DY 9: Statistical Physics far from Thermal Equilibrium

Time: Monday 15:00–18:30 Location: H47

DY 9.1 Mon 15:00 H47

Shear-driven diffusion with stochastic resetting — •Iman Abdoli, Kristian Stølevik Olsen, and Hartmut Löwen — Institut für Theoretische Physik II - Weiche Materie, Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany

Here, we explore the non-equilibrium dynamics that emerge from the interplay between linear shear flow and stochastic resetting. The particle diffuses with a constant diffusion coefficient while simultaneously experiencing linear shear and being stochastically returned to its initial position at a constant rate. We perturbatively derive the steady-state probability distribution that captures the effects of shear-induced anisotropy on the spatial structure of the distribution. We show that the dynamics, which initially spread diffusively, will at late times reach a steady state due to resetting. At intermediate timescales, the system approaches this steady state either by passing through a superdiffusive regime (in the shear-dominated case) or by exhibiting purely sub-diffusive behavior (in the resetting-dominated case). The steady state also gains cross correlations, a feature absent in simpler resetting systems. We also show that the skewness has a non-monotonic behavior when one passes from the shear-dominated to the resetting-dominated regime. We demonstrate that at small resetting rates, the energetic cost of maintaining the steady state becomes significantly higher due to the displacement caused by shear, a unique scaling not seen without shear. Surprisingly, if only the x-position is reset, the system can maintain a Brownian yet non-Gaussian diffusion pattern with non-trivial tails in the distribution.

DY 9.2 Mon 15:15 H47

Propulsion force and heat exchange for nonreciprocal nanoparticles — •Laila Henkes[1], Kiryl Asheichyk[2], and Matthias Krüger[1] — [1]Institute for Theoretical Physics, Georg-August-Universität — [2]Department of Theoretical Physics and Astrophysics, Belarusian State University

Nonreciprocity allows for interesting new phenomena in Casimir physics, such as propulsion forces pointing in translationally invariant directions, and persistent heat currents between objects of the same temperatures. To study these quantities, we derive general formulas for heat transfer and Casimir force involving a non-reciprocal point particle. These display how nonreciprocity of the particle couples to the nonreciprocity of the surrounding and also yield conditions for persistent heat current or propulsion force. Furthermore, we find a bound for the propulsion force acting on a point particle in terms of its heat exchange. This is, e.g., relevant for the efficiency of this arrangement when used as a heat engine.

DY 9.3 Mon 15:30 H47

Exponential change of relaxation rate by quenched disorder — •Jan Meibohm and Sabine H. L. Klapp — Technische Universität Berlin, Institut für Theoretische Physik, Hardenbergstraße 36, 10623 Berlin, Germany

We determine the asymptotic relaxation rate of a Brownian particle in a harmonic potential perturbed by quenched Gaussian disorder, a simplified model for rugged energy landscapes in complex systems. Depending on the properties of the disorder, we show that the mean and variance of the asymptotic relaxation rate are non-monotonous functions of the parameters for a broad class of disorders. In particular, the rate of relaxation may either increase or decrease exponentially compared to the unperturbed case, implying that the effect of disorder is stronger than that associated with other, well-studied anomalous-relaxation effects. In the limit of weak disorder, we derive the probability distribution of the asymptotic relaxation rate and show that it is Gaussian, with analytic expressions for the mean and variance that feature universal limits. Our findings indicate that controlled disorder may serve to tune the relaxation speed in complex systems.

DY 9.4 Mon 15:45 H47

Mean back relaxation for position, densities and others — •Gabriel Knotz and Matthias Krüger — Institute for theoretical physics, Göttingen, Germany

Recently, a so-called mean back relaxation (MBR) has been introduced, which correlates a scalar observable at three time points. The deviation of its long-time value from 1/2 has been shown to be a marker for breakage of time-reversal symmetry for observables with finite mean. We have extended the discussion by introducing a cut off length when evaluating the MBR from trajectories. For Gaussian systems we can derive a relation between MBR and the mean squared displacement and demonstrate that the MBR can be easily applied to stochastic observables like positions and densities. We discuss the application of the density MBR to multi-particle systems.

[1] Gabriel Knotz and Matthias Krüger, Mean back relaxation for position and densities, Phys. Rev. E 110, 044137 (2024)

[2] Till M. Muenker, Gabriel Knotz, Matthias Krüger and Timo Betz, Accessing activity and viscoelastic properties of artificial and living systems from passive measurement, Nature Materials 23, pages 1283*1291 (2024)

Invited Talk DY 9.5 Mon 16:00 H47

Large-deviation simulations of non-equilibrium stochastic processes — •Alexander K. Hartmann — University of Oldenburg, Germany

Stochastic processes are investigated by obtaining the probability distributions $P(S)$ of relevant quantities S of interest. A full description is obtained, if $P(S)$ is known over its full range of support. Also the structure of the entities contributing to the different parts of $P(S)$ are of interest. Usually analytical calculations are not feasible, so most of the time one has to use numerical simulations. Unfortunately, most of the support, in particular in the tails, is not accessible by standard algorithms.

