Optofluidic control of the diffusion of nanoscale dumbbells

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Optofluidic techniques provide a way to control the transport properties of nanoscale objects and have been applied to the guiding and sorting of particles in microfluidic flows [1, 2, 3, 4]. Numerical experiments have shown that we can tune the diffussivity of a dilute suspension of gold nanoparticles in water by placing them in the intersection of two perpendicular laser beams with a wavelength close to the plasmon resonance in water ($\lambda \approx 395$ nm). In particular, a phase difference of $\pi/2$ enhances the diffusion of a single nanoparticle by a factor proportional to the power density of the laser [5] due to the pattern formed by the standing waves in the electrical field, which form a checkerboard of vortices that propell the nanoparticles towards saddle nodes in the field. Because of thermal fluctuations, the particles leave the saddle nodes, randomly choosing one of two opposite directions and travelling to the next node [Fig. 1 (a)].

Interestingly, we can alter the dynamic behaviour completely just by attaching two nanoparticles by means of a polymer strand, as at the bottom of Fig. 1. We have developed numerical algorithms that take into account the interaction with the incident lasers, the thermal fluctuations and hydrodynamic interactions and have observed that, depending on the laser intensity and the length of the chain, the dumbbells will rotate [Fig. 1 (b)], become trapped in a fixed direction [Fig. 1 (c)] or experience enhanced diffusion. In some cases, the mean square displacement of the chain becomes as large as that of a single nanoparticle, but with an anomalous displacement distribution, in the sense that the motion is still Brownian, but the step size does not follow Gaussian statistics (Fig. 2).

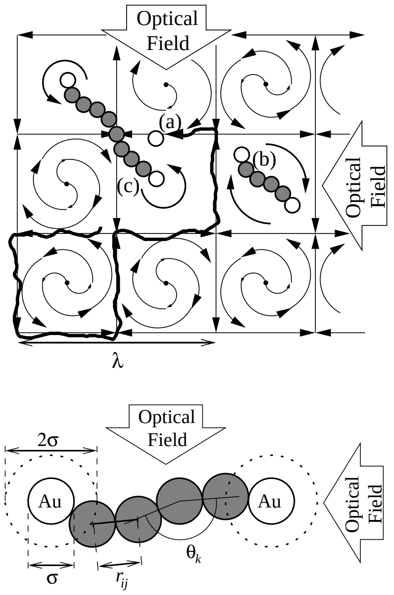

Fig. 1. (Top) Simplified representation of the forces in an optical vortex lattice. A single gold particle (a) experiences enhanced diffusion. Short dumbbells follow similar trajectories. In some cases, we can easily trap the dumbbells (b) and (c) using one or two vortices. (Bottom) The dumbbell is made with two gold particles attached by means of a FENE bead-spring chain (which limits the interparticle separation $r_{ij} < 3r$, where r is the radius of a bead) that interact with an optical force field. WCA interactions with diameter σ model excluded volume effects. An extra coat of transparent material (dotted lines) was included in some of the simulations. Angular springs between consecutive links oppose bending and tend to restore the angles to $\theta_k = \pi$ rad.

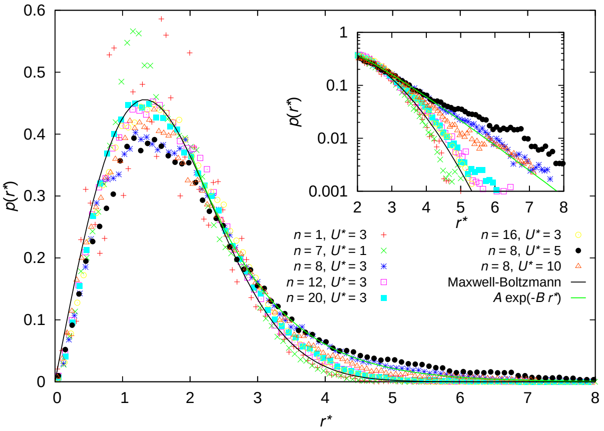

Fig. 2. Probability density function for the displacement of diffusing dumbbells. The horizontal axis represents a scaled step $r^* = r_{\Delta t}/\sqrt{(U^*/n)\Delta t}$, with $\Delta t = 100\ \sqrt{m\sigma^2/(k_B T)}$. The inset shows the distribution tails on a semi-logarithmic scale. The number of beads n includes the gold nanoparticles. U^* means $U/(k_B T)$, with U standing for the laser energy.

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