DY 9: Statistical Physics far from Thermal Equilibrium I

Time: Monday 9:30–12:15 Location: ZEU/0160

DY 9.1 Mon 9:30 ZEU/0160

Dissipation enables robust extensive scaling of multipartite correlations — •Krzysztof Ptaszyński[1,2], Maciej Chudak[1], and Massimiliano Esposito[2] — [1]Institute of Molecular Physics, Polish Academy of Sciences, Mariana Smoluchowskiego 17, 60-179 Poznań, Poland — [2]Complex Systems and Statistical Mechanics, Department of Physics and Materials Science, University of Luxembourg, 30 Avenue des Hauts-Fourneaux, L-4362 Esch-sur-Alzette, Luxembourg

We investigate the multipartite mutual information between N discrete-state stochastic units interacting in a network that is invariant under unit permutations [1]. We show that when the system relaxes to fixed point attractors, multipartite correlations in the stationary state either do not scale extensively with N, or the extensive scaling is not robust to arbitrarily small perturbations of the system dynamics. In particular, robust extensive scaling cannot occur in thermodynamic equilibrium. In contrast, mutual information scales extensively when the system relaxes to time-dependent attractors (e.g., limit cycles), which can occur only far from equilibrium. This demonstrates the essential role of dissipation in the generation and maintenance of multipartite correlations. We illustrate our theory with the nonequilibrium Potts model. Finally, we present a generalization of our approach to permutation-invariant open quantum systems [2].

[1] Phys. Rev. Lett. 135, 057401 (2025)
[2] Phys. Rev. E 112, 054137 (2025)

DY 9.2 Mon 9:45 ZEU/0160

Nested Stochastic Resetting: Nonequilibrium Steady States and Exact Correlations — •Callum Britton[1], Henry Alston[2], and Thibault Bertrand[1] — [1]Imperial College London, London, United Kingdom — [2]Laboratoire de Physique de l'Ecole Normale Supérieure, Paris, France

Stochastic resetting has gained a lot of traction over the past few years. It has been shown to drive the formation of nonequilibrium steady states and the optimization of first-passage properties in an analytically tractable setting. Yet, most works have thus far focused on single-particle stochastic resetting. In this talk, we introduce nested stochastic resetting, an exactly solvable, many-body stochastic resetting model achieved by harnessing resets as unilateral interactions between particles. We look at a system of n particles, where the position of particle i is independently reset to the instantaneous position of particle $i-1$ according to a Poisson process. We derive analytically the steady-state statistics of these nested stochastic resetting processes including the stationary distribution for each process as well as its moments. In this system, we go one step further and calculate exactly the steady-state two-point correlations $\langle x_i x_j \rangle$ between processes by mapping the problem to one of the ordering statistics of random counting processes. We expect this framework will both help build a model-independent framework for random processes with unilateral interactions and find immediate applications, e.g., in the modelling of lossy information propagation.

DY 9.3 Mon 10:00 ZEU/0160

Mutual linearity: A generic property of steady-state Markov networks — •Robin Bebon and Thomas Speck — Institute for Theoretical Physics 4, University of Stuttgart, Heisenbergstraße 3, 70569 Stuttgart, Germany

Nonequilibrium response theory has long sought universal principles to characterize the behavior of observables under external perturbations. While powerful tools exist near thermal equilibrium, general results far from equilibrium remain sparse and often rely on specific assumptions that severely limit their applicability, e.g., a specific parametrization of transition rates. In this work, we prove a remarkably simple, yet broadly applicable result: In a Markov network, any two steady-state probabilities remain linearly related when perturbing transition rates along a single edge of the network. This mutual linearity holds for every irreducible Markov network, arbitrarily far from equilibrium, and is independent of the chosen rate parametrization. As key implications, we demonstrate that the relative response of all states in the network is identical and show that analogous linear relations follow for a broad class of observables, including generic state-dependent and counting observables. Crucially, the coefficients that enter these linear relationships are empirically accessible, which makes our results not only conceptually significant but also provide a novel practical tool for inference and model validation in biological and chemical systems.