By applying special large-deviation algorithms, also the tails can be accessed, down to probabilities such as 10^{-200}, or even much smaller. Here, a very general *black-box* algorithm [1] is explained, which allows one to study rather arbitrary stochastic processes. Some application examples are shown, such as force-induced RNA unfolding [2], S being the physical work W; interface growth [3], S being the height H; fractional Brownian motion [4], S being the area A under the curve; or the spread of diseases [5], S being the number of infected.

[1] A.K. Hartmann, Phys. Rev. E **89**, 052103 (2014)
[2] P. Werner and A.K. Hartmann, Phys. Rev. E **104**, 034407 (2021)
[3] A.K. Hartmann, P. Le Doussal, S.N. Majumdar, A. Rosso and G. Schehr, Europhys. Lett. **121**, 67004 (2018)
[4] A.K. Hartmann and B. Meerson, Phys. Rev. E **109**, 014146 (2024)
[5] Y. Feld and A.K. Hartmann, Phys. Rev. E **105**, 034313 (2022)

15 min. break

DY 9.6 Mon 16:45 H47

Dissipation bounds precision of current response to kinetic perturbations — •Krzysztof Ptaszyński[1,2], Timur Aslyamov[1], and Massimiliano Esposito[1] — [1]Department of Physics and Materials Science, University of Luxembourg, L-1511 Luxembourg City, Luxembourg — [2]Institute of Molecular Physics, Polish Academy of Sciences, Mariana Smoluchowskiego 17, 60-179 Poznań, Poland

The precision of currents in Markov networks is bounded by dissipation via the so-called thermodynamic uncertainty relation (TUR). We conjecture [1] and prove [2] a similar inequality that bounds the precision of the static current response to perturbations of kinetic barriers. Perturbations of such type, which affect only the system kinetics but not the thermodynamic forces, are highly important in biochemistry and nanoelectronics. Our inequality cannot be derived from the standard TUR, but rather implies it and provides an even tighter bound for dissipation. We also provide a procedure for obtaining the optimal response precision for a given model.

[1] Phys. Rev. Lett. 133, 227101 (2024)
[2] arXiv:2410.17140

DY 9.7 Mon 17:00 H47

Theory of Nonequilibrium Responses for Markov Jump Processes — •Timur Aslyamov[1] and Massimiliano Esposito[2] — [1]University of Luxembourg, Luxembourg — [2]University of Luxembourg, Luxembourg

The theory of nonequilibrium responses in complex systems to parameter perturbations is fundamental, spanning disciplines from ecology to metabolic control and the design of low-noise devices. The framework of Markov jump processes is one of the most popular approaches for studying a broad range of nonequilibrium phenomena across various fields.

In recent papers [1, 2], we formulated a theory of static response for Markov jump processes under arbitrary parameterizations. Leveraging stochastic thermodynamics, we developed a novel approach based on simple linear algebra, enabling us to extend beyond previously known results. Through our analysis, we uncovered a novel fundamental property of Markov processes: the responses are constrained by specific linear combinations, which we term the Summation and Cycles Response Relations.

[1] Aslyamov, T., and Esposito, M. (2024). Nonequilibrium Response for Markov Jump Processes: Exact Results and Tight Bounds. Physical Review Letters, 132(3), 037101.

[2] Aslyamov, T., and Esposito, M. (2024). General Theory of Static Response for Markov Jump Processes. Physical Review Letters, 133(10), 107103.

DY 9.8 Mon 17:15 H47

How topologically distinct non-equilibrium currents imprint on projected observables — •Felix Tippner and Aljaz Godec — Max Planck Institute for Multidisciplinary Sciences, Göttingen, Germany

Almost all measurements track only a limited subset of degrees of freedom simultaneously. Mathematically, the higher-dimensional stochastic process governing a physical system (e.g., the dynamics of protein conformation) is accessible only through observables of projected dynamics, which, in practice, are constrained by strict experimental limitations. These projections not only introduce or amplify non-Markovian effects but also obscure features such as irreversible currents (e.g., driven versus non-driven systems) or barriers in the underlying energy landscape. In our work we investigate how topological and geometric properties imprint on projected dynamics that appear similar (i.e., those exhibiting the same observed steady state), both in and out of equilibrium. This is achieved by examining path-wise observables, such as empirical densities and currents inferred from projected trajectories, through a detailed analysis of their fluctuations and (cross-)correlations.

DY 9.9 Mon 17:30 H47

Slow relaxation in a facilitated trap model — •Gregor Diezemann — Department Chemie, JGU Mainz

Trap models have successfully been applied to understand a number of relaxation features of simulated and real-world supercooled liquids. A common choice for the transition rates is that the system leaves a trap and chooses the destination trap at random. Depending on the form of the prior distribution of trap energies, a broad the relaxation spectrum results. Recently, a facilitated trap model (FTM) in which each transition is accomponied by a small change in the energies of all traps equivalent to a diffusion of trap energies has been implemented. It has been shown that a strong asymmetry of susceptibilities can be obtained with reasonable assumptions regarding the model parameters(1).

