DY 6: Statistical Physics far from Thermal Equilibrium I

Time: Monday 9:30–13:00 Location: BH-N 334

Invited Talk DY 6.1 Mon 9:30 BH-N 334

Barrier crossing with non-Gaussian noise: Exponential transition rate gains and effects of active motion — •Peter Sollich[1], Adrian Baule[2], and Diego Tapias[1] — [1]Institute for Theoretical Physics, University of Goettingen, Friedrich-Hund-Platz 1, D-37077 Goettingen, Germany — [2]School of Mathematical Sciences, Queen Mary University of London, London E1 4NS, UK

Noise-induced escape from metastable states governs a plethora of transition phenomena in physics, chemistry, and biology. While the escape problem for thermal Gaussian noise has been well understood since the seminal works of Arrhenius and Kramers, many systems, in particular living ones, are effectively driven by non-Gaussian noise for which the conventional theory does not apply. Here we present a theoretical framework based on path integrals that allows the calculation of both escape rates and optimal escape paths for a generic class of non-Gaussian noises. We find that non-Gaussian noise always leads to more efficient escape and can enhance escape rates by many orders of magnitude compared with thermal noise, highlighting that away from equilibrium escape rates cannot be reliably modelled based on the traditional Arrhenius-Kramers result. Our analysis also identifies a new universality class of non-Gaussian noises, for which escape paths are dominated by large jumps. We outline finally how the approach can be extended to barrier crossing by self-propelled particles with active Brownian or run-and-tumble motion, and show that dynamical phase transitions can be used to sort such particles according to the persistence of their active motion.

DY 6.2 Mon 10:00 BH-N 334

Minimum-dissipation principle for synchronised stochastic oscillators far from equilibrium — •Jan Meibohm[1,2] and Massimiliano Esposito[3] — [1]Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany — [2]Department of Mathematics, King's College London, London WC2R 2LS, United Kingdom — [3]Complex Systems and Statistical Mechanics, Department of Physics and Materials Science, University of Luxembourg, L-1511 Luxembourg, Luxembourg

We study driven q-state Potts models with thermodynamically consistent dynamics and global coupling. For a broad range of parameters, these coupled-oscillator models exhibit a dynamical phase transition from a decoherent into a synchronised phase. We derive the normal form of the high-dimensional Hopf-Bifurcation that underlies the phase transition, for arbitrary dynamics and for all q. The normal-form equations are exact in the thermodynamic limit and close to the bifurcation. Making use of the symmetries, we solve these equations exactly and thus uncover the intricate long-time behaviour of driven Potts models, characterised by a rich phase diagram. Connecting with the macroscopic thermodynamics, we show that synchronisation always reduces dissipation. Remarkably, we find that the most stable synchronised states dissipate the least entropy. Close to the phase transition, we discover a linear dissipation-stability relation that connects dissipation with phase-space contraction, a widely-used stability measure. Our findings suggest a minimum-dissipation principle for driven Potts models that holds arbitrarily far from equilibrium.

DY 6.3 Mon 10:15 BH-N 334

Fluctuations in nonequilibrium complex systems: conditional entropy and weak correlation — •Yuichi Itto — Aichi Institute of Technology, Aichi, Japan — ICP, Universität Stuttgart, Stuttgart, Germany

Nonequilibrium complex systems are often organized hierarchically by different dynamics on different time scales. The statistical property of spatiotemporal fluctuations concerning the dynamics is known to be essential for treating a wide class of such systems. Maximum entropy principle has played a crucial role for describing the statistical fluctuation distribution in the literature, not limited to characterizing the equilibrium systems.

Here, an entropic approach [1] is discussed for describing the conditional distribution in nonequilibrium complex systems with two different dynamics that exhibit a weak correlation between associated fluctuations. It is shown that the conditional fluctuation distribution is governed by the weak correlation in a unified manner. The result is illustrated in heterogeneous diffusion phenomena observed in living cells: DNA-binding proteins in bacteria [2], as well as membraneless organelles in embryos [3] and beads in cell extracts [4] as further possible examples.

