DY 55: Focus Session: Emergent Transport in Active Systems (joint session DY/BP)

Collective motion and directed transport are hallmark phenomena of active matter, arising from the interplay of self-propulsion, interactions, and nonequilibrium fluctuations. Even in the absence of global biases, assemblies of active particles can exhibit spontaneous currents, self-organized chemotaxis, and rectified transport due to broken symmetries or nonlinear feedbacks. Directed transport often emerges in inhomogeneous environments, where variations in particle activity or interaction strength can bias motion and organization. Activity gradients represent a particularly relevant example, providing a tunable mechanism to steer collective motion and pattern formation. These processes link microscopic activity to macroscopic material behavior and transport. This focus session aims to bring together theorists and experimentalists working on the fundamental mechanisms and control of emergent transport in active systems.

Organized by Abhinav Sharma (Augsburg) and Jens-Uwe Sommer (Dresden)

Time: Thursday 15:00–18:00 Location: ZEU/0160

Invited Talk DY 55.1 Thu 15:00 ZEU/0160
Out-of-equilibrium synthetic cells: the future of active matter — •Laura Alvarez — Univ. Bordeaux, CNRS, CRPP, UMR 5031

Colloidal active swimmers are broadly used as model systems to design microswimmers, yet their rigid and solid architecture limits their adaptability and functionality. A promising alternative is using bioinspired soft compartments for the design of cell-mimetic functional architectures while avoiding the complexity of living cells.

Here, I will showcase our latest results on driving giant unilamellar vesicles (GUVs) out of equilibrium via controlled external actuation to mimic and study life-like processes. We fabricate phase-separated Janus lipid vesicles, harnessing membrane fluidity to obtain reconfigurable motion. Under external electric fields, these asymmetric compartments self-propel and display transient run-and-tumble-like dynamics arising from the coupling between mobile membrane domains and the field. By tuning lipid composition and using temperature as an external trigger, we modulate membrane fluidity and phase separation, enabling in situ control over the frequency of tumble events. Beyond motility, we exploit electric fields to induce controlled shape transformations and vesicle division events, showing that the same actuating scheme can access higher-order cell-like functions. In parallel, we use light to drive strong, localized membrane fluctuations, providing a route to study active, non-thermal shape dynamics in soft compartments. These results highlight synthetic cell membranes as versatile platforms in which different functions can be triggered using simple external fields.

DY 55.2 Thu 15:30 ZEU/0160
Biohybrid active matter: active cargo transport by motile cells — Jan Albrecht[1], Lara S. Dautzenberg[1], Manfred Opper[2], Carsten Beta[1], and •Robert Grossmann[1] — [1]University of Potsdam, Potsdam, Germany — [2]Technical University Berlin, Berlin, Germany

We describe the transport of polystyrene beads whose motion is actively driven by cells via direct mechanical contact. We will first discuss the stochastic dynamics of a single cell-cargo pair, focusing on the existence of an optimal cargo size that enhances the diffusion of the load-carrying cells, and estimate the active forces exerted by cells to move colloids. Furthermore, we present the collective transport of these micron-sized particles on a monolayer of motile cells. The colloids' mean-square displacement shows a crossover from superdiffusive to normal-diffusive dynamics. The particle displacement distribution is, however, distinctly non-Gaussian even at macroscopic timescales exceeding the measurement time. We attribute the non-Gaussian statistics to heterogeneity and non-stationarity of the dynamics, and particularly apply a likelihood-based inference framework to estimate the heterogeneity of the bead dynamics from their discretely sampled trajectories. We showcase how this approach can deal with information-scarce situations and provides natural uncertainty bounds for heterogeneity estimates. Similar transport properties are expected for many composite active matter systems. These results thus provide the basis for the future design of cellular microcarriers and for more advanced transport tasks in complex, disordered environments, e.g. tissues.