DY 9.4 Mon 10:15 ZEU/0160

Stochastic Path Integrals for Non-Markovian Dynamics: Fractional Operators, and Entropy Production — •Felipe Abril-Bermudez — Independent Researcher (formerly University of Aberdeen, UK)

Stochastic dynamics with long-range correlations, multiplicative noise, and memory effects give rise to rich non-equilibrium behaviors, including anomalous diffusion, metastability, and nontrivial entropy production. In this work, we develop a unified stochastic path integral (SPI) framework that extends the Parisi-Sourlas supersymmetric formalism to treat multidimensional Langevin systems with multiplicative noise, thresholds, and fractional operators driven by fractional Gaussian noise. The resulting generalized Fokker-Planck equation is solved for representative processes, enabling analytical estimation of Shannon entropy and entropy production rates, which exhibit the emergence of quasi-steady states with non-monotonic dissipation. In parallel, the formalism recovers the standard underdamped Langevin and Klein-Kramers results while providing a systematic treatment of non-Markovian dynamics responsible for anomalous transport, weak ergodicity breaking, and dynamical phases such as time glasses and time crystals. Thus, it is shown how the SPI can serve as a unified approach to study anomalous stochastic phenomena in complex systems.

DY 9.5 Mon 10:30 ZEU/0160

Thermophoresis of a tracer particle via coarse graining of an explicit nonequilibrium medium — •Wade Hodson and Aljaz Godec — Mathematical Physics and Stochastic Dynamics, Institute of Physics, University of Freiburg

We investigate the transport of a tracer particle embedded in an explicitly represented medium with a position-dependent temperature. The medium consists of a chain of harmonic oscillators, in which a temperature gradient is established by connecting each particle to its own heat reservoir. We then couple a tracer to this medium via a generic potential. Under these conditions, we find that the tracer preferentially diffuses in one direction due to the temperature gradient, a phenomenon known as thermophoresis. We study the model analytically in various regimes, including the weak coupling, low temperature, overdamped, Markovian, and hydrodynamic limits, and supplement these results with numerical computations. In the Markovian limit, we are able to coarse-grain over the medium's degrees of freedom to obtain a Langevin equation for the tracer, with a potential of mean force, a damping coefficient, and a diffusion coefficient which can be evaluated in the low-temperature regime. We focus on the analysis of this low-temperature Langevin equation, with a particular interest in the parameter regimes where the tracer can potentially exhibit negative thermophoresis, in which the tracer diffuses preferentially towards higher temperatures. Finally, we generalize our results to higher dimensions, by coupling the tracer to a two- or three-dimensional medium.

DY 9.6 Mon 10:45 ZEU/0160

Volterra Series leads to exact Dynamical Density Functional Theory — •Ion Santra — KU LEUVEN

We derive an exact Volterra series expansion for a mean mesoscopic field of an interacting particle system subject to a potential perturbation, expressing the Volterra expansion kernels in terms of the field's response functions, to any order. Applying this formalism to the mean particle density of a simple interacting fluid, we identify a form reminiscent of dynamical density functional theory, with, however, fundamental differences: A generally nonlocal mobility kernel appears, and the internal force derives from a functional of the *history* of mean density. In the limit of a slowly varying external force, the expansion kernels of this functional turn into the equilibrium direct correlation functions of the corresponding order, thereby, in this limit, recovering the equilibrium density functional. We identify a freedom in deriving this expansion, which, e.g., allows different forms of mobility kernels, and we explore two choices: A nonlocal mobility kernel results in a concise ans simple form to linear order. For interacting Brownian particles, a local mobility kernel results in a form reminiscent of previous forms for the density current.

15 min. break

DY 9.7 Mon 11:15 ZEU/0160

Thermal Relaxation on Random Graphs via Metropolis and Glauber Dynamics — •Marija Vucelja — University of Virginia, Charlottesville, US — MPI-PKS, Dresden, Germany

Efficient sampling algorithms rely on dynamics that drive a physical system rapidly toward its target state. I will introduce the Mpemba effect – an anomalous thermal relaxation phenomenon in which a system initially at a higher temperature cools down more quickly than one starting at a lower temperature – and its heating analog, in which a cooler initial state can lead to faster heating than a hotter initial state. We investigate thermal relaxation in quenched disordered systems under Metropolis and Glauber dynamics, examining how varying transition rates affect relaxation behavior. We show that Metropolis dynamics on a complete graph cannot exhibit the Mpemba effect, whereas on an incomplete graph it can. Even rank-one perturbations of the transition rates are sufficient to generate anomalous relaxation. Finally, we discuss the probability of observing the Mpemba effect in the large-temperature limit.

