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Stochastic Thermodynamics: Theory and Experiments

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Stochastic thermodynamics provides a framework for describing small systems embedded in a heat bath and externally driven to non-equilibrium. Examples are colloidal particles in time-dependent optical traps, single biomolecules manipulated by optical tweezers or AFM tips, and motor proteins driven by ATP excess. A first-law like energy balance allows to identify applied work and dissipated heat on the level of a single stochastic trajectory. Total entropy production includes not only this heat but also changes in entropy associated with the state of the small system. Within such a framework, exact results like an integral fluctuation theorem for total entropy production valid for any initial state, any time-dependent driving and any length of trajectories can be proven [1]. These results hold both for mechanically driven systems modelled by over-damped Langevin equations and chemically driven (biochemical) reaction networks [2]. These theoretical predictions have been illustrated and tested with experiments on a colloidal particle pushed by a periodically modulated laser towards a surface [3]. Key elements of this framework like a stochastic entropy can also be applied to athermal systems as experiments on an optically driven defect center in diamond show [4,5]. For mechanically driven non-equilibrium steady states, the violation of the fluctuation-dissipation theorem can be quantified as an additive term directly related to broken detailed balance (rather than a multiplicative effective temperature) [6]. Integrated over time, a generalized Einstein relation appears. If velocities are measured with respect to the local mean velocity, the usual form of the FDT holds even in non-equilibrium. [1] U. Seifert, Phys. Rev. Lett. 95: 040602/1-4, 2005. [2] T. Schmiedl and U. Seifert, cond-mat/0605080. [3] V. Blickle, T. Speck, L. Helden, U. Seifert, and C. Bechinger, Phys. Rev. Lett. 96: 070603/1-4, 2006. [4] S. Schuler, T. Speck, C. Tietz, J. Wrachtrup, and U. Seifert, Phys. Rev. Lett. 94: 180602/1-4, 2005. [5] C. Tietz, S. Schuler, T. Speck, U. Seifert, and J. Wrachtrup, Phys. Rev. Lett. 97: 050602/1-4, 2006. [6] T. Speck and U. Seifert, Europhys. Lett. 74: 391-396, 2006.