First Observation of Phonon-induced Ballistic Motion in Photonic Nanostructures

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The component parts of micro/nano-opto-mechanical (meta)materials, devices, sensors and systems are perturbed by collisions with atoms of ambient gas and by phonons in the crystal lattice of the constituent materials, causing movements of picometric (i.e. sub-atomic) amplitude at MHz frequencies. We report on the detection and quantitative mapping of this short-timescale ballistic (non-Brownian) regime of thermal motion.

Einstein realized in 1905 that the commonly held picture of Brownian motion, characterized by erratic, discontinuous changes in speed and direction, must break down at short (≤μs) time and (≤nm) length scales – that objects must move ballistically with a smooth position trajectory (Fig. 1a) and a Maxwell-Boltzmann distribution of instantaneous velocities. However, he could not envisage how this regime would ever be observable. While the required length and time scales are now accessible, mechanical thermodynamics in photonic and electro-optic nanostructures (inset to Fig. 1a), where oscillations can be strongly coupled and highly nonlinear, remain underexplored because there are no routinely available tools for quantitative mapping of fast nano/picoscale motion. We show that real-time spectral analysis of variations in secondary electron emission from moving objects interrogated with a focused electron beam provides for such measurement, with sub-atomic displacement sensitivity.

In this measurement regime resolution is ultimately constrained only by the Poisson statistics of secondary electrons impinging on the detector and a typical scanning electron microscope can be sensitive (at the sharp edges of a target) to displacements of sub-picometer amplitude, i.e. displacements that are smaller by orders of magnitude than the (~nm) electron beam spot size and the conventional static imaging resolution. Figure 1b shows the measured real-time position trajectory of a microcantilever with a fundamental out-of-plane oscillation period T ~0.17 ms. At short times (<< T) the distribution of instantaneous velocities (Fig. 1c) conforms exactly to the theoretical Maxwell-Boltzmann distribution – a signature of the ballistic regime. In contrast, at longer intervals (greater than a significant fraction of T), the observed velocity distribution is still Gaussian but with a width (corresponding to RMS velocity) that is constrained in a manner indicative of damped harmonic oscillation.

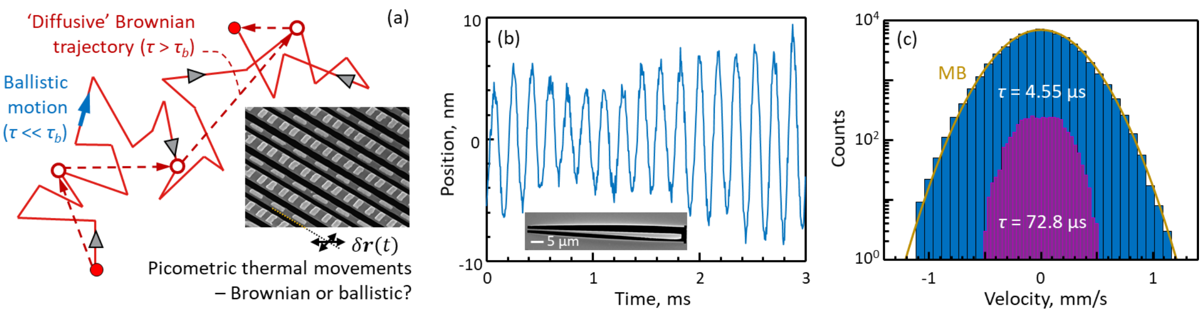

Fig 1 (a) Brownian vs. ballistic thermal motion: The observed regime depends upon the spatiotemporal resolution of measurements: The solid red line in this schematic represents the trajectory of a free particle undergoing thermal motion. An erratic 'Brownian' path [dashed lines] is seen at timescales τ longer than the momentum relaxation time τ_b, while at much shorter time intervals ballistic motion [blue line] is observed. [Inset] The component parts of nanomechanical photonic devices – e.g. a gold/silicon nitride opto-mechanically reconfigurable metamaterial shown here, are subject to thermal motion of characteristically pico- to nanometric amplitude. We ask whether the ballistic regime can be observed in such structures? (b) Measuring ballistic motion of a microcantilever: Real-time position trajectory of a free-standing, 30 nm thick gold cantilever, shown inset. (c) Corresponding velocity distributions at short [blue bars] and long [red] time intervals.

We can visualize real-time thermal movements occurring on at microsecond timescales with sub-atomic displacement sensitivity and nanoscale spatial resolution. This enables quantitative measurement of the instantaneous velocity of micro/nanomechanical structures and spatial mapping of nanoscale oscillatory mode shapes and dynamic mechanical properties in a wide variety of nano-engineered objects, photonic and optoelectronic devices, and 2D material structures, while also presenting applications in the exploration of fundamental nonequilibrium statistical (opto)mechanics.