CPP 11: Active Matter II (joint session DY/BP/CPP)

Time: Monday 15:00–18:30 Location: ZEU/0160

CPP 11.1 Mon 15:00 ZEU/0160

Field-controlled self-organization in an active spin system — Mintu Karmakar[1,2,3], •Matthieu Mangeat[4], Swarnajit Chatterjee[5,4], Heiko Rieger[4], and Raja Paul[3] — [1]WIUCAS, Beijing, China — [2]Universitat de Barcelona, Barcelona, Spain — [3]IACS, Kolkata, India — [4]Saarland University, Saarbrücken, Germany — [5]CY Cergy Paris Université, Cergy-Pontoise, France

We investigate the collective response of active Potts particles to an external magnetic field and uncover three striking nonequilibrium phenomena. We first examine how the flocking transition is reshaped for a homogeneous and unidirectional field: the coexistence regime between an apolar gas and a polar liquid is replaced by a phase separation between two polar-ordered phases, a low-density, weakly polarized background and a high-density, strongly polarized band, both moving along the field. Second, when the particles self-organize into a high-density longitudinal lane whose long axis is perpendicular to the field, the lane slowly treadmills against the field direction, driven by the weakly polarized background. Finally, we identify a field-induced interface pinning regime that arises when the domain is divided into two regions with opposite field directions, causing particles to accumulate and perform a back-and-forth motion at the interface. This pinning phenomenon also leads to the emergence of a disordered state in the presence of a random field orientation. A coarse-grained hydrodynamic theory supports and confirms the phenomena observed in our microscopic simulations.

CPP 11.2 Mon 15:15 ZEU/0160

Nucleation kinetics in two-dimensional polar active fluids — •Yuta Kuroda and Thomas Speck — Institute for Theoretical Physics IV, University of Stuttgart, Germany

Polar active fluids constitute one of the most important classes of active matter. These systems possess alignment interactions that cause the local polarization to align with that of neighboring particles, leading to a flocking transition in which global polar order emerges. Extensive numerical and analytical studies have established that the flocking transition is discontinuous, and consequently, the phase diagram possesses a coexistence region in which propagating polar bands appear. Despite intensive studies on flocking transitions, the nucleation mechanism responsible for the formation of these bands remains poorly understood. In this work, we numerically investigate the nucleation kinetics of polar bands using a particle model, namely active Brownian particles with a Kuramoto-type alignment interaction, and we report the behavior of the nucleation rate over a wide range of parameters.

CPP 11.3 Mon 15:30 ZEU/0160

Collision dynamics of active Brownian hard disks — •Jonas Buba — Soft Matter Theory Group, Theoretical Physics: Lab for Emergent Phenomena, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

Active matter systems, composed of self-driven agents, display emergent behaviors such as collective motion, clustering, and motility-induced phase separation (MIPS). To better understand the microscopic origin of MIPS, we study collisions of active Brownian hard disks within the framework of dynamical density functional theory (DDFT). The particle interactions are modeled using fundamental measure theory (FMT). Each particle is represented by a Gaussian density peak, which allows us to quantify the mean delay from collisions for different configurations. The post-collision density resulting from the simulation can be described by a convolution of the pre-collision density, enabeling the analysis of different contributions to the delay.

CPP 11.4 Mon 15:45 ZEU/0160

Active Ornstein-Uhlenbeck Particles: A Stochastic Path Integral Approach — •Carsten Littek, Mike Brandt, and Falko Ziebert — Institut für Theoretische Physik, Universität Heidelberg, Germany

In a recent publication (arXiv:2509.26296) we have developed a path integral formulation of the stochastic dynamics of a single active Brownian particle (ABP), with or without a constant torque, confined by a harmonic trap. This approach is based on the particle's microscopic degrees of freedom and we have derived exact analytic time-dependent expressions for key observable quantities such as the mean position and mean square displacement without the necessity of solving the Fokker-Planck equation. Here we present the application of this approach to the dynamics of active Ornstein-Uhlenbeck particles (AOUP). In particular, we generalize our formulation to systems of many AOUPs interacting via a suitable two-particle potential and derive the statistical quantities relevant in the context of collective phenomena, such as motility-induced phase separation (MIPS).

