DY 24: Focus Session: New Trends in Nonequilibrium Physics – Conservation Laws and Nonreciprocal Interactions I

Nonequilibrium phase transitions and pattern formation are known from numerous examples of open systems, where external reservoirs and gradients prevent relaxation to thermodynamic equilibrium. In recent years, related research in biology and soft matter systems in physics and chemistry has increasingly focused on active matter, where energy is injected locally. This often involves mass conservation constraints and, in many cases, in addition non-reciprocal interactions of the involved entities, such as macromolecules or cells. Both have far reaching consequences on the universal dynamical behavior of a wide range of nonequilibrium systems and require classical concepts of nonlinear and statistical physics, such as phase transitions, to be reconsidered and developed further. For example, well-known approaches to nonequilibrium pattern formation require substantial extensions to address conserved systems. Thus, recent theoretical studies in this field have revealed many novel phenomena, such as arrested coarsening, odd elasticity, oscillatory phase separation, persistent wave dynamics, and active turbulence. Many of these aspects have by now been confirmed by experimental findings, for example, in intracellular pattern formation or collective dynamics in colloidal systems. This symposium will provide a well-balanced overview of experimental and theoretical progress in this new, exciting area.

Organized by Markus Bär (Berlin) and Carsten Beta (Potsdam)

Time: Wednesday 9:30–13:00 Location: BH-N 243

Invited Talk DY 24.1 Wed 9:30 BH-N 243

The nonreciprocal Cahn-Hilliard model - properties and significance — •Uwe Thiele[1,2], Tobias Frohoff-Hülsmann[1], and Daniel Greve[1] — [1]Institut für Theoretische Physik, Universität Münster, Germany — [2]Center for Nonlinear Science (CeNoS), Universität Münster, Germany

The phenomenologically introduced nonreciprocal Cahn-Hilliard (NRCH) model couples densities with mass-conserving dynamics via a nonreciprocal interaction [1]. After discussing types of nonreciprocity and their relation to a 'spurious' gradient dynamics form (allowing for a Maxwell construction) we show that the NRCH model features conserved-Turing and conserved-Hopf instabilities beside the usual Cahn-Hilliard instability. Then, we discus the model's role as a high-codimension amplitude equation (AE) placing it within a hierarchy of AE for the eight types of instabilities of uniform steady states in homogeneous isotropic systems resulting from the combination of three features: large- vs small-scale, stationary vs oscillatory, and with vs without conservation law(s) [2]. Further, a codimension-one AE for the conserved-Hopf instability is discussed and compared to [3].

[1] ZH You, A Baskaran, MC Marchetti, PNAS 117, 19767 (2020); S Saha, J Agudo-Canalejo, R Golestanian, PRX 10, 041009 (2020); T Frohoff-Hülsmann, J Wrembel, U Thiele, PRE 103, 042602 (2021). [2] T Frohoff-Hülsmann, U Thiele, PRL 131, 107201 (2023). [3] A Nepomnyashchy, S Shklyaev, J Phys A 49, 053001 (2016); A Förtsch, W Zimmermann, DY 4.4, DPG Spring Meeting 2023, Dresden; A Förtsch, Thesis Bayreuth 2023.

DY 24.2 Wed 10:00 BH-N 243

Field-theoretical modeling of a zombie apocalypse* — •Michael te Vrugt[1], Julian Jeggle[2], and Raphael Wittkowski[2] — [1]DAMTP, Centre for Mathematical Sciences, University of Cambridge, Cambridge CB3 0WA, United Kingdom — [2]Institut für Theoretische Physik, Center for Soft Nanoscience, Universität Münster, 48149 Münster, Germany

The physics of systems with nonreciprocal interactions has attracted a significant amount of interest in recent years. A prototypical example are predator-prey systems. In this work [1], we connect the physics of nonreciprocal interactions to epidemiology by developing a dynamical density functional theory for a popular hypothetical infectious disease, namely a zombie outbreak. A numerical investigation of this model is used to compare different strategies for containing the spread of zombies.

