DY 31: Focus Session: Nonequilibrium Collective Behavior in Open Classical and Quantum Systems

Nonequilibrium classical and quantum systems coupled to thermal or (driven) non-equilibrium environments have recently been shown to exhibit rich collective phenomena and phase transitions without equilibrium counterparts. From the classical side, intriguing examples are flocking and phase separation in active matter, but also patterns and bifurcations in driven-diffusive systems and spontaneous parity-time symmetry breaking in systems involving nonreciprocal couplings. From the quantum side much interest has been devoted, e.g., to ordering and phase transitions in non-equilibrium steady states, the formation of time crystals, superradiance, as well as phase transitions or critical behavior in time. The symposium and the accompanying focus session is devoted to connections between the quantum and the classical realms, as they have been explored recently both in theory and experiment.

Organized by Sabine Klapp (TU Berlin) and André Eckhardt (TU Berlin)

Time: Thursday 9:30–12:45 Location: H37

DY 31.1 Thu 9:30 H37

Ultra-critical Fermi Surfaces, Quantum Oscillations, and Bosonic Metals — •Likun Shi and Inti Sodemann Villadiego — Institut für Theoretische Physik, Leipzig, Germany

Periodically driven quantum systems exhibit rich non-equilibrium phenomena that transcend equilibrium paradigms. We demonstrate the emergence of novel Fermi surface physics in particle-number-conserved fermionic and bosonic systems coupled to heat baths. In the fermionic case, we uncover "ultra-critical" Floquet non-Fermi liquid states characterized by persistent non-analyticities in momentum space occupation that remarkably retain their sharpness at finite temperature - a phenomenon without equilibrium analogues. These non-equilibrium Fermi surfaces manifest in quantum oscillation signatures and display power-law correlations immune to the finite-temperature bath. Extending beyond fermions, we discover analogous Fermi surface physics in bosonic systems, pointing to universal features in driven quantum systems that transcend particle statistics. Our findings open new avenues for realization of exotic non-equilibrium phases in driven quantum materials.

DY 31.2 Thu 9:45 H37

Giant Dynamical Paramagnetism in the driven pseudogap phase of YBa2Cu3O6+x — •Marios Michael[1], Duilio De Santis[2], Eugene Demler[3], and Patrick Lee[4] — [1]Max Planck Institute for the Structure and Dynamics of Matter, Luruper Chausse 149, 22761 Hamburg, Germany — [2]Physics and Chemistry Dept., Interdisciplinary Theoretical Physics Group, Palermo University, 90128 Palermo, Italy — [3]Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland — [4]Department of Physics, MIT, 77 Massachusetts Avenue, 02139 Cambridge, MA, USA

In this talk, I will discuss theory aimed at understanding recent experimental data on driven YBa2Cu3O6+x published recently in Nature: Fava, S., De Vecchi, G., Jotzu, G. et al. Magnetic field expulsion in optically driven YBa2Cu3O6+x Nature 632,75-80 (2024). Experiments on optically pumped YBa2Cu3O6+x in the pseudogap phase far above Tc have shown evidence of dynamical Meissner effect. In our effort to understand the new experimental signatures, we have uncovered a universal instability triggered in Josephson junctions under a magnetic field that are strongly driven with an AC field. The instability leads to the generation of giant paramagnetic currents at the edges of Josephson junctions. For strong enough drive such instabilities ultimately lead to a soliton ratchet after driving. I will focus on why this instability of a generic Josephson junction is applicable to the pseudogap YBa2Cu3O6+x far above Tc and how it matches the experimental observations.

DY 31.3 Thu 10:00 H37

entropy production in ultrafast quantum stochastic dynamics — •Yulong Qiao and Matthias Geilhufe — Department of Physics, Chalmers University of Technology, Gothenburg, Sweden

Thanks to advancements in femto- and atto-second laser technologies, thermodynamics has entered the ultrafast era. Ultrafast dynamics provides a unique way to probe the transient properties of materials. In [1], ultrafast stochastic thermodynamics was developed based on X-ray scattering experiments [2], and has been successfully applied to the study of entropy production in laser-excited phonons. However, how to develop a unifying theory for both classical and quantum systems remains an open challenge [3].

In the quantum realm, fluctuations arising from the uncertainty principle do not depend on temperature, meaning they are inevitable even in a vacuum. As a result, in the quantum analogues of the Langevin equations, classical stochastic forces are replaced by quantum noise operators. In this talk, I will discuss how to handle the quantum nosies in the frame of open quantum systems. I will also present the impact of quantum effects on the entropy production in the ultrafast processes.

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

[2] M. Kozina. et al., Nat. Phys. 15, 387 (2019).

[3] G.T. Landi and M. Paternostro, Rev. Mod. Phys. 93, 035008 (2021).