CPP 11.5 Mon 16:00 ZEU/0160

Self-alignment and chirality in dense active matter: from flocking to circling crystals — •Marco Musacchio[1], Alexander Antonov[1], Hartmut Löwen[1], and Lorenzo Caprini[2] — [1]Institut für Theoretische Physik II: Weiche Materie, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, D-40225 Düsseldorf, Germany — [2]Physics Department, University of Rome La Sapienza, P.le Aldo Moro 5, IT-00185 Rome, Italy

Several experimental systems in active matter are characterized, at the single-particle level, by an effective torque that aligns particle orientation with their instantaneous velocity. This mechanism, known as self-alignment, appears in both biological and granular active systems. In dense active systems, a sufficiently strong self-alignment can suppress mips and drive the system from a clusterized flocking state to an homogeneous one, where all particles move collectively, with aligned velocities. This flocking transition is approached for a broad range of densities, even close to maximal packing, where the system is in a crystalline configuration. Specifically, in the crystal case, the flocking transition can be predicted analytically since the dynamics can be mapped onto a velocity-dependent Landau*Ginzburg free energy, revealing that this disorder*order transition is second order. The onset of chirality drives the system from collective flocking to a circling crystal phase, characterized by coherent circular motion of all the system. Further increasing chirality suppresses the global rotation, leading to a vortex-like structure in the velocity field. These findings are experimentally testable in systems governed by self-alignment and chirality.

CPP 11.6 Mon 16:15 ZEU/0160

Number fluctuations distinguish different self-propelling dynamics — •Tristan Cerdin[1,2], Sophie Marbach[2], and Carine Douarche[1] — [1]Université Paris-Saclay, CNRS, FAST, 91405, Orsay, France — [2]CNRS, Sorbonne Université, Physicochimie des Electrolytes et Nanosystèmes Interfaciaux, F-75005 Paris, France

In nonequilibrium suspensions, static number fluctuations N in virtual observation boxes reveal remarkable structural properties, but the dynamic potential of $N(t)$ signals remains unexplored. Here, we develop a theory to learn the dynamical parameters of self-propelled particle models from $N(t)$ statistics.

Theoretical plots of the mean-squared number difference $\langle \Delta N^2(t) \rangle$ exhibit 3 scaling regimes in time corresponding to the 3 regimes of self-propelled particles: diffusive, advective and effectively diffusive again at long times. By expanding the theory in each of these regimes, we recover limiting laws for the number fluctuations, which can be used in practice to quantify self-propulsion properties.

Additionally, unlike traditional trajectory analysis, $N(t)$ statistics distinguish between models, by sensing subtle differences in reorientation dynamics that govern re-entrance events in boxes. This paves the way for quantifying advanced dynamic features in dense, out-of-equilibrium suspensions.

CPP 11.7 Mon 16:30 ZEU/0160

Flocking transitions in dense mixtures of active self-aligning and passive particles — •Weizhen Tang[1], Amir Shee[2], Zhangang Han[1], Pawel Romanczuk[3,4], Yating Zheng[3,4], and Cristián Huepe[1,5,6] — [1]School of Systems Science, Beijing Normal University, Beijing, China — [2]Department of Physics, University of Vermont, USA — [3]Department of Biology, Humboldt Universität zu Berlin, Unter den Linden 6, Berlin, Germany — [4]Research Cluster of Excellence 'Science of Intelligence', Berlin, Germany — [5]Northwestern Institute on Complex Systems and ESAM, Northwestern University, Evanston, USA — [6]CHuepe Labs, 2713 West Augusta Blvd #1, Chicago, USA

We investigate the passivity-driven flocking transition in a dense mixture of self-aligning active particles and passive particles, using a min-

imal model of active polar disks. We show that anisotropic damping leads to a discontinuous flocking transition as a function of the fraction of passive components, whereas isotropic damping produces a smooth transition where the final ordered state can display sustained oscillations and remain trapped in a metastable state, depending on the exact spatial arrangement of the passive particles. We also explore in detail the emergence of metastable oscillatory ordered states and their relation to the spatial distribution of passive particles and interstitial voids. Our findings demonstrate that heterogeneous activity and mobility anisotropy can result in a rich variety of self-organized states in various biological systems, synthetic active materials, and robotic swarms.

15 min. break

Invited Talk CPP 11.8 Mon 17:00 ZEU/0160

Topological transition in filamentous cyanobacteria: from motion to structure — •Marco Mazza — Loughborough University, Loughborough, UK

Many active systems are capable of forming intriguing patterns at scales significantly larger than the size of their individual constituents. Cyanobacteria are one of the most ancient and important phyla of organisms that has allowed the evolution of more complex life forms. Despite its importance, the role of motility on the pattern formation of their colonies is not understood. Here, we investigate the large- scale collective effects and rich dynamics of gliding filamentous cyanobacteria colonies, while still retaining information about the individual constituents' dynamics and their interactions. We investigate both the colony's transient and steady-state dynamics and find good agreement with experiments. We furthermore show that the Péclet number and aligning interaction strength govern the system's topological transition from an isotropic distribution to a state of large-scale reticulate patterns. Although the system is topologically non-trivial, the parallel and perpendicular pair correlation functions provide structural information about the colony, and thus can be used to extract information about the early stages of biofilm formation. Finally, we find that the effects of the filaments' length cannot be reduced to a system of interacting points. Our model proves to reproduce both cyanobacteria colonies and systems of biofilaments where curvature is transported by motility.

