Mimicking high-temperature reservoirs for colloidal particles using noisy electric fields

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In the last decades, several models have been introduced to describe Brownian motion of particles in gases and liquids in conditions where fluctuations are important. An experiment in which the temperature of a colloidal particle is controllable is of interest to study the Brownian motion at different temperatures and to construct microscopic-sized heat engines[1].

We design an experiment to control the effective temperature of a colloidal particle from room temperature to several thousand kelvins. We trap microscopic polystyrene particles in water using optical tweezers. Our particles have inherit electric changes, therefore by applying an electrostatic force that is of the form of a Gaussian white noise we can mimic a second thermal bath in our system. We experimentally observe that the amplitude of the Brownian motion in the direction of the force increases when increasing the intensity of the electrostatic force. The particle moves like if it were in a thermal bath of a higher temperature than the surrounding water. To check that our setup is equivalent to a thermal bath that is at a higher temperature than the water, we study the fluctuations of the position of the bead and the response of the bead to nonequilibrium perturbations.

We first study the fluctuations of the position of the bead in the direction in which the electric field is applied ($x-$axis for simplicity). Let x be the position of the bead and x_t the position of the center of the trap, both in $x-$axis. The trap generates a harmonic optical potential of stiffness κ that is centered around x_t, i.e. $V(x) = \frac{1}{2}\kappa(x - x_t)^2$. We define the *kinetic temperature* of the bead as $T_{\rm kin} = \kappa\langle(x-x_t)^2\rangle_{\rm ss}/k$, where ss stands for steady state and k is Boltzmann's constant. Kinetic temperature is equal to the temperature of the water when no field is applied, and it increases with the amplitude of the field. The maximum temperature that we experimentally observe is around $3000K$ as we show in Fig. 1. Notice that Brownian motion at high temperatures has only been observed in laser-heating experiments[2], where the temperature achieved is always smaller than the vaporization temperature of water. Another proof that the particle is describing Brownian motion at high temperatures is done by calculating the Fourier transform of the correlation of the position, called Power Spectrum Density (PSD). When applying the external field, the shape of the PSD is equal to the PSD of a bead trapped with the same stiffness κ but immersed in a thermal bath that is at a larger temperature than the temperature of the water in our experiment.

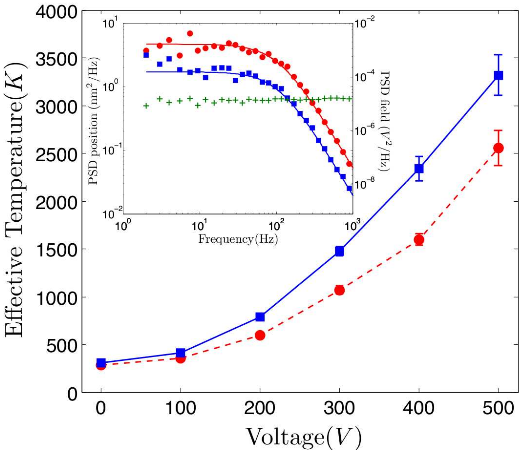

FIG. 1. Experimental value of the effective temperature of the bead as a function of the maximum voltage applied between the electrodes: $T_{\rm kin}$ (blue squares), and T_c (red circles). *Inset*: Power spectrum density of the position of the bead as a function of the frequency: Without external field (blue squares) and with a maximum voltage of $200V$ (red circles). Solid lines are fits to a Lorentzian. We also plot the PSD of the electric noise (green "+").

To analyse the response of the particle in the presence of the random electric field we move the trap center following the nonequilibrium protocol that we now describe: First the trap is moved at constant velocity v and the bead is allowed to relax to the new equilibrium position. Then, the reverse process is implemented, moving the trap with velocity $-v$ and letting the bead to relax to equilibrium again. We experimentally check Crooks fluctuation theorem[3] when no external field is applied. We then define by T_c the temperature at which Crooks theorem is satisfied when the electric field is on. We show in Fig. 1 that T_c is of the same order of magnitude than the kinetic temperature obtained from the analysis position fluctuations.

We therefore prove that our setup is equivalent to a thermal bath where the temperature can be externally controlled. With a simple experiment, we are able to use our setup to heat a particle from $300K$ to $3000K$ in a timescale that is of order γ/κ, being γ the friction coefficient of the bead in water.

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