Active Matter Workshop 2022

VENUE:
CMMA, Meiji University
and via Zoom webinar

DATE:
28 - 29 January, 2022

Organiser

共同利用・共同研究拠点　明治大学
先端数理科学インスティテュート（MIMS）現象数理学拠点

MEXT Joint Usage/Research Center Meiji University
"Center for Mathematical Modeling and Applications" (CMMA)

Organisation committee

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Web page

https://sites.google.com/view/activematter2022

Contact

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Program

2022/1/28 Fri.

12:30 - 13:00	**Self-Registration**
13:00 - 13:10	**opening**
13:10 - 14:00	**[IL:oS] Yamamoto, Takashi** "Behavioral measurement of animals by biologging"
14:00 - 14:25	**[En:oL] Kuroda, Yuta** "Anomalous Long-Range Correlations in Fluid Phase of Active Brownian Particles with Inertia"
14:25 - 14:50	**[Jp:oL] Hamada, Keisei** "Spatial Correlation and Relaxation Time in Active E. coli Suspensions"
14:50 - 15:30	Break
15:30 - 15:55	**[En:oL] Sugino, Yujiro** "Rheology of Condensed Active Colloidal Suspension"
15:55 - 16:20	**[Jp:oL] Matsumoto, Eiji** "Mechanical adaptation of intracellular structures"
16:20 - 16:45	**[En:oL] Yasuda, Kento** "Statistical property of the stochastic system with odd elasticity"
16:45 - 17:00	**discussion**

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Presentation time

IL: Invited lectures [50 min each, including discussions]

En/Jp: Contributed presentation in English/Japanese [25 min each including discussions]

oL/oS: online/on-site presentations, on-site presentations are also broadcast via the Zoom webinar.

2022/1/29 Sat.

9:30 - 10:00	**Self-Registration**
10:00 - 10:05	**opening of Day 2**
10:05 - 10:55	**[IL:oS] Matsuo, Muneyuki** "Self-oscillating propulsion of chemically active droplet"
10:55 - 11:20	**[En/oL] Ishikawa, Hiroaki** "Pairing-induced motion driven by the surface tension gradient and attractive lateral capillary interaction."
11:20 - 11:45	**[En/oS] Moreau, Clement** "Self-organised swimming with odd elasticity"
11:45 - 13:15	Break
13:15 - 13:40	**[En/oS] Schnyder, Simon** "Role of the Cell Cycle in Collective Cell Dynamics"
13:40 - 14:05	**[En/oS] Li, Jintao** "Mechanical competition between different cell types"
14:05 - 14:30	**[Jp/oL] Takada, Sakura** "Shaping dynamic and static patterns in artificial cells by modulating reaction-diffusion coupling of Min system"
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15:25 - 15:50	**[En:oL] Yamagishi, Manami** "Defining a Quantum Active Particle Using Non-Hermitian Quantum Walk"
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16:40 - 17:00	**discussion and closing**

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Abstracts

Day 1
28 Jan., 2022

12:30 - 13:00	**Self-Registration**
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Behavioral measurement of animals by biologging

Takashi Yamamoto

Meiji Institute for Advanced Study of Mathematical Sciences, Meiji University

Active matter includes living and non-living systems. Regarding animals, a classic example of active matter system is a flock of birds. Observation is the fundamental method used to study behavior of animals. However, it is usually logistically difficult to keep chasing and observing free-ranging animals such as birds and mammals in terrestrial/marine nature environments, and, therefore, taking observation/experiment is often limited in time and space as well as situation. Recently, biologging technology, defined as 'the use of miniaturized animal-attached tags for logging and/or relying data about an animal's movements, behavior, physiology, and/or environment' [1], enables us to take measurements from free-ranging animals as they move undisturbed through their environment and interacting with other individuals [2]. For examples, GPS device can record high-resolution spatiotemporal movement of animals (<1 second), and tracking a flock of homing pigeons (a consist of 10 individuals) revealed a synchronized role in pairwise interactions between individuals [3]. Not only capturing movements, but also the use of tri-axial accelerometer tags has begun to resolve details of the 3-dimensional movement of animals [4], which can be indicative of energy expenditures (i.e. the absolute sum of dynamic acceleration) [5]. Furthermore, the ability to instrument animals and actively record physiological parameters such as body temperature, oxygen utilization [6], heart rate [7] or EEG (electrical brain activity) [8] has provided important new knowledge about how animals function. Gathering such novel insights constructs a conceptual framework depicting the interplay among four basic mechanistic components of organismal movement: the internal state (why), motion (how), and navigation (when/where) capacities of the individual and external factors affecting movement, named 'movement ecology' [9]. Biologging techniques could constitute an aspect of active matter, and may enhance our understanding of complex but interesting organisms' system.

