DY 43: Stochastic thermodynamics and information processing

Time: Wednesday 10:00–13:45 Location: BH-N 243

DY 43.1 Wed 10:00 BH-N 243

Stochastic thermodynamics in the strong coupling regime: An unambiguous approach based on coarse graining — •Philipp Strasberg and Massimiliano Esposito — Complex Systems and Statistical Mechanics, Physics and Materials Science, University of Luxembourg, L-1511 Luxembourg, Luxembourg

We consider a classical and possibly driven composite system XY weakly coupled to a Markovian thermal reservoir R so that an unambiguous stochastic thermodynamics ensues for XY. This setup can be equivalently seen as a system X strongly coupled to a non-Markovian reservoir YR. We demonstrate that only in the limit where the dynamics of Y is much faster than X, our unambiguous expressions for thermodynamic quantities, such as heat, entropy, or internal energy, are equivalent to the strong coupling expressions recently obtained in the literature using the Hamiltonian of mean force. By doing so, we also significantly extend these results by formulating them at the level of instantaneous rates and by allowing for time-dependent couplings between X and its environment. Away from the limit where Y evolves much faster than X, previous approaches fail to reproduce the correct results from the original unambiguous formulation, as we illustrate numerically for an underdamped Brownian particle coupled strongly to a non-Markovian reservoir.

DY 43.2 Wed 10:15 BH-N 243

Conservation Laws in Nonequilibrium Thermodynamics — •Riccardo Rao and Massimiliano Esposito — Complex Systems and Statistical Mechanics, Physics and Materials Science Research Unit, University of Luxembourg, L-1511 Luxembourg, G.D. Luxembourg

Starting from the most general formulation of stochastic thermodynamics—i.e. a thermodynamically consistent nonautonomous stochastic dynamics describing systems in contact with several reservoirs—, we define a procedure to identify the conservative and the minimal set of nonconservative contributions in the entropy production. The former is expressed as the difference between changes caused by time-dependent drivings and a generalized potential difference. The latter is a sum over the minimal set of flux–force contributions controlling the dissipative flows across the system. When the system is initially prepared at equilibrium (e.g. by turning off drivings and forces), a finite-time detailed fluctuation theorem holds for the different contributions. Our approach relies on identifying the complete set of conserved quantities and can be viewed as the extension of the theory of generalized Gibbs ensembles to nonequilibrium situations.

[1] R. Rao & M. Esposito. arXiv 1709.01951.
[2] M. Polettini, G. Bules-Cuetara & M. Esposito. Phys. Rev. E 94, 052117 (2016).

DY 43.3 Wed 10:30 BH-N 243

Fluctuation theorems for detached path probabilities — •Jannik Ehrich and Andreas Engel — Institut für Physik, Carl von Ossietzky Universität, 26111 Oldenburg, Germany

Systems with interacting degrees of freedom play a prominent role in stochastic thermodynamics. We apply the concept of causal conditioning to define a detached entropy production for a general bipartite Markov process. This quantity simplifies the dissection of the mutual influence the interacting degrees of freedom have on each other [1]. We elaborate on a series of special cases including measurement-feedback systems, sensors and hidden Markov models. For these special cases we show that fluctuation theorems involving the detached entropy production recover known results which have been obtained separately before. Additionally, we show that the fluctuation relation for the detached entropy production can be used in model selection for data stemming from a hidden Markov model.

[1] J. Ehrich and A. Engel, Phys. Rev. E **96**, 042129 (2017)

DY 43.4 Wed 10:45 BH-N 243

Fluctuations of Apparent Entropy Production in Networks with Hidden Slow Degrees of Freedom — •Matthias Uhl, Patrick Pietzonka, and Udo Seifert — II. Institut für Theoretische Physik, Universität Stuttgart, 70550 Stuttgart

The fluctuation theorem for entropy production is a remarkable symmetry of the distribution of produced entropy that holds universally in non-equilibrium steady states with Markovian dynamics. However, in systems with slow degrees of freedom that are hidden from the observer, it is not possible to infer the amount of produced entropy exactly. Previous work suggested that a relation similar to the fluctuation theorem may hold at least approximately for such systems if one considers an apparent entropy production. By extending the notion of apparent entropy production to discrete bipartite systems, we investigate which criteria have to be met for such a modified fluctuation theorem to hold in the large deviation limit [1]. We use asymptotic approximations of the large deviation function to show that the probabilities of extreme events of apparent entropy production always obey a modified fluctuation theorem and, moreover, that it is possible to infer otherwise hidden properties.