DY 31.4 Thu 10:15 H37

Cooling dynamics of the 2D Kitaev honeycomb model coupled to phonons — •Arkadeep Mitra, Francesco Piazza, and Markus Heyl — Theoretical Physics III, Center for Electronic Correlations and Magnetism, Institute of Physics, University of Augsburg, 86135 Augsburg, Germany

The ground state of the Kitaev spin-1/2 model on a 2D honeycomb lattice hosts a quantum spin liquid (QSL) phase where excitations fractionalize into Majorana fermions. At high temperatures, however, it has recently been observed to enter a disorder-free localized phase, so that any experimental cooling of a Kitaev material has to cross this localized and associated phase transition. Motivated from this, we study theoretically the cooling dynamics upon coupling the Kitaev model to phonons. We envisage that signatures obtained from this dynamics could act as probes for QSL.

DY 31.5 Thu 10:30 H37

Hydrodynamic description of emergent long-range coherence in active quantum flocks — •Byjesh N Radhakrishnan[1,2], Thomas L. Schmidt[1], and Markus Heyl[2] — [1]Department of Physics and Material science, University of Luxembourg — [2]Theoretical Physics III, Center for Electronic Correlations and Magnetism, Institute of Physics, University of Augsburg, D-86135 Augsburg, Germany

The quantum analog of classical active matter flocking has recently been reported in [arXiv:2308.01603]. The reported model introduces the concept of active quantum matter in a system of hard-core bosons in a one-dimensional lattice. The results provide both analytical and large-scale numerical evidence that these systems can give rise to quantum flocks due to the interplay of spin-flipping and alignment interactions. One of the key findings is that these flocks, unlike classical ones, exhibit distinct quantum properties by developing strong quantum coherence over long distances. Our work focuses mainly on developing a hydrodynamics description to study the origin and properties of this long-range quantum coherence. We systematically explore the relationship between long-range coherence and system parameters like alignment strength and quantum amplitude and compare our analytical results with large-scale numerical simulations.

Invited Talk DY 31.6 Thu 10:45 H37

Strong coupling and coherence in quantum thermodynamics — •Janet Anders[1,2], Federico Cerisola[2], James Cresser[2], and et al[2] — [1]Universität Potsdam, Germany — [2]Exeter University, UK

The interaction of nanoscale and quantum systems with their environment can be relatively strong, and alter the equilibrium state. For open quantum systems, explicit expressions of these so-called mean force (MF) equilibrium states have been missing. In this talk I will report on useful analytic expressions of these states, valid for a general quantum system in contact with a bosonic bath [1]. The results are illustrated with the well-known spin-boson model, for which we provide the first classification of coupling regimes, from weak to ultrastrong, and for both the quantum and classical setting [2].

In the second part of the talk, I will briefly comment on quantum signatures that arise in thermodynamic processes due to the presence of coherences. For example, the work distribution of time-varying quantum systems violates the corresponding classical fluctuation-dissipation relation for slowly driven processes [3]. A geometric framework is proposed to find optimal trade-offs between dissipation and fluctuations. Coherences also give rise to quantum irreversibility. We unravel how this irreversibility manifests itself in energetic exchanges that differ from those in the classical regime [4].

[1] PRL 127, 250601 (2021)
[2] NJP 26, 053032 (2024)
[3] PRL 123, 230603 (2019)
[4] Comm. Phys. 3, 1 (2020)

15 min. break

DY 31.7 Thu 11:30 H37

Ultrafast Dynamics Across the Phase Transition of the Charge Density Wave in $K_{0.3}MoO_3$ — •Rafael T. Winkler[1], Larissa Boie[1], Yunpei Deng[2], Matteo Savoini[1], Serhane Zerdane[2], Abhishek Nag[2], Sabina Gurung[1], Davide Soranzio[1], Tim Suter[1], Vladimir Ovuka[1], Janine Zemp[1], Elsa Abreu[1], Simone Biasco[1], Roman Mankowsky[2], Edwin J Divall[2], Alexander R. Oggenfuss[2], Mathias Sander[2], Christopher Arrell[2], Danylo Babich[2], Henrik T. Lemke[2], Paul Beaud[2], Urs Staub[2], Jure Demsar[3], and Steven L. Johnson[1,2] — [1]Institute for Quantum Electronics, Physics Department, ETH Zurich, Zurich, Switzerland — [2]SwissFEL, Paul Scherrer Institute, Villigen, Switzerland. — [3]Faculty - Institute of Physics, Johannes Gutenberg-University Mainz

Blue Bronze ($K_{0.3}MoO_3$) is a quasi 1D material exhibiting a charge density wave (CDW) with a periodic lattice distortion (PLD). In a time resolved x-ray experiment, we study the dynamics of the PLD by pumping $K_{0.3}MoO_3$ with short laser pulses and probing it using x-ray diffraction. We construct reciprocal space maps (RSM) of superlattice reflections at different delays. The RSMs indicate a transient inversion of the phase of the CDW. We attribute the suppression of the diffracted x-ray intensity after this phase inversion to a fast decoherence of the CDW driven by local pinning of the phase of the CDW in the material. These observations were confirmed by numerical simulations of the time dependent Ginzburg-Landau equations, extended by including defects which favor a particular phase of the CDW in combination with a temperature dependent coherence factor.