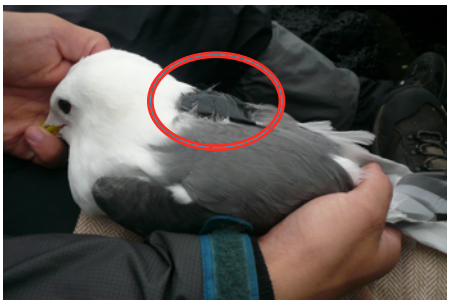

Fig.1: Data logger attached on the back of a seabird.

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Anomalous Long-Range Correlations in Fluid Phase of Active Brownian Particles with Inertia

Yuta Kuroda[1], **Hiromichi Matsuyama**[1], **Takeshi Kawasaki**[1], **Kunimasa Miyazaki**[1]

[1]Department of Physics, Nagoya University

Self-propelled particles have been widely studied as a model of active matter. The Vicsek model is one of the most famous self-propelled particles. This model has the ordered phase reminiscent of bird flocks. In the ordered phase, the system does not only exhibit the long-range order but is also accompanied by the anomalous increase of the number fluctuation, so-called giant number fluctuation (GNF) [1]. Another famous example of self-propelled particles is the active Brownian particles (ABP). This model does not have the alignment interaction like the Vicsek model. In the high activity regime, however, particles assemble spontaneously and separate into dilute and dense phases. This phenomenon is called motility induced phase separation (MIPS).

The standard ABP model does not have the inertia term and is described by the overdamped Langevin equation. Recently, it was found that adding the inertia term to the ABP model suppresses the MIPS, and the system remains in the fluid phase even in high activity [3]. There are some studies of the effects of inertia on the MIPS, but the fluid state with high activity, which arises by adding the inertia term, has not attracted much attention so far.

We study properties of the fluid phase of the ABP with inertia term at the high activity regime and relatively low-density. We have performed the Brownian dynamics simulation for this model and found that the velocity and density correlation become long-ranged and GNF is observed. While long-range velocity correlation in the ABP model had been observed in only high-dense phases in previous studies [4], our results indicate that this long-range velocity correlation is not an intrinsic feature of dense systems but is a general feature of the ABP system. Additionally, we have found that the longitudinal part of velocity correlation is related to the density correlation and GNF. Theoretically, the part of these results can be captured by the fluctuating hydrodynamics description qualitatively [4,5].

References

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Spatial Correlation and Relaxation Time in Active *E. coli* Suspensions

Keisei Hamada, Yujiro Sugino, Hiroyuki Ebata, Daisuke Mizuno

Department of Physics, Faculty of Science, Kyushu Univ.

When colloidal suspensions are concentrated, rearrangements of colloids become increasingly rare, leading to their dynamic arrest (glass transition). It has been believed that the cooperativity or heterogeneity of thermal fluctuations underlies this anomalous phenomenon. Meanwhile, a thick suspension of self-driven colloids, referred to as "active glass" attracts recent interests. Numerical studies have suggested that the active glass may avoid glass transition and remain fluidic [Nandi *et al.*, *PNAS* (2018) **115**, 7688] whereas cooperative dynamics during the active fluidization are largely elusive.

The purpose of this study is to establish an experimental model system of active glass and investigate the glassy dynamics associated with the active fluidization. By exchanging small-molecular metabolites and metabolic byproducts via a semipermeable membrane, active glass composed of migrating *E. coli* were prepared up to a volume fraction of about 40%. By varying the ratio of migrating and non-migrating *E. coli*, we investigated the cooperativity of the fluctuations and the relaxation time for the rearrangement of bacteria. From the velocity fields measured by PIV (Particle Image Velocimetry) (Fig. 1, 2), the spatial correlation of the fluctuation was calculated for both longitudinal (∥) and transversal (⊥) directions (Fig. 3). The relaxation time of the density correlation was also obtained by the image analysis of the *E. coli* suspensions (Fig. 4). It was observed that the strength of the fluctuation and the relaxation time depended on migration activity whereas the spatial correlation of the fluctuation did not.