[1] M. Uhl, P. Pietzonka, U. Seifert, arXiv:1708.09786

15 min. break

DY 43.5 Wed 11:15 BH-N 243

Stochastic thermodynamics of a self-oscillating isothermal machine — •Christopher W. Wächtler[1], Philipp Strasberg[2], Sabine H. L. Klapp[1], Gernot Schaller[1], and Chrisotpher Jarzynski[3] — [1]Institut für Theoretische Physik, Technische Universität Berlin, Germany — [2]Complex Systems and Statistical Mechanics, University of Luxembourg, Luxembourg — [3]Institute for Physical Science and Technology, University of Maryland, USA

Self-oscillation describes the generation and maintenance of a periodic motion by a source of energy that is lacking a corresponding periodicity. We here examine a theoretically and experimentally studied model of a nanomechanical resonator coupled to a single-electron transistor, i.e. a single electron shuttle. While the dynamics of this system has been studied from different points of view the thermodynamical aspects have not been addressed before. Within the formalism of stochastic thermodynamics we are able to find a consistent thermodynamical description of the system at the semiclassical level including two sources of noise: thermal fluctuations of the resonator and stochastic jumps of the electrons. We derive the first and second law and, furthermore, demonstrate that the system can also serve as an isothermal machine, which performs useful work while maintaining its periodic motion.

DY 43.6 Wed 11:30 BH-N 243

Stochastic thermodynamics of periodically driven systems: Fluctuation theorem for currents and unification of two classes — •Somrita Ray and Andre Barato — Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Straße 38, 01187 Dresden

Periodic driving is used to operate machines that go from standard macroscopic engines to small nonequilibrium microsized systems. Two classes of such systems are small heat engines driven by periodic temperature variations, and molecular pumps driven by external stimuli. Well-known results that are valid for nonequilibrium steady states of systems driven by fixed thermodynamic forces have been generalized to heat engines operated by external periodic drive only recently [1]. These results include a general expression for entropy production in terms of currents and affinities, and symmetry relations for the Onsager coefficients from linear-response theory. For nonequilibrium steady states, the Onsager reciprocity relations can be obtained from the more general fluctuation theorem for the currents. We present a fluctuation theorem for the currents for periodically driven systems [2] that implies a fluctuation dissipation relation, symmetry relations for Onsager coefficients, and further relations for nonlinear response coefficients. Our results are valid for both heat engines and molecular pumps.

1. K. Brandner, K. Saito and U. Seifert, Phys. Rev. X 5, 031019 (2015) 2. SR and A. C. Barato, Phys. Rev. E 96, 052120 (2017)

DY 43.7 Wed 11:45 BH-N 243

Relations between long-time and finite-time fluctuation theorems in 2-level system under periodic drive — •Ivan Khaymovich[1,2] and Avinash Mandaiya[3] — [1]Max Planck Institute for the Physics of Complex Systems, D-01187 Dresden, Germany — [2]Institute for Physics of Microstructures, Russian Academy of Sciences, 603950 Nizhny Novgorod, GSP-105, Russia — [3]Indian Institute of Science, Bangalore 560012, India

Mesoscopic systems driven out of equilibrium experience large fluctuations of a stochastic entropy production. Fluctuation relations (FR) taking into account these fluctuation and generalizing the second law of thermodynamics are of particular interest for last decades. Gallavotti-Cohen relation being a remarkable example of long-time (LT) FR focuses on the large deviation regime and it is insensitive to initial conditions, while Crooks relation works with finite-time (FT) protocols and needs a special initial conditions both for forward and reversed system evolution in time. In general all FR are based on a some kind of reversion of a time-dependent protocol applied to a system. These FR are significantly simplified for the protocols symmetric to that reversion operation. In the present work we find sufficient conditions for asymmetric protocols for which simplified versions of LT and FT FR are still valid and derive the relation between these conditions. We give several examples of these protocols in a simplest case of 2-level system showing the link between LT and FT fluctuation relations.

