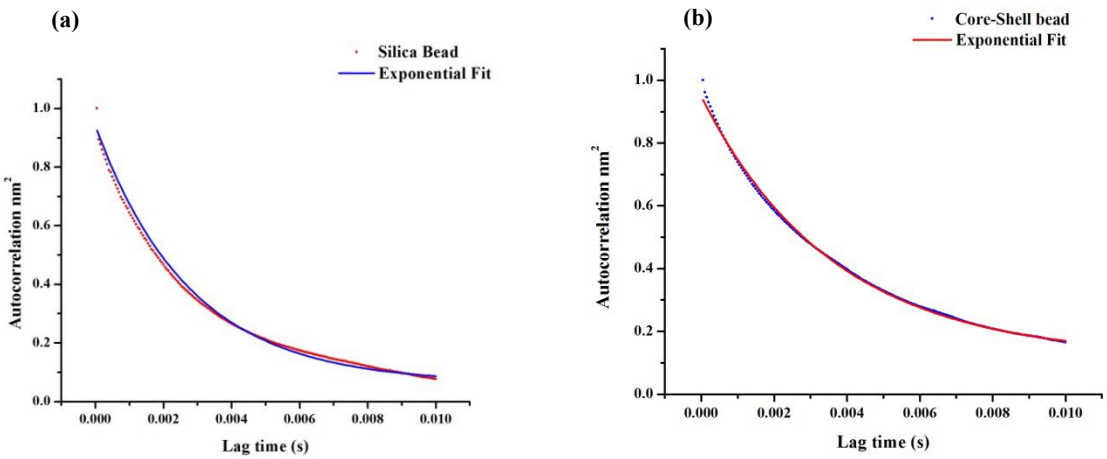

Figure 4: Autocorrelation plots of (a) Silica bead (b) core – shell bead when trapped at 69.9mW laser power

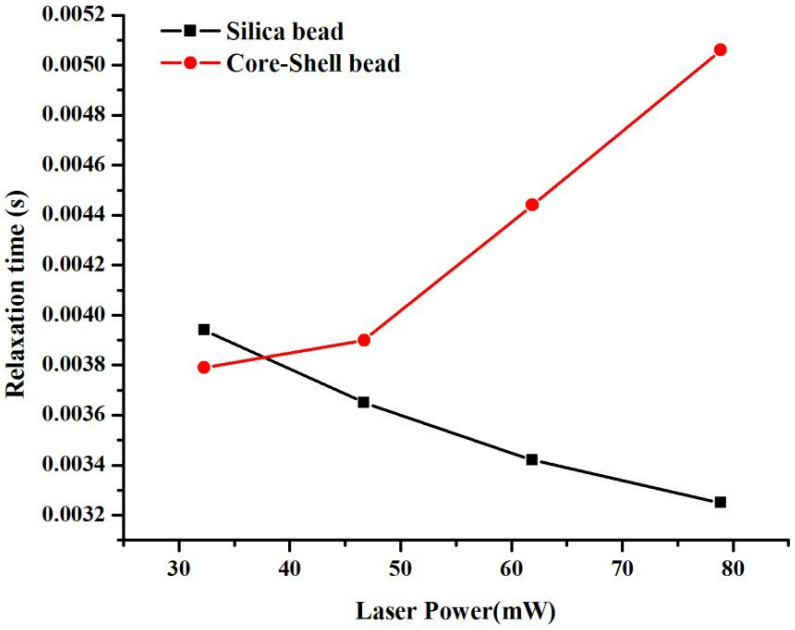

Figure 5: Variation in the measured relaxation time of a trapped silica bead (black) and a trapped core shell bead (red) with increase in laser power. (The lines joining the data points are a guide to the eye)

If one were to compute the local viscosity using the relation between the slow relaxation time (τ), the trap stiffness (κ) and viscosity (η) as given in [9] by

$$\tau = \frac{6\pi\eta a}{\kappa} \qquad (1)$$

where a is the radius of the trapped microbead, we would erroneously conclude that there is an increase in the viscosity of suspension medium in the vicinity of the trapped bead as the laser power is increased. This would be in contradiction to our assertion that there is an increase in the temperature in the immediate surroundings of the trapped core - shell bead with an increase of trapping laser power, as an increase in temperature ought to lead to a decrease in the viscosity of the suspension medium which is water [17] in this case. This is due to the fact that equation (1) does not explicitly incorporate the effect of changes in ambient temperature and is thereby insufficient in situations where a change in the local temperature is the most likely scenario.