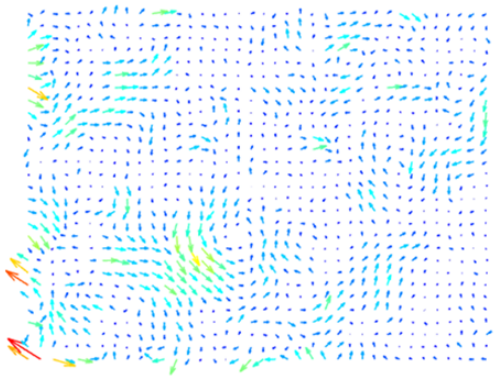

Fig. 1: Velocity field (w/o migration)

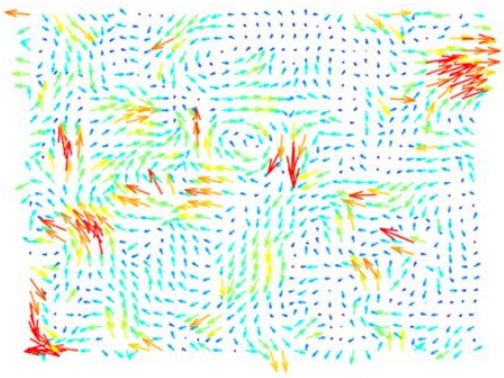

Fig. 2: Velocity field (w/ migration)

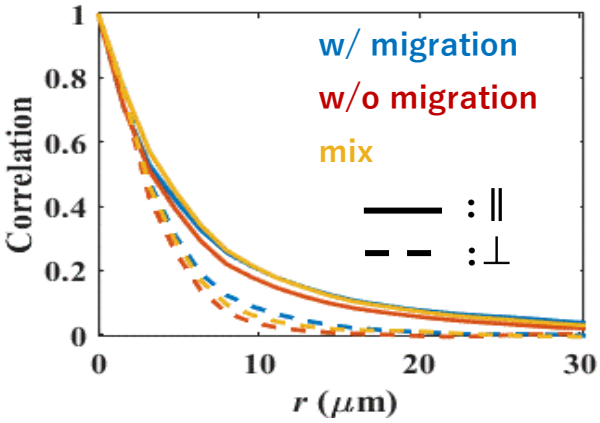

Fig. 3: Spatial correlation of velocity field

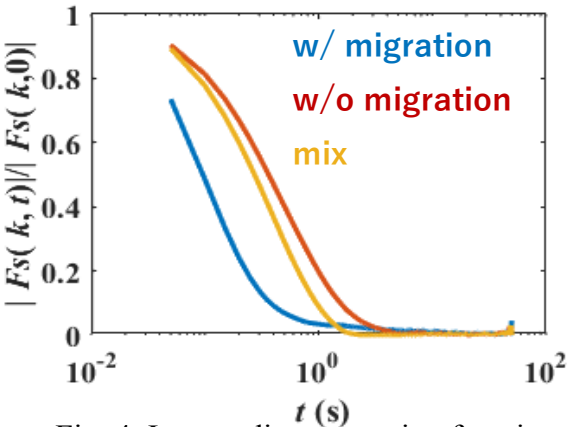

Fig. 4: Intermediate scattering function

Rheology of Condensed Active Colloidal Suspension

Yujiro Sugino[1], **Hiroyuki Ebata**[1] **and Daisuke Mizuno**[1]

[1]Dept. of Phys., Kyushu Univ.

Colloidal suspension exhibits a dramatic increase of viscosity of colloids in higher volume fraction. Such dynamic arrest is known as the glassy transition. Computational studies, on the other hand, describe that the non-equilibrium driving force of dense colloids cause fluidization from the glass state [1]. Besides, inside of cells, molecular crowding cause glassy behavior of cytoplasm, while living cells are fluidized by their metabolic activity [2]. Active forces generated by mechanoenzymes may induce the fluidization of the glassy cytoplasm. Therefore, the exploration of the influence of the active force on rheological properties of dense colloids contributes to clarify the glassy physics and cell biology. However, experimental investigation associated with the study still lack.

In this study, condensed bacterial suspension was used as the model of self-propelled active colloids. We then measured rheological properties of the suspensions (w/motility and w/o motility) by using optical tweezers and laser interferometry technique (Fig. 1a). Because of the condensed bacteria consume a lot of metabolites, we also constructed dialysis chamber which provide the metabolites and excrete byproducts. The violation of fluctuation-dissipation theorem was observed in the motile bacterial suspension (Volume fraction of bacteria $\varphi \sim 40$ %) as shown in Fig. 1b. In addition, mobility was reduced by their driving force at low frequencies (Fig. 1b). In another works, viscosity of bacterial suspension was reduced for long time scale (Fig. 1c). In this presentation, we discuss the relation between the driving force and rheological properties of dense bacterial suspensions.