DY 43.8 Wed 12:00 BH-N 243

Collective power: Minimal model for thermodynamics of nonequilibrium phase transitions — •Tim Herpich, Juzar Thingna, and Massimiliano Esposito — Complex Systems and Statistical Mechanics, Physics and Materials Science Research Unit, University of Luxembourg, L-1511 Luxembourg, Luxembourg

We establish a direct connection between the linear stochastic dynamics, the nonlinear mean-field dynamics, and the thermodynamic description of a minimal model of driven and interacting discrete oscillators. These exhibit at the mean-field level two bifurcations separating three phases: a single stable fixed point, a stable limit cycle indicative of synchronization, and multiple stable fixed points. The apparent contradiction with the underlying linear Markovian dynamics which ensures convergence to a unique steady state is resolved via metastability, i.e. the appearance of gaps in the upper real part of the spectrum of the Markov generator. The dissipated work of the stochastic dynamics exhibit signatures of nonequilibrium phase transitions over long metastable times which disappear in the infinite-time limit. Remarkably, it is also reduced by attractive interactions between oscillators. When operating as a work-to-work converter we study the power output and efficiency of our device in the presence of nonequilibrium phase transitions. We find that the maximum power output is achieved far-from-equilibrium in the synchronization regime and that the efficiency at maximum power is surprisingly close to the universal linear regime prediction. Our work builds bridges between thermodynamics of nonequilibrium phase transitions and bifurcation theory.

15 min. break

DY 43.9 Wed 12:30 BH-N 243

Records of entropy production in a double quantum dot — •Edgar Roldan[1], Shilpi Singh[2], Izaak Neri[1], Ivan Khaymovich[1], Dmitry Golubev[2], Ville Maisi[3], Joonas Peltonen[2], Frank Jülicher[1], and Jukka Pekola[2] — [1]Max Planck Institute for the Physics of Complex System (Dresden, Germany) — [2]Low Temperature Laboratory, Aalto University (Aalto, Finland) — [3]Lund University (Lund, Sweden)

Little is known about extreme-value statistics of thermodynamic fluxes characterising the most extreme deviations from the average behaviours. We report on the experimental measurement of stochastic entropy production and of records of negative entropy. For this purpose we employ a metallic double dot under a constant external DC bias which realizes Markovian nonequilibrium steady states. We find that the cumulative distribution of entropy production's negative record is bounded at all times by a limiting exponential distribution with a mean value equal to minus the Boltzmann constant. Using this result, we derive an upper bound for the average maximal entropy influx from the environment to a mesoscopic system in a finite time, and demonstrate this result with experimental data. Our work provides bounds for the maximal fluctuations of single-electronic currents against the direction of the electric field. Furthermore, our results may shed light on the statistics of overheating events in single-electronic devices which are key for the design of reversible computing nano-devices operating near Landauer's principle of minimal heat dissipation.

DY 43.10 Wed 12:45 BH-N 243

Testing optimality of sequential decision-making — •Izaak Neri[1,2,5], Meik Dörpinghaus[3,5], Édgar Roldán[1,5], Heinrich Meyr[4,5], and Frank Jülicher[1,5] — [1]Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Straße 38, 01187 Dresden, Germany — [2]Max Planck Institute of Molecular Cell Biology and Genetics, Pfotenhauerstraße 108, 01307 Dresden, Germany — [3]Vodafone Chair Mobile Communications Systems, Technische Universität Dresden, 01062 Dresden, Germany — [4]Institute for Integrated Signal Processing Systems, RWTH Aachen University, 52056 Aachen, Germany — [5]Center for Advancing Electronics Dresden, 01062 cfaed, Germany

Sequential decision making studies how a device makes as fast as possible decisions based on the sequential observation of a stochastic process. Here, a statistical test for the optimality of black box decision devices and a related measure for the divergence to optimality of black box decision devices are presented; a device is optimal if the average decision time – over different realisations of the observed process – is minimal given a certain maximal allowed error probability. A relation between the presented statistical test and the recently derived fluctuation theorems for first-passage times of entropy production is discussed [1]. Numerical experiments illustrate the use of the test for practical purposes.

