Mechanics of Polar Active Solids

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Abstract

Polar active solids are composed of polar active units embedded in an elastic matrix. Such active solids have recently been explored in a model system composed of polar active agents that are free to reorient, but are trapped at the nodes of a periodic lattice. The generic presence of a non-linear elasto-active coupling between the orientation of the active forces and the elastic strain is responsible for a transition between a disordered phase and a collective actuation phase, where the orientations all rotate synchronously. In the present talk, we will discuss the mechanical properties of the disordered phase of such solids. First, analyzing the correlation matrix of the displacements, we find that the vibrational eigenmodes of the solid being coupled, an energy flow from the high-frequency to the low-frequency modes leads to a condensation of energy at low-frequency, which can be reinterpreted into a strong effective softening of the solid eventually leading to vanishingly small elastic moduli. Second, when put under traction, the polar active solids exhibits a variety of strongly anomalous response. At low activity, one recovers the softening of the solid, expected from the analysis of the fluctuations. Increasing the activity, this softening becomes so strong that the elastic modulus indeed vanishes, and an oscillating instability sets in.

*Speaker

Evidence of robust, universal conformal invariance in living biological matter

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Abstract

Collective cellular movement plays a crucial role in many processes fundamental to health, including development, reproduction, infection, wound healing, and cancer. The emergent dynamics that arise in these systems are typically thought to depend on how cells interact with one another and the mechanisms used to drive motility, both of which exhibit remarkable diversity across different biological systems. I will discuss recent findings, where we report experimental evidence of a universal feature in the patterns of flow that spontaneously emerges in groups of collectively moving cells. Specifically, I demonstrate that the flows generated by collectively moving dog kidney cells, human breast cancer cells, and by two different strains of pathogenic bacteria, all exhibit conformal invariance. Remarkably, not only do the results show that all of these very different systems display robust conformal invariance, but we also uncover that the precise form of the invariance in all four systems is described by the Schramm-Loewner Evolution (SLE), which allows us to reveal the universality class. A continuum model of active matter can recapitulate both the observed conformal invariance and SLE form found in experiments. The presence of universal conformal invariance reveals that the macroscopic features of living biological matter exhibit universal translational, rotational, and scale symmetries that are independent of the microscopic properties of its constituents. The results show that the patterns of flows generated by diverse cellular systems are highly conserved and that biological systems can unexpectedly be used to experimentally test predictions from the theories for conformally invariant structures.

*Speaker

Barrier crossing and rare fluctuations of active particles

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Abstract

We study barrier crossing processes for active particles. Using a low-noise Kramers limit we derive the effective activation barriers for three standard descriptions: active Brownian (ABP), active Ornstein-Uhlenbeck (AOUP) and run-and-tumble particles (RTP). We find that, because barrier crossing is dominated by rare fluctuations, there are significant qualitative differences between these, opening the way to e.g. designing potentials that could sort active particles according to their self-propulsion mechanism. For ABPs one key result is that, for potentials with a symmetry axis, activity can generate optimal escape paths that break this symmetry.

*Speaker

Emergent polar order in nonpolar mixtures with nonreciprocal interactions

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Abstract

Self-organization in living and active systems arises from simple microscopic interactions, often leading to collective behavior through spontaneous symmetry breaking. To study these phenomena, we employ a field-theoretical approach that predicts large-scale properties based on fundamental features such as symmetries and conservation laws. While these principles are typically inherent to the constituents, new phenomena can emerge when composite units related to emergent symmetries dominate the system's behavior.

We present a generic class of active matter models with two scalar fields that represent the concentration of molecular species interacting non-reciprocally. When non-reciprocity crosses a critical threshold, the system transitions from a phase-separated equilibrium configuration to an out-of-equilibrium stationary state, where parity and time-reversal symmetries are broken. The two species system evolves into a traveling-wave state, with one density field chasing the other in a spontaneously chosen direction. This is a striking example of polar order arising from non-polar particles, contrarily to many active matter models that assume polarity at a microscopic level.

We study analytically and numerically the stability of the ordered state and demonstrate the existence of true long-range orientational order in two dimensions and higher. We go beyond a linear approximation and perform a Renormalization Group analysis to study the effect of non-linearities. We show that the dynamics of concentration fluctuations around the ordered state map onto the Kardar-Parisi-Zhang universality class. This classification allows us to prove a conclusive violation of the Mermin–Wagner theorem and to predict the large-scale behavior of systems with non-reciprocal interactions at any dimension.