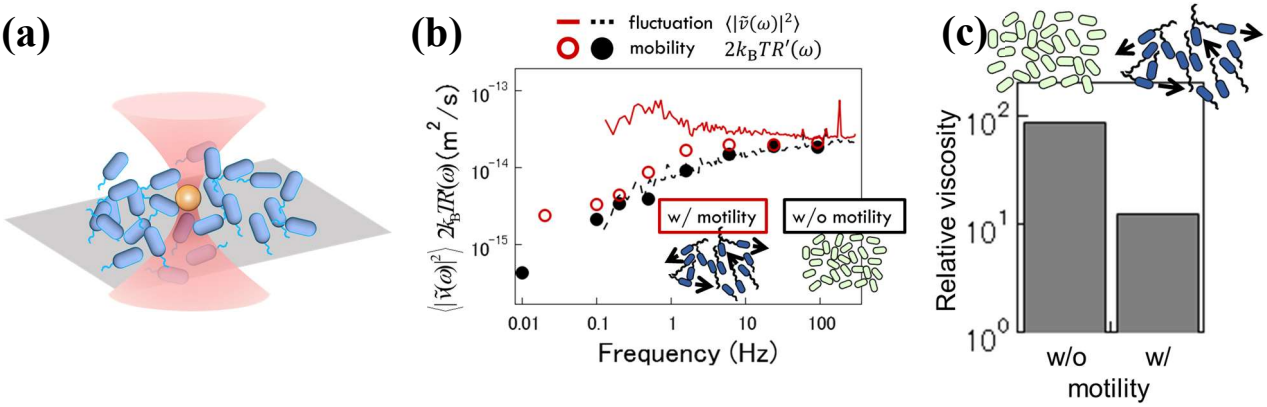

Fig. 1: (a) Bacterial suspension as a model of condensed active colloidal suspension (volume fraction of bacteria φ = 40 % ~). Rheological properties were measured by using the optical tweezers and laser interferometry technique [3, 4]. (b) Power spectral density of bacterial suspension ($\varphi \sim 40$ %). Spontaneous fluctuation (lines) and mobility (circles) were measured for w/ (red) and w/o (black) motile system. (c) Viscosity of bacterial suspension (w/o motile and w/ motile) were calculated at lowest frequency. The viscosities were divided by the viscosity of the solvent.

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Mechanical adaptation of intracellular structures

Eiji Matsumoto[1], **Daiki Matsunaga**[2], **Shinji Deguchi**[2]

[1] School of Engineering Science, Osaka University
[2] Graduate School of Engineering Science, Osaka University

1. Introduction

In the cell, there are various protein polymers (e.g. actin filaments and microtubules), which are implicated in cell motility and detection of the surrounding environment. These structures allow the cell to maintain homeostasis through turnover, in which the basic condition of the cell is sustained. Currently, it remains unclear how these structures enable homeostasis under changes in surrounding mechanical environment. In this study, we describe the adaptative behavior of intracellular structures subjected to turnover to evaluate the cellular mechanical homeostasis.

2. Theory

In this study, intracellular structures – such as actin filaments – subjected to turnover are considered and assumed to be a one-dimensional homogeneous and isotropic linear viscoelastic body (Voigt model). The structures are assumed, as experimentally suggested[1,2], to have a stable stress σ_s in a mechanically adaptative state (tensional homeostasis). We show with this model how the structure exhibits adaptive response in response to stress fluctuations caused by, e.g., interaction with the surrounding environment and other proteins. The model is described by

$$\sigma(t) = E\epsilon(t) + \eta\frac{d\epsilon(t)}{dt} = E\frac{\lambda + d - \delta(t)}{L + \delta(t)} - \eta\frac{L + \lambda + d}{\left(L + \delta(t)\right)^2}\frac{d\delta(t)}{dt} \tag{1}$$

$$\frac{d\delta(t)}{dt} = k(\sigma(t) - \sigma_s) \tag{2}$$

where stress, σ; strain, ϵ; Young's modulus, E; viscosity, η; initial length, L; stable elastic deformation, λ; disturbance, d; length change for turnover, δ; and, turnover rate, k.

3. Result and discussion

With a linear approximation in the adaptive model consisting of equations (1) and (2), we showed that the turnover behaves as a first-order lag system with time constant of $T = \frac{L+k\eta}{kE}$, and that the structures are described by a specific feedback system containing an integral element that assures stabilization of the structures (Fig. 1).

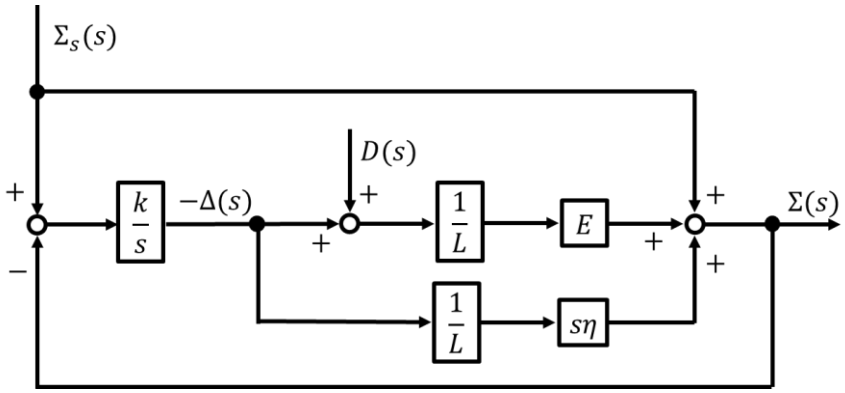

Fig. 1 Block diagram of the adaptation of intracellular structures

4. Conclusion

We focused on the adaptation of intracellular structures and described their behavior. Our results show that the time constant of the adaptation that characterizes the response of the system contains the turnover rate and how it relates to the intrinsic viscoelastic properties of the intracellular structures.