DY 31.8 Thu 11:45 H37

Optimal dynamical regimes for reservoir computing with soft matter — •Mario U. Gaimann and Miriam Klopotek — Stuttgart Center for Simulation Science (SimTech), Cluster of Excellence EXC 2075, University of Stuttgart, Germany

Reservoir computing with physical systems is a promising approach for next-generation and *in materio* computing. Recently, active matter systems for reservoir computing were introduced by Lymburn *et al.* (*Chaos* 31(3), 033121, 2021). However, the optimal properties of active matter systems for reservoir computing remain poorly understood. Here we show that viscoelastic, overdamped dynamics yield high predictive performances. This is remarkable since it was previously believed that optimal swarm dynamics are found at a gas-to-liquid phase transition. We relate predictive performance to correlations of agent velocities and their fluctuations. The optimal overdamped swarms show rich phenomenology: interface formation and breaking, local shear thinning, and self-healing. We show that the overdamped regime is optimal across a range of different chaotic attractors. Notably the optimal dynamics are already uncovered by studying reservoir computing with a single particle. Our results demonstrate the importance of tuning basic dynamical properties in physical reservoir substrates to generate optimal correlative effects. Reservoir computing with viscoelastic soft matter inspires novel mechanisms for computing in matter and novel computing devices based on these principles.

DY 31.9 Thu 12:00 H37

Universality in time-crystalline matter — •Carl Philipp Zelle, Romain Daviet, Achim Rosch, and Sebastian Diehl — University of Cologne

Dynamical phases of matter in which time translation symmetry is broken spontaneously are fascinating examples of phases that can only occur far from equilibrium. In this talk, we show that paradigmatic O(N) models display time-crystalline order once driven suitably out of equilibrium.

We employ dynamic RG techniques to determine the universal phenomena at the ensuing transitions as well as within the time-crystalline phase: The transition between an ordered phase and the time-crystal occurs through a critical exceptional point which we show cause a fluctuation-induced first order transition. The transition between a symmetric and a time-crystalline phase defines a new, genuinely non-thermal universality class. We show, that the Goldstone-modes within the dynamical phases are a realisation of the KPZ universality class and offer new generalisations of KPZ to larger symmetry groups.

Surprisingly, these phenomena can be realized by rather simple driving protocols, i.e. weakly irradiating a ferrimagnetic spin system. Furthermore, we connect our results to recent advances in nonreciprocal active matter.

Based on
1) Zelle, Daviet, Rosch, Diehl; Phys. Rev. X 14, 021052 (2024)
2) Daviet, Zelle, Rosch, Diehl; Phys. Rev. Lett. 132, 167102 (2024)
3) Zelle, Daviet, Asadollahi, Diehl; in preparation

DY 31.10 Thu 12:15 H37

Thermalizing Lindbladians for many-body systems — •Nico Albert[1], Shovan Dutta[2], and Masudul Haque[1] — [1]Technische Universität Dresden, Dresden, Germany — [2]Raman Research Institute, Bangalore, India

Thermalization is closely associated with the effect of a bath. For quantum systems, the most prominent type of bath is a Markovian bath, whose dynamics are governed by a Lindblad master equation. Therefore, it is important to understand Lindbladians that lead to a thermal (Gibbs) steady state. We will present some properties of thermalizing Lindbladians for many-body systems.

DY 31.11 Thu 12:30 H37

Signatures of Quantum Chaos and fermionization in the incoherent transport of bosonic carriers in the Bose-Hubbard chain — Pavel Muraev, Dmitri Maksimov, and •Andrey Kolovsky — Krasnoyarsk, Russia

We analyse the stationary current of Bose particles across the Bose-Hubbard chain connected to a battery, focusing on the effect of inter-particle interactions. It is shown that the current magnitude drastically decreases as the strength of inter-particle interactions exceeds the critical value which marks the transition to quantum chaos in the Bose-Hubbard Hamiltonian. We found that this transition is well reflected in the non-equilibrium many-body density matrix of the system. Namely, the level-spacing distribution for eigenvalues of the density matrix changes from Poisson to Wigner-Dyson distributions. With the further increase of the interaction strength, the Wigner-Dyson spectrum statistics changes back to the Poisson statistics which now marks fermionization of the Bose particles. With respect to the stationary current, this leads to the counter-intuitive dependence of the current magnitude on the particle number.