*Speaker

Stability of Discrete and Continuous-Symmetry Flocks

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Abstract

The talk will discuss the stability of flocking phases which exhibit symmetry breaking. For models which break a discrete symmetry, both an active Ising model and a hydrodynamic description will be used to show that droplets of particles moving in a direction opposite to that of the ordered phase nucleate and grow ballistically in all directions. The results imply that, in the thermodynamic limit, discrete-symmetry flocks are metastable in all dimensions. Following this the ordered phase of a flocking model which breaks a continuous symmetry will be considered and argued to be stable in parts of the phase diagram. This implies that in flocking models, in contrast to equilibrium systems, breaking a continuous symmetry is easier than a discrete one.

*Speaker

Active colloidal mixtures: clustering, seggregation and collective motion

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Abstract

In nature, the complex interactions driving collective motion lead to fascinating out-of-equilibrium self-organization processes. Cells of the same and/or different species coordinate their movement to enhance environmental exploration, achieving efficient navigation and maximizing survival through emergent cooperative and competitive behaviors. Group dynamics are often explored with dense suspensions of active colloids as synthetic model systems. While significant progress has been made in understanding collective behavior in single-species systems (1,2,3), active mixtures of different motilities remain largely unexplored. Here, we present a system of active colloids that exhibit flocking and spatial segregation driven by external electric fields, with particles having distinct motilities and independently tunable interactions (4). We experimentally and numerically report on the formation of highly dynamic polar clusters of both species of particles, with alignment occurring regardless of their propulsion speed. In dense binary mixtures, effective segregation emerges, with the dynamics of fast and slow particles influenced by interspecies interactions. These results highlight synergistic effects in the self-organization of active mixtures, offering insight into designing systems with advanced group dynamics (5).

(1) Boudet, et.al. Science Robotics 6, (2021)
(2) Theurkauff, et.al, Phys. Rev. Lett. 108, 268303466 (2012).
(3) Nkayama, et.al., Proceedings of the National Academy of Sciences (2023)
(4) L. Alvarez, E.Sesé-Sansa, D. Levis, et.al. (in preparation)
(5) C. van Baalen, L. Alvarez, et.al. (submitted)

*Speaker

Non-equilibrium phenomena via exact hydrodynamic analysis of active matter models

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Abstract

We discuss lattice models of self-propelled particles for which the large-scale hydrodynamic behaviour can be derived exactly, see for example (1). First we consider a model of with flocking behaviour (2) where we impose thermodynamic consistency in that self-propulsive forces are the only source of external work. These modelling assumptions lead to significant changes in the phase diagram and the entropy production rate, compared to previous models. Second, we consider a mixture of active and passive particles where non-reciprocal effective interactions generate dynamical patterns (3). (1) M Kourbene-Hossene, C Erignoux, T Bodineau, J Tailleur, Phys Rev Lett 120, 268003 (2018).
(2) T Agranov, RL Jack, ME Cates, and E Fodor, New J Phys 26, 063006 (2024).
(3) J Mason, RL Jack, and M Bruna, arXiv:2408.03932.

*Speaker

Active granular matter with bristlebots: how far from equilibrium ?

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Abstract

Bristlebots are centimeter-sized granular particles that are self-propelled by an internal vibration mechanism. Assemblies of such particles are obviously out-of-equilibrium systems but the question we would like to address here is how far from equilibrium such systems are? In some situtations, bristlebots show dynamial states that are somehow similar to equilibirum states with order/disorder transitions for example. This is the case when a set of brisltebots is placed in a circular rigid arena. At low surface densities, the particles mostly behave as a gas and for higher surface densities, the particles form boundary ordered clusters that coexist with the particle gas state.

However, if some physical parameters are modified such as the softness/mobility of the arena boundary or the chiral properties of the particles, some collective states can emerge that have no equivalent in equilibrium statistical mechanics.

In this talk, I would like to review some of the experimental results we have with bristlebots and try to give some illustrations of what out-of-equilibirum can mean for active granular matter.

*Speaker

Dynamical steady states with macroscopic currents in nonreciprocal systems

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Abstract

Nonequilibrium conditions often break the symmetry between actions and reactions, giving rise to effective nonreciprocal couplings. In this talk, I discuss the emergence of dynamical steady states with macroscopic currents due to nonreciprocal interactions. First, I consider fluctuating field theories with conserved dynamics describing travelling waves in nonreciprocal fluid mixtures. We find that close to PT-symmetry breaking phase transitions, fluctuations not only inflate, as is known from equilibrium criticality, but also become increasingly irreversible. Second, I consider single-species disordered spin systems, where we find that nonreciprocal interactions lead to dynamical states with coherent oscillations but incoherent phases, but can also give rise to chaotic phases and suppress or enhance glassy behaviour.

*Speaker