Invited Talk DY 55.3 Thu 15:45 ZEU/0160
Chemotactic like behavior in by active Brownian particles: from single particles to to polymers — •Hidde Vuijk — University of Augsburg, Universitätsstraße 1, 86159, Augsburg, Germanz

Active Brownian particles can be used as simplified models for microscopic, motile organisms. This research investigates the behavior of such self-propelled objects in spatial gradients of activity, where their self-propulsion speed varies with position. A single active particle tends to accumulate in low-activity regions. When activity is assumed to be proportional to fuel, this corresponds to antichemotactic like behavior. We demonstrate how this behavior can be reversed by structuring particles into simple complexes. For example, by connecting active particles to passive cargo or linking them into chains, we predict a crossover from accumulation in low-activity regions to accumulation in high-activity regions, that is chemotaxic like behavior. These active dimers and polymers can autonomously move up an activity gradient, accumulating where the fuel concentration is highest. This emergent gradient-sensing arises from the physical interactions, offering a novel mechanism for the design of active matter and providing insight into how primitive life forms without complex information processing might have located nutrients.

DY 55.4 Thu 16:15 ZEU/0160
Fluctuation-induced transition in transport of active colloidal cells — •Shashank Ravichandir[1,2], Jens-Uwe Sommer[1,2], and Abhinav Sharma[1,3] — [1]Leibniz Institute of Polymer Research, Dresden, Germany — [2]Technical University Dresden, Dresden, Germany — [3]University of Augsburg, Augsburg, Germany

The transport of active-passive assemblies and their self-localization behavior have been studied in some detail in recent years [1,2]. The "chemotactic" property these exhibit has been attributed to the separation of time scales, i.e between the persistence time of the active particle and the characteristic time scale associated with the interaction between the particles (ex - harmonic springs). We consider a gas of active particles enclosed in a circular vesicle and observe that the transport behavior of the vesicle depends on the density of the enclosed gas or the number of active particles. This is a new mechanism for achieving desired transport of active colloidal cells as no new timescales are introduced by changing the number of active particles. This transition in transport behavior of these vesicles seems to be driven by fluctuations. The proposed model is also experimentally reproducible, contrary to the active-passive assemblies that have been studied so far.

References: [1] H. D. Vuijk et al., Phys. Rev. Lett., 126(20), 2021. [2] P. L. Muzzeddu et al., Phys. Rev. Lett., 133(11), 2024.

15 min. break

Invited Talk DY 55.5 Thu 16:45 ZEU/0160
From non-reciprocal torques towards shape-flexible and responsive prototypic worms — •Holger Stark and Jeanine Shea — Institute of Physics and Astronomy, Theoretical Physics, Technische Universität Berlin, Hardenbergstr. 36, 10623 Berlin, Germany

Non-reciprocal interactions as seen in active matter allow the formation of novel collective states that are only observable in the non-equilibrium. They may serve as prototypes for mimicking what is observed in the real world or for guiding robotic applications.

We start from non-reciprocal orientational interactions, where an active Brownian particle turns away from its neighbors [1]. By varying range and strength of the torque, we discover novel states such as travelling bands or dynamic flocking. Reversing the sign, makes

the orientational interaction cohesive. We combine it with aligning torques and again for varying range and torque strength observe multiple, rotary, and persistent worms as well as an aster state [2]. In particular, the persistent worm represents a prototype for a flock of active constituents, either natural or robotic, which shows a remarkable flexibility and integrity when performing shape changes. This becomes obvious when hunting a prey, which leaders inside the worm sense via some chemotactic mechanism. In contrast to the macroscopic world, here without inertia, moving on a straight line seems the best strategy to escape. We also observe that the worm stays intact, even when squeezing through a narrow, long pore.

[1] M. Knezevic, T. Welker & H. Stark, Sci. Rep. 12, 19437 (2022).
[2] Jeanine Shea & Holger Stark, EPJE 48, 22 (2025).