References

1. Huang et al., "Mechanosensitive myosin II but not cofilin primarily contributes to cyclic cell stretch-induced selective disassembly of actin stress fibers", *American Journal of Physiology Cell Physiology* **320**, C1153–C1163 (2021).
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Statistical property of the stochastic system with odd elasticity

K. Yasuda[1], **A. Kobayashi**[2], **L.-S. Lin**[2], **Y. Hosaka**[2], **I. Sou**[2], **S. Komura**[2,3,4]

[1]Research Institute for Mathematical Sciences, Kyoto University
[2]Department of Chemistry, Graduate School of Science, Tokyo Metropolitan University
[3]Wenzhou Institute, University of Chinese Academy of Sciences
[4]Oujiang Laboratory

Recently, the concept of odd viscosity and elasticity has been introduced to describe interactions in the active materials[1]. To describe the stochastic dynamics of a micromachine such as an enzyme (Fig.1(a)), we have considered the over damped Langevin equations with odd elasticity which represents the activity induced by catalytic chemical reaction. In this talk, we focus on two statistical quantities, the time-correlation functions and the most probable path.

As the first topic, we focus on the time reversal symmetry of time-correlation functions and show that it will be broken in the presence of odd elasticity[2]. The time reversal symmetry holds for the cross-correlation function for systems in equilibrium, such symmetry does not exist for non-equilibrium systems. We found that the time reversal symmetry of time correlation functions is broken in proportion to the odd elasticity.

In the second work, we investigate how the presence of odd elasticity influences the most probable path that is derived by the variation of the OM integral, i.e., the OM variational principle. We show that the most probable outward path is different from that of the return path in micromachines (Fig.1(b)), and hence the whole process becomes non-reciprocal due to odd elasticity[3].

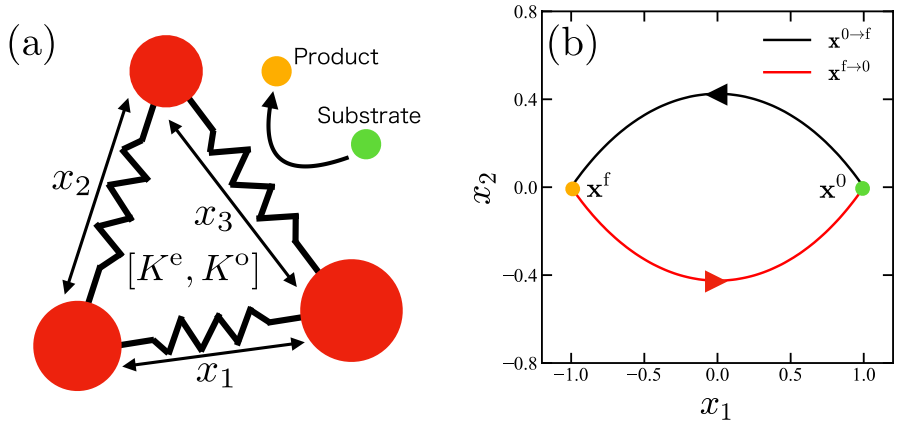

Figure 1 (a) A coarse-grained model of an enzyme consisting of domains that are connected to springs. A substrate (green circle) changes into a product (orange circle) via a catalytic chemical reaction. (b) The most probable outward path (black line) and the return path (red line). The initial and final conditions are green circles and orange circles, respectively.

References
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2. K. Yasuda *et al.*, in preparation.
3. K. Yasuda *et al.*, J. Phys. Soc. Jpn. **91**, 015001 (2022).

