Realization of non-equilibrium thermodynamic processes using external colored noise

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I. INTRODUCTION

The thermodynamics of small systems is strongly affected by the thermal fluctuations of the surroundings. Although often looked as an unwanted source of noise, fluctuations also bring to life phenomena such as stochastic resonances, temporal violations of the Second Law of Thermodynamics or the possibility to build engines at the micro scale of a greater efficiency than that of their macroscopic counterparts. At the microscale, the amplitude of the fluctuations of the thermodynamic quantities depends on the temperature of the environment. Unfortunately, temperature control has remained challenging due to the difficulties found to isolate microscopic systems and the presence of convection effects in fluids.

To overcome these difficulties we propose to use random forces acting on a colloidal particle as a heat source to mimic the behavior of a thermal bath ranging on the thousands of degrees. In this context we manage non-equilibrium thermodynamic processes with an optically trapped microsphere in a virtual thermal bath. The virtual bath consists of a noisy electric force on the particle with a Gaussian white noise spectrum[1]. The method is validated by verifying that the temperatures obtained from equilibrium and non-equilibrium measurements match[2].

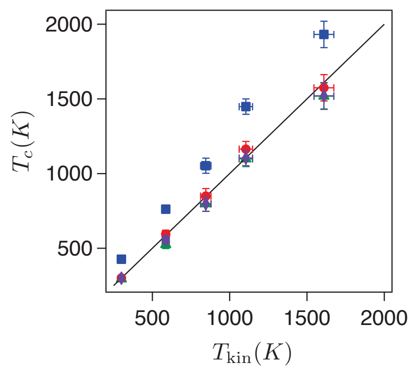

FIG. 1. Effective nonequilibrium kinetic temperature, T_c, vs effective equilibrium kinetic temperature, $T_{\rm kin}$, for different amplitudes of the external noise. Different symbols correspond to results obtained for different sampling rates: 1 kHz (blue squares), 2 kHz (red circles), 5 kHz (green triangles) and 10 kHz (magenta diamonds). Solid black line corresponds to $T_c = T_{\rm kin}$.

Backed-up by theory and simulations[3], our experiments highlight the importance of properly choosing the sampling rate and noise bandwidth. We apply this technique to study non-equilibrium isothermal compression-expansion cycles at different temperatures ranging from room temperature to 3000K. We calculate thermodynamic functionals for these processes such as work, heat and entropy. We show that work distributions verify the Crooks fluctuation theorem, and that they fit well to a generalized Gamma function:

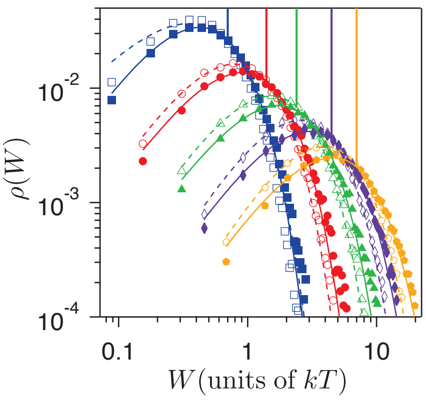

FIG. 2. Work distributions in the isothermal compression [$\rho(W)$, filled symbols] and isothermal expansion [$\tilde{\rho}(-W)$, open symbols] for different values of the noise intensities corresponding to the following nonequilibrium effective temperatures: Without external field, $T_c = 300$ K (blue squares), $T_c = 610$ K (red circles), $T_c = 885$ K (green triangles), $T_c = 1920$ K (magenta diamonds) and $T_c = 2950$ K (orange pentagons). Solid and dashed curves are fits to Eq. (1). Vertical lines of the corresponding color show the expected value for the free energy change at the given temperatures. Data acquisition rate to calculate the work: $f = 2$ kHz.

$$\rho(W) = C_F\, W^{z_F}\, e^{-W/\alpha_F} \tag{1}$$

where the fit parameters C_F, C_B, α_F and α_B depend on the amplitude of the external noise, but not z_F and z_B (data not shown).

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[3] A. Gomez-Marin, J. Parrondo, and C. Van den Broeck, Physical Review E **78**, 011107 (2008).