[1] M. te Vrugt, J. Jeggle, and R. Wittkowski, arXiv:2307.00437 (2023)

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DY 24.3 Wed 10:15 BH-N 243

Maxwell construction for a nonreciprocal Cahn-Hilliard model — •Daniel Greve[1], Tobias Frohoff-Hülsmann[1], and Uwe Thiele[1,2] — [1]Universität Münster — [2]Center for Nonlinear Science (CeNoS), Universität Münster

Two important models for active, anti-dissipative phenomena are the nonreciprocal two-field Cahn-Hilliard (NRCH) model [1, 2] and active model B+. The latter is a one-field model describing motility-induced phase-separation (MIPS), for which Solon et al. have analyzed phase coexistence through the derivation of a Maxwell construction in terms of a "generalized thermodynamics" [3]. Using a generalised unifying formalism, we provide phase diagrams for a NRCH model. In contrast to active model B+, where only a stationary large-scale instability occurs, the NRCH model exhibits a rich phenomenology, that includes large- and small-scale stationary as well as large-scale oscillatory instabilities [1, 2, 4]. This leads to the occurrence of a crystal-like phase whose coexistence with liquid-like phases we discuss. In passing, we also show how time-periodic behaviour may coexist with stationary one. Finally, we indicate that the relation of the obtained phase diagrams and the behaviour of corresponding finite-size systems resembles the one for passive systems.

[1] Z. H. You et al., Proc. Natl. Acad. Sci. U. S. A. 117, 19767 (2020).
[2] S. Saha et al., Phys. Rev. X 10, 041009 (2020).
[3] A. P. Solon et al., Phys. Rev. E 97, 020602 (2018).
[4] T. Frohoff-Hülsmann et al., Phys. Rev. E 103, 042602 (2021).

DY 24.4 Wed 10:30 BH-N 243

Non-reciprocal alignment can induce asymmetric clustering in active repulsive mixtures — •Kim L. Kreienkamp and Sabine H. L. Klapp — Technische Universität Berlin

It is now well established that non-reciprocal systems exhibit intriguing, novel dynamical phases, the characteristics of which are shaped by the type and degree of non-reciprocity [1-3]. Here, we study a paradigmatic model of non-reciprocal active matter, namely a binary mixture of motile particles with completely symmetric repulsive interactions and non-reciprocal alignment couplings [3]. Using a combination of hydrodynamic theory, linear stability analysis, and particle-based simulations, we find dynamical, asymmetrical clustering situations, in which weakly polarized clusters form out of only one of the two species. Importantly, these asymmetric clusters emerge even though the isotropic repulsive interactions do not distinguish one species. Instead, the clustering is driven solely by non-reciprocal orientational couplings. For systems with antagonistic (anti-)alignment couplings, the resulting single-species clusters move and chase more dilute accumulations of the other species. We present a full non-equilibrium phase diagram in the parameter space of inter-species coupling strengths and compare with particle-based simulations, highlighting the impact of non-reciprocity on various scales.

[1] Z. You et al., PNAS 117, 19767 (2020).
[2] M. Fruchart et al., Nature 592, 363 (2021).
[3] K. L. Kreienkamp and S. H. L. Klapp, New J. Phys. 24, 123009 (2022).

DY 24.5 Wed 10:45 BH-N 243

Mobility-induced condensation and (rotating) crystallization in a higher-order active Phase Field Crystal model — •Alina Barbara Steinberg[1], Max Philip Holl[2], and Uwe Thiele[1,3] — [1]Institut für Theoretische Physik, Universität Münster — [2]Department of Chemistry and Materials Science & Department of Bioproducts and Biosystems, Aalto University — [3]Center for Nonlinear Science, Universität Münster

Active soft matter consisting of self-propelled particles can show a variety of motility-induced phenomena, including phase separation and crystallization, i.e. the formation of clusters with respective liquid-like and crystal-like inner structure. We demonstrate this using an (active) Phase-Field-Crystal model [1-3] of higher order [4]. We consider active and passive cases, present morphological phase diagrams, and examples of localized states that represent the various types of clusters. Finally, we take a closer look at rotating crystallites and the dependence of their properties on control parameters.

[1] H. Emmerich et al., Adv. Phys., 61:665-743, 2012. [2] A. M. Menzel & H. Löwen, Phys. Rev. Lett., 110:055702, 2013. [3] L. Ophaus et al., Phys. Rev. E 98:022608, 2018. [4] Z.-L. Wang et al., Phys. Rev. Materials, 4:103802, 2020.