DY 9.8 Mon 11:30 ZEU/0160

Fermionic quantum criticality far from equilibrium — •Rohan Mittal, Tom Zander, Johannes Lang, and Sebastian Diehl — Universität Zu Köln

Driving a quantum system out of equilibrium while preserving its subtle quantum mechanical correlations on large scales presents a major challenge, both fundamentally and for technological applications. At its core, this challenge is pinpointed by the question of how quantum effects can persist at asymptotic scales, analogous to quantum critical points in equilibrium. In this work, we construct such a scenario using fermions as building blocks. These fermions undergo an absorbing-to-absorbing state transition between two topologically distinct and quantum-correlated dark states. Starting from a microscopic, interacting Lindbladian, we derive an effective Lindblad-Keldysh field theory in which critical fermions couple to a bosonic bath with hydrodynamic fluctuations associated with particle number conservation. A key feature of this field theory is an emergent symmetry that protects the purity of the fermions' state even in the presence of the thermal bath. We quantitatively characterize the critical point using a leading-order expansion around the upper critical dimension, thereby establishing the first non-equilibrium universality class of fermions. The symmetry protection mechanism, which exhibits parallels to the problem of directed percolation, suggests a pathway toward a broader class of robust, universal quantum phenomena in fermionic systems.

DY 9.9 Mon 11:45 ZEU/0160

ultrafast thermodynamics of the ferroelectric soft mode in laser-excited SrTiO3 — •Yulong Qiao and R. Matthias Geilhufe — Department of Physics, Chalmers University of Technology, Gothenburg, Sweden

Intense THz laser pulses allow to selectively pump and control optical phonon modes. This has led to the realization of metastable phases of matter, phonon-induced magnetism, and ultrafast magnetic switching. Following such a nonthermal path-way in the sub-picosecond timescale, has recently sparked questions on the temporal evolution of thermodynamic quantities, such as heat and entropy production, in the context of ultrafast thermodynamics [1].

In this work, we simulate the dynamics of the ferroelectric soft mode in SrTiO3 driven by a THz laser pulse using molecular dynamics [2]. We show that both the soft-mode dynamics and the associated energy transfer from the soft mode to other ionic degrees of freedom are accurately described by our stochastic thermodynamic theory. Moreover, the molecular dynamics simulations clearly reveal that the power spectral density of the noise is frequency-dependent. This indicates that the commonly adopted Markovian approximation breaks down. In this talk, I will also discuss the non-Markovian effects induced by the ultrafast laser pulse.

[1] L. Caprini, H. Löwen, and R. M. Geilhufe, Nature. Communication. 15, 94 (2024).

[2] F. Eriksson, Y. Qiao, E. Fransson, R. M. Geilhufe, and P. Erhart, in preparation.

DY 9.10 Mon 12:00 ZEU/0160

Ultrafast Thermodynamics - entropy, heat and criticality on picosecond timescales — •R. Matthias Geilhufe — Chalmers University of Technology, Gothenburg, Sweden

Materials are composed of a vast number of ions and electrons, arranging themselves in regular patterns. Due to immense progress in ultrafast spectroscopy, ranging from the low-frequency infrared to high-frequency X-ray regimes, collective excitations of charge, spin, lattice, and orbital degrees of freedom can now be triggered and probed on their characteristic time and length scales. Probing such excitations far from equilibrium motivates the field of ultrafast thermodynamics, which translates well-understood concepts, such as entropy and heat, to picosecond dynamics. I will introduce the concept of ultrafast thermodynamics using the example of entropy production due to laser-driven phonons [1] and magnons [2] using stochastic thermodynamics. Furthermore, I will show extensions of the formalism to non-Markovian behavior and quantum mechanics.

[1] L. Caprini, H. Löwen, R. M. Geilhufe, Nature Communications, 15, 94 (2024) [2] F. Tietjen, R. M. Geilhufe, PNAS Nexus, 4, 3 (2025)