In the present contribution, we present the numerical solution of the master equation for the FTM and discuss the relaxation behavior of various one-time and two-time quantities, both in equilibrium and in the particular non-equilibrium situation encountered after temperature jumps, such as in typical aging experiments. Using a model of random rotational jumps for the reorientational motion, the linear dielectic susceptibility in thermal equlibrium is found to be given as a convolution of a Debye-like response originating from the energy drift inherent in the FTM and the response of the original trap model.

(1) C. Scalliet, B. Guiselin, and L. Berthier, J. Chem. Phys. 155, 064505 (2021).

DY 9.10 Mon 17:45 H47

Nonequilibrium shortcuts and anomalous thermal relaxations: the Mpemba effect — •Gianluca Teza[1], John Bechhoefer[2], Antonio Lasanta[3], Oren Raz[4], and Marija Vucelja[5] — [1]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany — [2]Simon Fraser University, Burnaby, Canada — [3]Universidad de Granada, Ceuta, Spain — [4]Weizmann Institute of Science, Rehovot, Israel — [5]University of Virginia, Charlottesville, USA

Most of our intuition about the behavior of physical systems is shaped by observations at or near thermal equilibrium. However, even a phenomenon as basic as a thermal quench leads to states far from any thermal equilibrium, where counterintuitive effects can occur. A prime example of anomalous thermal relaxation is the Mpemba effect, a phenomenon in which a hot system cools down faster than an equivalent colder one. Although originally witnessed in water, perspectives towards the design of optimal heating/cooling protocols and observations in a variety of systems pushed the development of a high-level characterization in the framework of nonequilibrium statistical mechanics. In this talk, I will review the phenomenology of this and related anomalous relaxation effects, in which nonmonotonic relaxation times act as the common denominator. With a focus on Ising systems, I will provide insight on the physical mechanisms that enable their emergence. I will show how they can survive arbitrarily weak couplings, highlighting the role played by equilibrium and dynamical features, as well as experimental observation of these effects in quantum simulators.

DY 9.11 Mon 18:00 H47

Power-Efficiency Trade-offs in Finite-Time Thermodynamics: From Minimal Model to General Principle — •Shiling Liang[1,2,3,4], Yu-Han Ma[5,6], Daniel Maria Busiello[4], and Paolo De Los Rios[1] — [1]EPFL, Lausanne, Switzerland — [2]Okinawa Institute of Science and Technology, Okinawa, Japan — [3]Center for Systems Biology Dresden, Dresden, Germany — [4]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany — [5]Beijing Normal University, Beijing, China — [6]Graduate School of China Academy of Engineering Physics, Beijing, China

Thermodynamic systems operating in finite time face fundamental trade-offs between power output and efficiency. While conventional wisdom dictates that Carnot efficiency is only attainable in the quasistatic limit with vanishing power, we demonstrate theoretically that this constraint can be circumvented in finite-time operations. We present a minimal heat engine model incorporating intrinsic energy level degeneracy that achieves Carnot efficiency at maximum power in the thermodynamic limit. The enhanced performance originates from first-order phase transitions far from the linear response regime, enabled by collective effects in many-body systems. Our results reveal how collective advantages can fundamentally alter power-efficiency trade-offs and suggest new strategies for designing efficient heat engines operating at finite times far from equilibrium.

[1] Liang, S., Ma, Y. H., Busiello, D. M., & De Los Rios, P. (2023). A Minimal Model for Carnot Efficiency at Maximum Power. arXiv preprint arXiv:2312.02323.

DY 9.12 Mon 18:15 H47

Fluctuating diffusivity in living cells: Analog of Carnot engine — •Yuichi Itto — Aichi Institute of Technology, Japan — ICP, Universität Stuttgart, Germany

The diffusivity fluctuating over local areas of living cells is experimentally known to obey the exponential law for normal/anomalous diffusion. In Ref. [1], a formal analogy of the fluctuating diffusivity to thermodynamics has been studied. Remarkably, the exponential law is formally equivalent to the "canonical distribution": the diffusivity, which is proportional to local temperature of the cell in nonequilibrium stationary states [2], is identified with the analog of the system energy. Consequently, the analogs of the internal energy, the quantity of heat, work, and the Clausius inequality have been established.

Here, the analog of the heat engine is constructed for the fluctuating diffusivity [3]. This heat-like engine consists of processes realized by compression/expansion of the cell and the change of temperature, along which the average value of the diffusivity or local temperature is kept fixed. The efficiency of the engine in a cycle, which characterizes how much the diffusivity change as the analog of work is extracted, is found to formally take that of Carnot's. The result is expected to be useful, for example, for tuning the rates of biochemical reactions in cells, see, e.g., Ref. [4].

References [1] Y. Itto, Entropy, 23, 333 (2021). [2] Y. Itto and C. Beck, J. Royal Society Interface, 18, 20200927 (2021). [3] Y. Itto, in preparation. [4] N. Bellotto, J. Agudo-Canalejo, R. Colin, R. Golestanian, G. Malengo, and V. Sourjik, eLife, 11, e82654 (2022).