DY 24.6 Wed 11:00 BH-N 243

Deciphering the interface laws of Turing foams — Henrik Weyer[1], •Tobias Roth[1], and Erwin Frey[1,2] — [1]Arnold Sommerfeld Center for Theoretical Physics and Center for NanoScience, Department of Physics, Ludwig-Maximilians-Universität München, Theresienstraße 37, D-80333 München, Germany — [2]Max Planck School Matter to Life, Hofgartenstraße 8, D-80539 Munich, Germany

Protein pattern formation is central to the spatiotemporal self-organization of both prokaryotic and eukaryotic cells. It is also employed as a key spatial control system in the design of artificial cells. However, it remains unclear how the properties of the macroscopic, highly nonlinear reaction–diffusion patterns can be systematically linked to the underlying reaction network [1]. Here, we show—based on protein-mass conservation—that protein patterns are governed by an effective interfacial tension arising from cyclic steady-state currents of attachment and detachment at the interface. Furthermore, we recover generalized Plateau and von-Neumann laws for two-dimensional liquid foams in two-dimensional mesh patterns. This leads us to introduce "Turing foams," which show generic behavior governed by the interplay of interfacial-tension-driven dynamics and interrupted coarsening, and that we observe experimentally in the *in vitro* Min protein system. Our theory offers a new ansatz to find principles of macroscopic self-organization in mass-conserving systems far from equilibrium.

[1] Halatek, J., Brauns, F. & Frey, E. Philos. Trans. R. Soc. B Biol. Sci. 373, 20170107 (2018).

15 min. break

DY 24.7 Wed 11:30 BH-N 243

Traveling waves and arrested coarsening in a simple model for protein patterns on biomembranes — •Benjamin Winkler[1], Sergio Alonso[2], and Markus Bär[1] — [1]Physikalisch-Technische Bundesanstalt, Berlin, Germany — [2]UPC, Barcelona, Spain

The formation of protein patterns on membranes is important for spatial organization, growth and division of biological cells. In many cases these dynamics is described by coupled, mass-conserving reaction-diffusion equations. Here, we study the dynamics emergent from the coupling of two well-known, mass-conserved systems. System A is given by a simplified reaction-diffusion model for the emergence of cell polarity by proteins undergoing active phase separation. The proteins are fast-diffusing in the bulk of the cell and become activated when they bind to the cell membrane. System B is a Cahn-Hilliard-like equation describing the mixing dynamics of two different lipids. When introducing a coupling between system A and B due to a concentration-dependent interaction affinity, we observe the emergence of traveling waves in system A and likewise, a systematic slowing of the coarsening in system B depending on the coupling strength between the two systems. The primary linear instabilities of the homogeneous steady for the coupled system are all stationary, hence the traveling wave emerge from a secondary instability of a stationary pattern. Our results exemplify the interaction between pattern forming systems with well-separated length scales and illustrate how complex behavior in biological systems can arise from the coupling of simpler subsystems.

DY 24.8 Wed 11:45 BH-N 243

Defect Solutions of the Non-reciprocal Cahn-Hilliard Model: Spirals and Targets — •Navdeep Rana[1] and Ramin Golestanian[1,2] — [1]Max Planck Institute for Dynamics and Self-Organization (MPI-DS), D-37077 Goettingen, Germany — [2]Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford OX1 3PU, United Kingdom

We study the defect solutions of the Non-reciprocal Cahn-Hilliard model (NRCH). We find two kinds of defects, spirals with unit magnitude topological charge, and topologically neutral targets. These defects generate radially outward travelling waves and thus break the parity and time-reversal symmetry. For a given strength of non-reciprocity, spirals and targets with unique asymptotic wavenumber and amplitude are selected. We use large-scale simulations to show that at low non-reciprocity, a disordered state evolves into quasi-stationary spiral network. With increasing non-reciprocity, we observe networks composed primarily of targets. Beyond a critical threshold, a disorder-order transition from defect networks to travelling waves emerges. The transition is marked by a sharp rise in the global polar order.

DY 24.9 Wed 12:00 BH-N 243

Liquid mechanics - Exploring instabilities in active condensates — •Florian Rasshofer[1], Simon Bauer[1], Alexander Ziepke[1], Ivan Maryshev[1], and Erwin Frey[1,2] — [1]Arnold Sommerfeld Center for Theoretical Physics, LMU Munich, Germany — [2]Max Planck School Matter to Life, Munich, Germany

This study employs a theoretical framework to investigate the stability and morphology of active condensates. Active condensates, characterized by their consumption of chemical energy (fuel), exhibit unique features absent in passive systems. Their non-equilibrium nature allows for stationary pattern-forming states and more exotic phenomena such as self-propelled domains and dividing droplets.