Day 2
29 Jan., 2022

10:00 - 10:05	**opening of Day 2**
10:05 - 10:55	**[IL:oS] Matsuo, Muneyuki** "Self-oscillating propulsion of chemically active droplet"
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Self-oscillating propulsion of chemically active droplet

Muneyuki Mastuo[1]
[1]Graduate School of Integrated Life Sciences, Hiroshima University

The significant factor enabling the self-organization of organisms is the recursiveness of the living thing itself or a part of its state. In order to develop highly sustainable artificial systems, introducing such oscillatory phenomenon into the system is an essential approach. Recently, recursively growing and dividing that is proliferating droplets have been reported via an autocatalytic reaction with periodic addition of a precursor and a stimulus[1]. Generally, droplets could easily transport materials in and out of the liquid phase because droplets are in a liquid phase. The construction of self-propelled droplets that self-oscillate is expected to develop highly sustainable intelligent materials. Here we report a novel chemically active droplet that exhibits self-oscillating propulsion independently of any oscillating reactions or perturbations in an isotropic environment.

A hydrolysis reaction of menthylacetate (MA) into methanol (MOH) and acetic acid was introduced to the experimental system. When MA (2-8 μL) was dropped onto 3 mL of NaOH aqueous solution (0.1-10 mM) or ultrapure water which filled a glass Petri dish, MA spread wet on the surface of an aqueous solution. However, MA gradually re-aggregated, and MA droplets were formed. The formed droplets exhibited self-propulsion. Surface tension measurements revealed that the hydrolysis product MOH reduced the interfacial tension by up to 13 mN/m. Droplets composed of decyl acetate, in which MOH was replaced by decanol, did not exhibit self-propulsion. These results strongly suggest that self-propulsion is induced by the MOH-derived inhomogeneity of the surface tension (Figure 1). The droplet could be regarded as a chemically active swimmer.

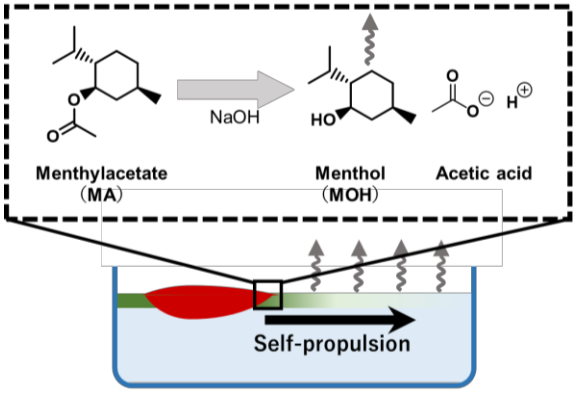

Figure 1. Self-propulsion mechanism of MA droplet

Furthermore, at a NaOH concentration of 10 mM, MA droplets with an initial volume of more than 6 μL exhibited oscillatory self-propulsion, i.e., repeatedly stopped and moved (Figure 2a). The oscillation was led by the deformation of the droplet (Figure 2b). When a droplet position was fixed, a droplet beat, i.e., repeatedly swelled and shrank. When a Petri dish was covered with a cap, no oscillating and beating were observed. These results indicate that the oscillatory motion of the droplets is due to the synergy of MOH production and sublimation. Synchronization of chemically active droplets in self-oscillating propulsion was also observed and should be induced by long-range interactions generated by the synergy of MOH.

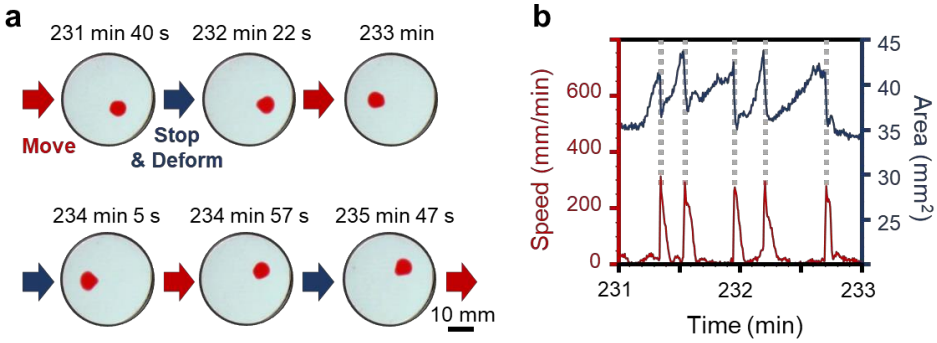

Figure 2. (a) Self-oscillatory motion of MA droplet.
(b) Synchronization between motion speed and deformation.

Acknowledgments
This work was financially supported by the Astrobiology Center, National Institutes of Sciences, Project Research (AB031012).

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Pairing-induced motion driven by the surface tension gradient and attractive lateral capillary interaction.

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A self-propelled particle refers a particle that creates its momentum by a free energy consumption. In this study [1], we focus on self-propelled particles driven by the gradient in the chemical concentration fields. In particular, we consider a system in which two species with different effects on concentration are mixed. In such a binary mixed particle system, as a pioneering theoretical work, a certain type of particle chases other particles [2]. However, the previous studies have not considered the distortion of the concentration field due to the velocity of the particles. Therefore, we considered a situation where the relaxation of the concentration field is not sufficiently fast with respect to the velocity of the particles.