References
[1] Y. Itto, Entropy, 25, 556 (2023).
[2] A.A. Sadoon and Y. Wang, Phys. Rev. E, 98, 042411 (2018).
[3] R. Benelli and M. Weiss, New J. Phys., 23, 063072 (2021).
[4] K. Speckner and M. Weiss, Entropy, 23, 892 (2021).

DY 6.4 Mon 10:30 BH-N 334

Non-equilibrium generalized Langevin equation from a generic time-dependent Hamiltonian — •Benjamin Héry and Roland R. Netz — Fachbereich Physik, Freie Universität Berlin, 14195 Berlin, Department of Physics

It has become standard practice to describe non-equilibrium phenomena by heuristic Langevin equations with colored noise and time-dependent friction kernels that do not obey the fluctuation-dissipation theorem. Since these models are not derived from first-principle Hamiltonian dynamics, it is not clear whether they correspond to physically realizable scenarios. By exact Mori projection in phase space, we derive the non-equilibrium generalized Langevin equation (GLE) from a generic many-body Hamiltonian with a time-dependent force h(t) acting on an arbitrary phase-space dependent observable. The GLE is obtained in explicit form to all orders in h(t). We show that if the observable that is described by the GLE is Gaussian and related to the time-dependent Hamiltonian perturbation term, the resultant non-equilibrium GLE has the same form as the equilibrium GLE and obeys a fluctuation-dissipation theorem. This means that the extraction and simulation methods developed for equilibrium GLEs can be used also for non-equilibrium Gaussian variables. This is a non-trivial and very useful result, as many observables that characterize non-equilibrium systems display Gaussian statistics.

DY 6.5 Mon 10:45 BH-N 334

Non-equilibrium thermodynamics of a particle driven by time-delayed feedback — •Robin A. Kopp and Sabine H. L. Klapp — Institut für Theoretische Physik, TU Berlin, Berlin, Germany

Time-delayed feedback can act as a propulsion mechanism, which has recently been demonstrated and studied both theoretically [1] and experimentally [2]. In two-dimensional systems and for suitable feedback parameters, persistent motion occurs despite fluctuations, resembling the behavior of self-propelled particles [3]. Using the framework of stochastic energetics [4] we here study the thermodynamic properties of a colloidal particle in two dimensions driven by time-delayed feedback. Focusing on the dissipated heat, we combine analytical and numerical methods to gain insights into the onset of persistent motion, which occurs above a threshold value in parameter space. Above the threshold of persistent motion we furthermore compare to the well-established active Brownian particle model for self-propulsion with corresponding parameters. Finally we show that even below the threshold a non-zero heat dissipation is to be expected and can indeed be found in numerical simulations.

[1] Kopp R. A. and Klapp S. H. L., Phys. Rev. E, **107** (2023) 024611
[2] Bell-Davies M. C. R., Curran A., Liu Y. and Dullens R. P. A., Phys. Rev. E, **107** (2023) 064601
[3] Kopp R. A. and Klapp S. H. L., EPL **143**, 17002 (2023)
[4] Sekimoto K., Prog. Theor. Phys. Supp. **130**, 17 (1998)

DY 6.6 Mon 11:00 BH-N 334

Memory induced Magnus forces in viscoelastic fluid — •Debankur Das[1], Niklas Windbacher[2], Xin Cao[2], Matthias Krueger[1], and Clemens Bechinger[2] — [1]University of Goettingen — [2]University of Konstanz