CPP 11.9 Mon 17:30 ZEU/0160

Novel Phase Coexistence in a Multi-Species Vicsek Model — •Eloise Lardet[1], Letien Chen[1,2], and Thibault Bertrand[1] — [1]Imperial College London, UK — [2]University of Edinburgh, UK

A hallmark in natural systems, self-organization often stems from very simple interaction rules between individual agents. While single-species self-propelled particle (SPP) systems are well understood, the behavior of mixtures of self-propelled particles with general alignment interactions remains largely unexplored with a few scattered results hinting at the existence of a rich emergent phase behavior. Here, we first present a generalization of the two-species Vicsek model with reciprocal intra- and interspecies (anti-)alignment couplings, uncovering a rich phenomenology of emergent states. Notably, we show that rather than destroying polar order, anti-aligning interactions can promote phase separation and the emergence of global polar order. Secondly, we derive a kinetic theory for the system, finding good agreement between theoretical predictions and particle simulations. This includes a novel mechanism for microphase separation, as predicted by a Turing instability. We finally show that these coexistence patterns can be generalized to multi-species systems with cyclic alignment interactions.

CPP 11.10 Mon 17:45 ZEU/0160

Flocking in weakly nonreciprocal mixtures — •Charlotte Myin — Max Planck Institute for Dynamics and Self-Organization (MPI-DS), 37077 Goettingen, Germany

We show that weakly nonreciprocal alignment leads to large-scale structure formation in flocking mixtures. By combining numerical simulations of a binary Vicsek model and the analysis of coarse-grained continuum equations, we demonstrate that nonreciprocity destabilizes the ordered phase formed by mutually aligning or anti-aligning species in a large part of the phase diagram. For aligning populations, this instability results in one species condensing in a single band that travels within a homogeneous liquid of the other species. When interactions are anti-aligning, both species self-assemble into polar clusters with large-scale chaotic dynamics. In both cases, the emergence of structures is accompanied by the demixing of the two species, despite the absence of repulsive interactions. Our theoretical analysis allows us to elucidate the origin of the instability, and show that it is generic to nonreciprocal flocks.

CPP 11.11 Mon 18:00 ZEU/0160

Collective behavior in nonreciprocal multi-species Vicsek model with permutation symmetry — •Jae Dong Noh[1], Chul-Ung Woo[2], and Heiko Rieger[2] — [1]Department of Physics, University of Seoul, Seoul 02504, Korea — [2]Department of Theoretical Physics and Center for Biophysics, Saarland University, Saarbrücken, Germany

Nonreciprocal systems are typically built upon asymmetric roles among interacting agents, such as a pursuer-evader relationship. We propose a multi-species nonreciprocal active matter model that is invariant under permutations of the particle species. The nonreciprocal, yet symmetric, interactions emerge from a constant phase shift in the velocity alignment interactions, rather from an asymmetric coupling matrix. This system displays rich collective behaviors, including a species-mixed chiral phase with quasi-long-range polar order and a species-separated vortex cell phase. We present numerical evidence for these phases using particle-based Monte Carlo simulations and analytic evidence using continuum Boltzmann and hydrodynamic equations. Our work demonstrates that multi-species chiral fluids can be realized by a nonreciprocal but symmetric alignment interaction, where the rich collective behavior is a consequence of the interplay between nonreciprocity and permutation symmetry.

CPP 11.12 Mon 18:15 ZEU/0160

Flocking with random non-reciprocal interactions — •Jiwon Choi[1], Jae Dong Noh[2], and Heiko Rieger[1] — [1]Department of Physics & Center for Biophysics, Saarland University, Campus E2 6, 66123 Saarbrücken, Germany — [2]Department of Physics, University of Seoul, Seoul, 02504, Korea

Flocking is ubiquitous in nature and emerges from alignment interactions among self-propelled agents. Two species that anti-align or interact non-reciprocally exhibit complex collective phenomena, ranging from parallel and anti-parallel flocking and run-and-chase behavior to chiral phases. Whether such behavior survives in the presence of many species with random non-reciprocal interactions has remained unclear. As a first step, we study a continuous-time Vicsek-like model with fully random non-reciprocal interactions between particles. For infinite-range interactions, flocking emerges once the alignment bias becomes comparable to the non-reciprocal interactions, and deep inside this phase random non-reciprocity can still support slow global chiral and oscillating states. For short-range interactions, even without alignment bias, self-organized cliques form, where medium-sized clusters with predominantly aligning interactions remain stable over long times. We further investigate the robustness of clique formation and the coexistence phase under angular noise using a discrete-time Vicsek model with random non-reciprocal interactions. These results provide a basis for studying multi-species flocking with complex non-reciprocal interactions.