Here, we construct an experimental system in which a pair of source and inert particles is driven by surface tension gradient and attractive force. The source particle spreads the surface-active molecules around itself, though the inert particle does not affect the concentration field. The source and inert particles are driven by the surface tension gradient due to the inhomogeneous concentration field. In the present system, we used a camphor disk as the source particle. As for the inert particle we used a metal washer. In the actual experimental systems, an attractive lateral capillary force is exerted between them through the distortion of the aqueous surface. As a result, they got close to each other and then started pairing-induced motion. They exhibited circular (Fig.1(a)) and straight (Fig.1(b)) motions for the lower and higher PEG concentrations, respectively. Numerical calculations using a model that considers forces caused by the surface tension gradient and lateral capillary interaction reproduced the observed circular (Fig. 1(c)) and straight motions. In both the cases, the inert particle was in the front side, while the source particle was in the rear side. Our results show that the effect of particle velocity cannot be overlooked in order to describe the interaction through the concentration field.

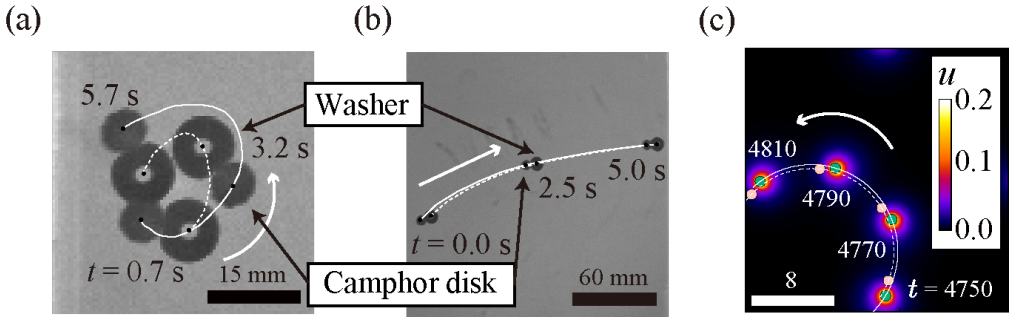

Figure 1: (a, b) Experimental results representing by superimposed images of the camphor disk and the metal washer. (a) Circular and (b) straight motions observed on the PEG aqueous solutions at C =(a) 0.001 and (b) 10 g/L. (c) Obtained by numerical results representing by superimposed images obtained using numerical calculations, in which the color map shows the profile of the concentration field u. The green and pink disks represent the source and inert particles, respectively.

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Self-organised swimming with odd elasticity

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Swimming in a fluid is generated by interactions between elasticity and activity of a material. In particular, time-periodic wave-like beating is ubiquitous in nature, as seen from active elastic filaments of cilia and flagella at the microscopic scale. For an elastic material, this activity has recently been described by anti-symmetric components of material elastic moduli, termed as *odd elasticity* [1].

In this talk, using the fundamental Purcell's three-link microswimmer model, we will show how odd elasticity can generate a self-organised, stable swimming gait resembling those of a "pusher" swimmer. Moreover, motivated by the shape fluctuations originating from internal molecular motors, we demonstrate that this type of swimmer can produce net motion in one direction from random noise [2].

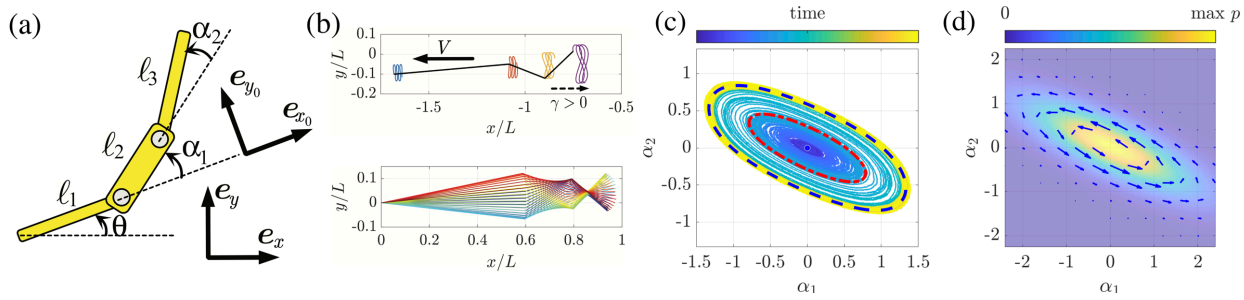

Fig. 1 : Odd-elastic three-link swimmer and its cyclic behaviour.