[1]I Neri, É Roldán, F Jülicher, Statistics of Infima and Stopping Times of Entropy Production and Applications to Active Molecular Processes, Physical Review X 7, 011019 2017

DY 43.11 Wed 13:00 BH-N 243

Towards a (stochastic) thermodynamic description of non-Markovian delayed systems — •Sarah A. M. Loos and Sabine H. L. Klapp — Institut für Theoretische Physik, TU Berlin, Hardenbergstraße 36, D-10623 Berlin, Germany

Stochastic thermodynamics provides a consistent description of a wide class of Langevin systems, but the Markov assumption is often crucial [1]. However, time-delayed feedback control – which commonly arises for example in biological processes and technical applications – renders stochastic dynamics non-Markovian [2]. Therefore, some basic concepts need to be revisited [3]. Time-delay further pushes the steady states out of thermodynamic equilibrium (even in the absence of probability currents), as reflected by a non-zero mean entropy production. This is explicitly shown in [4] for the case of linear forces and an exponential memory kernel in one dimension.

Here, we discuss the possibility of calculating key thermodynamic quantities in the steady state of overdamped Langevin systems involving different memory kernels and nonlinear external forces. Using a Markovian embedding, we find a divergent entropy production in the case of error-free and continuous measurement. Furthermore, we present an analytical expression for the heat exchange rates that only involves positional moments.

[1] U. Seifert, Rep. Prog. Phys. **75**, 126001 (2012).
[2] S. A. M. Loos and S. H. L. Klapp, PRE **96**, 012106 (2017).
[3] M. L. Rosinberg, T. Munakata, G. Tarjus, PRE **91**, 042114 (2015).
[4] A. Crisanti, A. Puglisi, D. Villamaina, PRE **85**, 061127 (2012).

DY 43.12 Wed 13:15 BH-N 243

Stochastic aspects of thermodynamic irreversibility in nanoscale friction — •Paola Carolina Torche, Andrea Silva, Denis Kramer, Tomas Polcar, and Ondrej Hovorka — University of Southampton, Southampton, UK

Understanding the energy dissipation occurring during the nanoscale friction processes remains an open challenge. This is partly due to the lack of availability of a consistent and sufficiently general thermodynamic framework that would allow separating the microscopic, fluctuating, work performed by a nanoscale slider into the relevant internal energies and the irreversible heat produced during the motion.

In this talk we discuss the possibility of applying the principles of the modern stochastic thermodynamics [1] to quantify the fluctuating work and irreversible heat at the coarse-grained level of description of nanoscale friction, namely to the stochastic trajectories generated by the tip of Friction Force microscope [2]. By considering the Prandtl-Tomlinson model of a stick-slip frictional motion augmented by thermal fluctuations modelled by the transition state theory, we show that it is possible to fully quantify the stochastic entropy, work and heat distributions associated with the sliding motion. We then discuss the possibilities of validating the developed computational approach with Atomic Force Microscopy experiments.

[1] U. Seifert, Stochastic thermodynamics, fluctuation theorems, and molecular machines, Rep. Prog. Phys. 75, 126001 (2012).
[2] Gnecco et al, Velocity dependence of atomic friction, Phys. Rev.

Lett. 84, 1172 (2000).

DY 43.13 Wed 13:30 BH-N 243

Coherence of biochemical oscillations is bounded by driving force and network topology — •Andre Barato — Max Planck Institute for the Physics of Complex Systems

Biochemical oscillations are prevalent in living organisms. Systems with a small number of constituents cannot sustain coherent oscillations for an indefinite time because of fluctuations in the period of oscillation. We show that the number of coherent oscillations that quantifies the precision of the oscillator is universally bounded by the thermodynamic force that drives the system out of equilibrium and by the topology of the underlying biochemical network of states. Our results are valid for arbitrary Markov processes, which are commonly used to model biochemical reactions. We apply our results to a model for a single KaiC protein and to an activator-inhibitor model that consists of several molecules. From a mathematical perspective, based on strong numerical evidence, we conjecture a universal constraint relating the imaginary and real parts of the first nontrivial eigenvalue of a stochastic matrix.

A. C. Barato and U. Seifert; Phys. Rev. E 95, 062409 (2017)