When a spinning object moves through a fluid, its direction of motion becomes deflected due to the Magnus force that is perpendicular to both the moving direction and the spinning axis. Since the Magnus effect is caused by inertial effects within the surrounding medium, it is expected to vanish at micro scales where viscous forces dominate over inertia. Our recent experiments have observed a surprisingly strong Magnus effect when spinning colloids are driven through a viscoelastic fluid. Here, we discuss a theoretical framework for such motion, which shows that the Magnus force is caused by finite memory of the viscoelastic fluid, which can last of the order of seconds. This causes a deformation of the fluidic network around the moving particle. When the particle additionally spins, the deformation field becomes misaligned relative to the particle's moving direction, leading to a force perpendicular to the direction of travel and the spinning axis. Our theory predicts that the Magnus motion persists for some time even when the spinning stops, successfully verified by our experiments. The presence of strongly enhanced memory-induced Magnus forces at microscales opens novel applications for particle sorting and steering, the creation and visualization of anomalous flows and more.

15 min. break

DY 6.7 Mon 11:30 BH-N 334

Thermal relaxation asymmetry in reversible and driven systems — •Cai Dieball[1], Miguel Ibáñez[2], Gerrit Wellecke[1,3], Antonio Lasanta[2], Raúl A Rica[2], and Aljaz Godec[1] — [1]Max Planck Institute for Multidisciplinary Sciences, Göttingen — [2]Universidad de Granada, Spain — [3]Present address: Max Planck Institute for Dynamics and Self-Organization, Göttingen

It was theoretically predicted that small systems subject to temperature changes that push the system far from thermodynamic equilibrium feature an asymmetric thermal relaxation. More precisely, heating was predicted to be faster than cooling [1]. Here, by using an optically trapped colloidal particle, we confirm this prediction [2]. Developing a new theoretical framework that we call *thermal kinematics*, we quantify relaxation between arbitrary pairs of temperatures.

To complete the non-equilibrium picture of thermal relaxation, we also prove the relaxation asymmetry for systems inherently driven out of equilibrium [3]. The resulting relaxation highlights the absence of local equilibria and surprisingly features opposing rotational motions during heating and cooling.

References:
[1] Lapolla & Godec, *Phys. Rev. Lett.* **125**, 110602 (2020)
[2] Ibáñez, Dieball, Lasanta, Godec & Rica, accepted in *Nat. Phys.* (2023)
[3] Dieball, Wellecke & Godec, accepted in *Phys. Rev. Research* (2023)

DY 6.8 Mon 11:45 BH-N 334

Powerful ordered collective heat engines — •Fernando Silva Filho[1,2,3], Gustavo Forao[1], Daniel Busiello[4], Bart Cleuren[3], and Carlos Fiore[1] — [1]University of São Paulo, Instituto de Física, Rua do Matão, 1371, 05508-090 São Paulo, SP, Brazil — [2]Institute for Theoretical Physics IV, University of Stuttgart - 70569 Stuttgart, Germany — [3]UHasselt, Faculty of Sciences, Theory Lab, Agoralaan, 3590 Diepenbeek, Belgium — [4]Max Planck Institute for the Physics of Complex Systems, 01187 Dresden, Germany

In this talk, we present a recently published work (PhysRevResearch.5.043067) about a class of interacting heat engines in which the regime of units operating synchronously (in ordered phase) can boost the performance. Our approach encompasses a minimal setup composed of N interacting units placed in contact with two thermal baths and subjected to a constant driving worksource. The interplay between unit synchronization and interaction leads to an efficiency at maximum power between the Carnot η_C and the Curzon-Ahlborn bound η_{CA}. Moreover, these limits can be respectively saturated maximizing the efficiency, and by simultaneous optimization of power and efficiency. We show that the interplay between Ising-like interactions and a collective ordered regime is crucial to operate as a heat engine. The main system features are investigated developing an effective discrete-state model that captures the effects of the synchronous phase. The robustness of our findings extends beyond the all-to-all interactions and paves the way for the building of promising far from equilibrium thermal engines based on ordered structures.