DY 55.6 Thu 17:15 ZEU/0160

Directed motion of active collectives in activity gradients — •Hossein Vahid[1], Jens-Uwe Sommer[1,2], and Abhinav Sharma[1,3] — [1]Leibniz-Institut für Polymerforschung Dresden, 01069 Dresden, Germany — [2]Technische Universität Dresden, 01069 Dresden, Germany — [3]Institute of Physics, University of Augsburg, Universitätsstraße 1, 86159 Augsburg, Germany

Directed motion appears across all scales of active matter, from biomolecular condensates inside cells to large assemblies of migrating filaments. By simulating active particles and polymers, we identified the mechanisms that enable activity gradients to steer these collectives and control their assembly [1,2]. In cohesive mixtures, droplets climb activity gradients, fragment when the activity becomes too intense, and reassemble in low activity regions. This creates a robust cycle of positioning without needing any biochemical feedback. Similarly, in assemblies of active polar polymers, spatial gradients in activity, combined with temporally stochastic propulsion, generate net body forces on dimers, asters, and multiarm structures. This biases their motion toward high-activity regions and stabilizes long-lived entangled clusters even at low concentrations.

[1] H. Vahid, J.-U. Sommer, A. Sharma, Self-Organization and Cyclic Positioning of Active Condensates, arXiv preprint arXiv:2510.15771 (2025). [2] H. Vahid, J.-U. Sommer, A. Sharma, Collective dynamics in active polar polymer assemblies, Phys. Rev. Res. 7, L042031 (2025).

DY 55.7 Thu 17:30 ZEU/0160

Activity hallmarks in kinetic theory: Exceptional Points, Disorder Regularization, Non-Reciprocal Orientation-Displacement Coupling — •Horst-Holger Boltz and Thomas Ihle — University Greifswald, Institute for Physics, Greifswald

The dynamics of active systems are not subject to the same constraints as that of passive classical systems. This is particularly true for self-propelled particles with alignment interactions that have orientation-displacement coupling, i.e. the alignment is dependent on the relative position of the interacting particles to each other. We present recent work within first-principle kinetic theory that highlights key hallmarks of these more generalized dynamics. In particular, we discuss the effect of a cascade of exceptional points in the relevant dynamical operators under finite noise and also how to generally include noise in collision-based kinetic theory beyond mean-field. This allows us to provide analytical insights into the numerically established scaling relations (Kürsten, 2025) underlying the critical exponents in flocking transitions. Also, we are going to explain how to derive a systematic mesoscopic description for aligning self-propelled particles with orientation-displacement coupling and will present results showing a flocking transition in a system of a single species with purely anti-aligning torques and without any forces, simplifying an earlier reported flocking by turning-away mechanism (Das et al, 2024).

References: Boltz, Ihle, in preparation; Kürsten, arXiv:2402.18711 (2025); Das et al, Phys. Rev. X 14, 031008 (2024); Boltz et al, Entropy, 26(12), 1054 (2024); Ihle et al, arXiv:2303.03357 (2023)

DY 55.8 Thu 17:45 ZEU/0160

Rouse Polymers in Time-dependent Nonequilibrium Baths — •Bhavesh Valecha[1] and Abhinav Sharma[1,2] — [1]Mathematisch-Naturwissenschaftlich-Technische Fakultät, Institut für Physik, Universität Augsbur, Augsburg, Germany — [2]Leibniz-Institut für Polymerforschung Dresden, Institut Theory der Polymere, Dresden, Germany

Directed transport is a characteristic feature of numerous biological systems in response to nutrient and chemical gradients. These signals are often time-dependent owing to the high complexity of interactions in these systems. In this study, we focus on the steady-state behavior of polymeric systems responding to such time varying signals. We model them as ideal Rouse chains submerged in a time-dependent and inhomogeneous nonequilibrium bath, which is described by a spatially and temporally varying self-propulsion wave field experienced by the monomer units. Through a coarse-graining analysis, we show that these chains display rich emergent response to the temporal stimuli as a function of their length and topology. In particular, for slow moving waves, short chains composed of up to 3 monomers drift against self-propulsion wave, whereas, longer chains drift in the direction of the wave. In contrast, for fast moving waves, all chains drift along the wave regardless of their length. Moreover, we find that the star topology displays the highest drift for both slow and fast moving waves. We confirm these analytical predictions with robust numerical simulations, showing that response of polymeric systems to temporal stimuli can be controlled by the topology or the length of the polymer.