We present a unifying theory that rationalizes dynamical instabilities observed in various systems, encompassing chemotactic motility-induced phase separation to enzymatically active droplets. Analytical results obtained from classical perturbation theory are shown to be in good agreement with finite element simulations, providing valuable insights into the intricate behavior of active condensates.

Beyond theoretical contributions, our work envisions practical applications. The emergent dynamical phases uncovered offer insights into the potential design of self-assembling micro machines capable of extracting work on a scale not admissible to classical mechanics.

DY 24.10 Wed 12:15 BH-N 243

Self-excited oscillations and motion of sessile drops covered by autocatalytic surfactants — •Florian Voss and Uwe Thiele — Institute for Theoretical Physics, University of Münster, Germany

We consider shallow sessile drops of a nonvolatile liquid covered by a mixture of surfactants that can transform into each other via a simple autocatalytic conversion reaction. Based on the form of a passive gradient dynamics model for fields with conserved and nonconserved dynamics we develop a fully reciprocal three-field model with two conservation laws that captures coupled droplet hydrodynamics [1] and a chemical reaction [2]. We then drive the mechanically, thermodynamically and chemically reciprocal system permanently out of equilibrium by in- and outfluxes of surfactants controlled by external chemostats. Then, we study the resulting active system using linear stability analysis, numerical continuation and time simulations. As the chemostat driving strength is varied, we find, inter alia, the emergence of surfactant (Turing) patterns, breathing and swaying drop oscillations, and oscillatory self-propulsion.

[1] U. Thiele, A. J. Archer, M. Plapp, Phys. Fluids, 2012, 24, 102107
[2] D. Zwicker, Curr. Opin. Colloid Interface Sci., 2022, 61, 101606

DY 24.11 Wed 12:30 BH-N 243

Escaping kinetic traps using non-reciprocal interactions — Saeed Osat[1], •Jakob Metson[1], Mehran Kardar[2], and Ramin Golestanian[1,3] — [1]Max Planck Institute for Dynamics and Self-Organization (MPI-DS), 37077 Göttingen, Germany — [2]Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, United States — [3]Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford OX1 3PU, United Kingdom

A prominent problem for systems trying to find a global energy minimum is getting trapped in deep local minima. In this work we show that by using non-reciprocal interactions we can drive systems out of these kinetic traps to end up at a global minimum. We use multifarious self-assembly as a model system, where systems are designed to store and assemble multiple different structures. Firstly we demonstrate that by introducing non-reciprocal interactions we enable systems to escape from chimeric states (kinetic traps), which with only reciprocal interactions are practically impossible to escape from. Then we look in more detail at the escape dynamics in our model system. The principle escape mechanism is interface growth. We find that the interface dynamics in our non-reciprocal system falls into the KPZ universality class. Furthermore, we study escape via spiraling point defects. These can either annihilate pairwise, leaving the system trapped, or reach the boundary of the structure which leads to successful escape. Although we focus on multifarious self-assembly as a model system, in principle these ideas can be applied to a wide range of complex systems, being particularly impactful for systems with rough energy landscapes.

DY 24.12 Wed 12:45 BH-N 243

Correlation effects in the non-reciprocal Ising system — •Kristian Blom[1], Uwe Thiele[2], and Aljaz Godec[1] — [1]Max Planck Institute for Multidisciplinary Sciences, Göttingen — [2]Universität Münster, Münster

Non-variational continuum models like the non-reciprocal Cahn-Hilliard model are typically constructed using phenomenological reasoning, and their full consistency with microscopic models may thus not be taken for granted. In this talk, we focus on the bottom-up construction of a non-reciprocal phase field system, starting from a pair of opposing non-reciprocally coupled Ising models evolving according to Kawasaki or Glauber dynamics. To analyze the thermodynamic properties of the system, we develop a kinetic variant of the Bethe-Guggenheim approximation that explicitly accounts for pair-correlations, and thus goes beyond the mean field reasoning. Unlike the mean field approximation, our approach provides results for both, the magnetization and local defects within and between the lattices. The coupling between the magnetization and defects gives rise to a rich kinetic phase diagram. Our results reveal the conditions under which the various phases are stable, and how they depend on both, the reciprocal and non-reciprocal coupling between spins.