DY 6.9 Mon 12:00 BH-N 334

Conditioning in equilibrium and nonequilibrium baths — •Ion Santra and Matthias Krüger — University of Goettingen

Generalized linear Langevin equations are a popular way of describing tracer dynamics in viscoelastic baths. In this talk, starting from a microscopic bath model, I will discuss how the usual form of Generalized Langevin equations are no more valid in the case of nonequilibrium baths. We show that the term dependent on the initial conditions, which is usually dropped for equilibrium baths, become important. A simple way to understand the contribution from this term is to look at conditioned displacements of the tracer in stationary state.

DY 6.10 Mon 12:15 BH-N 334

Thermophoresis and the breakdown of local equilibrium in a far-from-equilibrium bath — •Wade Hodson[1] and Aljaz Godec[2] — [1]Max Planck Institute for Multidisciplinary Sciences, Göttingen, Germany — [2]Max Planck Institute for Multidisciplinary Sciences, Göttingen, Germany

We investigate the nonequilibrium steady state properties of a far-from-equilibrium bath, consisting of a chain of harmonic oscillators coupled at the ends to stochastic heat reservoirs at different temperatures. This system, if coupled to a tracer particle, can serve as a medium in which the tracer diffuses in response to the applied thermal gradient, a phenomenon known as thermophoresis. We evaluate interparticle correlations, time-integrated heat current statistics, and other diagnostic properties of the harmonic bath to study how local thermal equilibrium breaks down for large temperature gradients, a regime where thermophoresis still lacks a general theoretical description. These analytical results are supplemented by numerical computations. We also present a preliminary analysis of the effect of the bath on a tracer using the Kac-Zwanzig formalism, which produces an effective equation of motion for the tracer alone.

DY 6.11 Mon 12:30 BH-N 334

Mean Back Relaxation for Position and Densities — •Gabriel Knotz and Matthias Krüger — Institute for Theoretical Physics, Göttingen, Germany

Quantifying detailed balance breakage from particle trajectories is an important problem in simulation and experiment. Recently, it was shown that the mean back relaxation (MBR) of displacements along a particle trajectory can serve as a non-equilibrium marker in confinement. To extend the validity to unconfined systems, we propose a new version of the MBR that is defined on the microscopic particle density function which marks the breakage of detailed balance even in bulk, and discuss general properties of the MBR. [1][2]

[1] Till M. Muenker, Gabriel Knotz, Matthias Krüger and Timo Betz. *Onsager regression characterizes living systems in passive measurements.* bioRxiv:2022.05.15.491928
[2] Gabriel Knotz, Matthias Krüger. *Mean Back Relaxation for Position and Densities.* arXiv:2311.17477

DY 6.12 Mon 12:45 BH-N 334

Selfconsistent diagrammatic transport for light including time reversal symmetric entropy production — •Regine Frank[1,2] and Bart A. van Tiggelen[3] — [1]College of Biomedical Sciences, Larkin University, Miami, Florida, USA — [2]Donostia International Physics Center, 20018 Donostia-San Sebastian, Spain — [3]University Grenoble Alpes, Centre National de la Recherche Scientifique, LPMMC, Grenoble, France

We present novel theory and numerics for transport of light in random complex media, where the production of entropy is positive under time reversal, an Onsager scenario. Numerical solutions based on weighted essentially non-oscillatory solvers (WENO) are introduced. Anderson localization is quantitatively discussed.

[1] R. Frank, A. Lubatsch, Phys. Rev. Research 2, 013324 (2020). [2] D. Vollhardt and P. Wölfle, Phys. Rev. B 22, 4666 (1980). [3] P. D. Lax and R. D. Richtmyer, Commun. Pure Appl. Math. 9, 267 (1956). [4] A. Lubatsch, J. Kroha, K. Busch, Phys. Rev. B.71, 184201 (2005) [5] R. Frank, A. Lubatsch, J. Kroha, Phys. Rev. B 73, 245107 (2006). [6] B. A. van Tiggelen, A. Lagendijk, and A. Tip, Phys. Rev. Lett. 71, 1284 (1993). [7] B. A. Van Tiggelen, Diffuse Waves in Complex Media, 1-60 (1999).