On the other hand, going by an empirical model relating the temperature and viscosity of the medium as proposed by Reynolds [18]

$$\eta = \eta_0 Exp(-bT) \qquad (2)$$

where η_0 and b are constants, we see that viscosity drops exponentially with increase in temperature. The ratio of effective viscosity to temperature as computed from the relaxation time should thereby show a decrease with increasing laser power if indeed there is a rise in the temperature in the vicinity of the trapped bead. The normalized autocorrelation function is fitted to an exponential function given by

$$\langle x(0)x(t)\rangle = Ae^{-\frac{t}{\tau}} \quad (3)$$

The fit parameter A signifies the variance of the displacements and hence changes as the Brownian fluctuations of the trapped bead change. From Equations (1) and (3) and the trap stiffness $\kappa = 2\pi\gamma f_c$, where f_c stands for the corner frequency, we can compute the ratio of the effective viscosity to temperature as

$$\frac{\eta}{T} = \frac{k_B}{12\pi^2 f_c a A} \quad (4)$$

k_B being the Boltzmann's constant. Figure 6 shows the ratio of the effective viscosity to the temperature as a function of the trapping laser power for the two varieties of beads. In agreement with our assertion that there is a rise in temperature with increasing laser power for a core-shell bead, we see a decrease in this ratio when a core – shell bead is trapped, but no change in it when a dielectric bead is trapped.

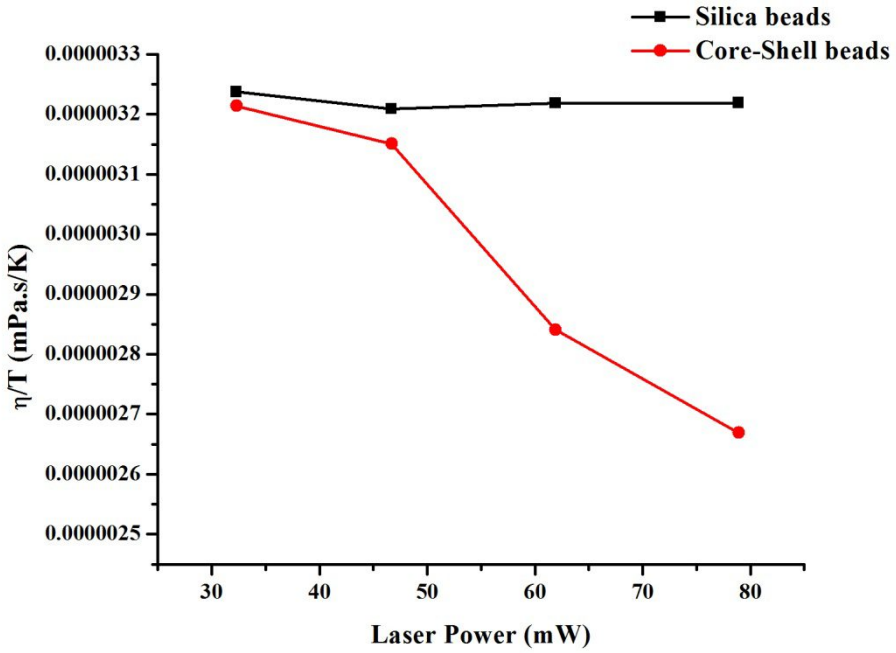

Figure 6: Ratio of the viscosity (η) to Temperature (T) as a function of laser power. (The lines joining the data points are guides to the eye)

CONCLUSIONS

We have carried out a comparison of the trapping characteristics of a metal oxide core – dielectric shell bead with that of a bead of identical size made out of the same dielectric material that forms the matrix material of the core – shell bead. We find that unlike the situation for the silica bead in the trap, the trap stiffness corresponding to the core –shell bead in the trap decreases with increasing laser power. We attribute this to an increased dissipation of the laser power as heat in the local vicinity of the trapped bead. We compute the autocorrelation functions of both the silica and the core – shell beads and find that the trends in relaxation time support our conjecture of increasing fluctuations and a lowering of trap stiffness with increasing laser power for the situation involving the core – shell bead. We

compute a ratio of viscosity to the local temperature from the autocorrelation data and find that the variation of this ratio with trapping laser power lends additional support to our conjecture of heightened temperatures at the trapping site of the core – shell bead as compared to an ordinary dielectric silica bead when they are each trapped at identical laser powers.

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