We focus on the elastic three-link swimmer (Fig. 1a), to which we add an antisymmetric elasticity component. We will numerically investigate the existence of a stable limit cycle producing net locomotion, depending on the geometry and elasticity parameters. With shape fluctuations added as a Gaussian noise, we will then analytically study the net displacement of the swimmer using gauge field formalism [3].

The stability analysis and numerical simulations show a bifurcation occurring from a critical value of the odd elasticity strength, with the appearance of a stable swimming pattern (Fig. 1b) materialised by a closed loop in the phase plane of the shape angles α_1, α_2 (Fig. 1a,c). Furthermore, we explicitly calculate the displacement produced by random shape fluctuations and observe that the noisy swimmer can reach the limit cycle from its equilibrium position (Fig. 1c,d). Beyond Purcell's swimmer, we additionally show how our theoretical formalism for odd elastic fluctuations can be applied to a general swimmer such as an elastic flagellum.

This study provides a simple yet powerful model of odd elastic material to produce beating-like swimming patterns and contributes to the understanding of the role of shape fluctuations in the displacement of micro-organisms. General features of the microscopic noisy elastohydrodynamics will be useful in modelling, understanding and designing biological and artificial active materials.

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Role of the Cell Cycle in Collective Cell Dynamics

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Living cells coexist in colonies or tissues. We develop a simplified model of the cell cycle, the fundamental regulatory network controlling growth and division, and couple this to physical stress [1]. In its simplest form, this model involves three characteristic times (for adaptation of the cell cycle, τ_r, and volume, τ_v as well as a division time, τ_{div}), two cell volumes (unstressed and quiescent) and a pressure at which the cell cycle stalls. We employed both particle-based computer simulations and a continuum theory to study quasi-2D colonies growing in a channel, see Fig. 1, and on a substrate. These colonies exhibit moving growth fronts with a profile and speed that are non-trivially related to the substrate friction and the mechano-chemical cell cycle parameters, providing a possible approach to measure such parameters in experiments. In this talk we focus on the continuum theory.

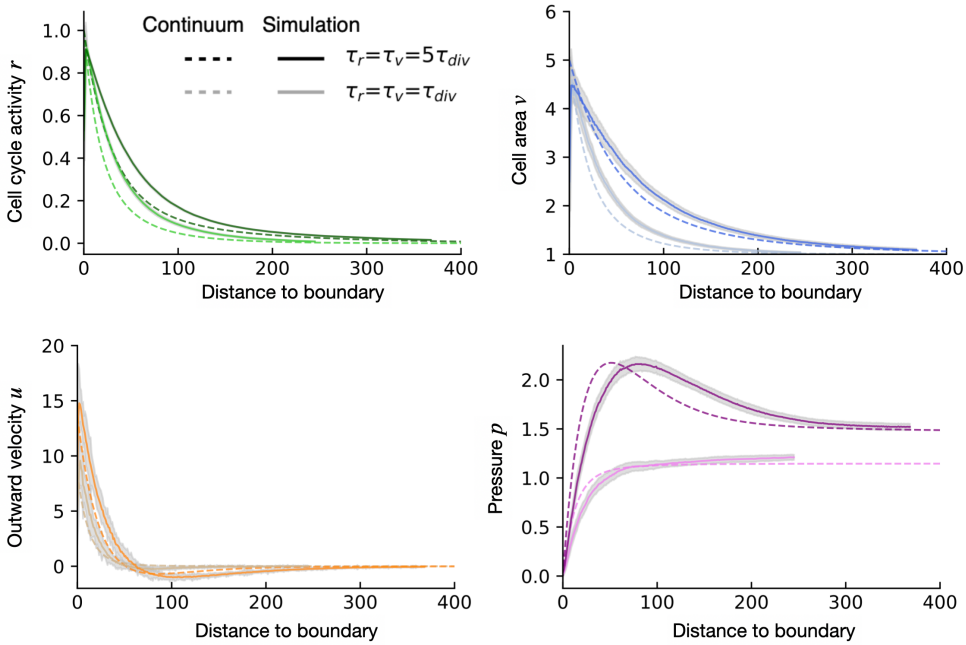

Fig. 1: The mechanochemical variables exhibit different profiles behind the moving growing front with the simulations and continuum theory in semiquantitative agreement. Shown are steady-state average values of (a) lab-frame cell velocity u, (b) local cell pressure p, (c) cell-cycle activity r, and (d) 2D cell volume (area) v, measured a distance z behind the leading edge of the growing colony. The solid lines are from particle-based simulations with $\tau_r = \tau_v = 5\,\tau_{div}$ (darker) and $\tau_r = \tau_v = \tau_{div}$ (lighter) (one standard deviation shown in gray). The dashed lines show the continuum solution.

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Mechanical competition between different cell types

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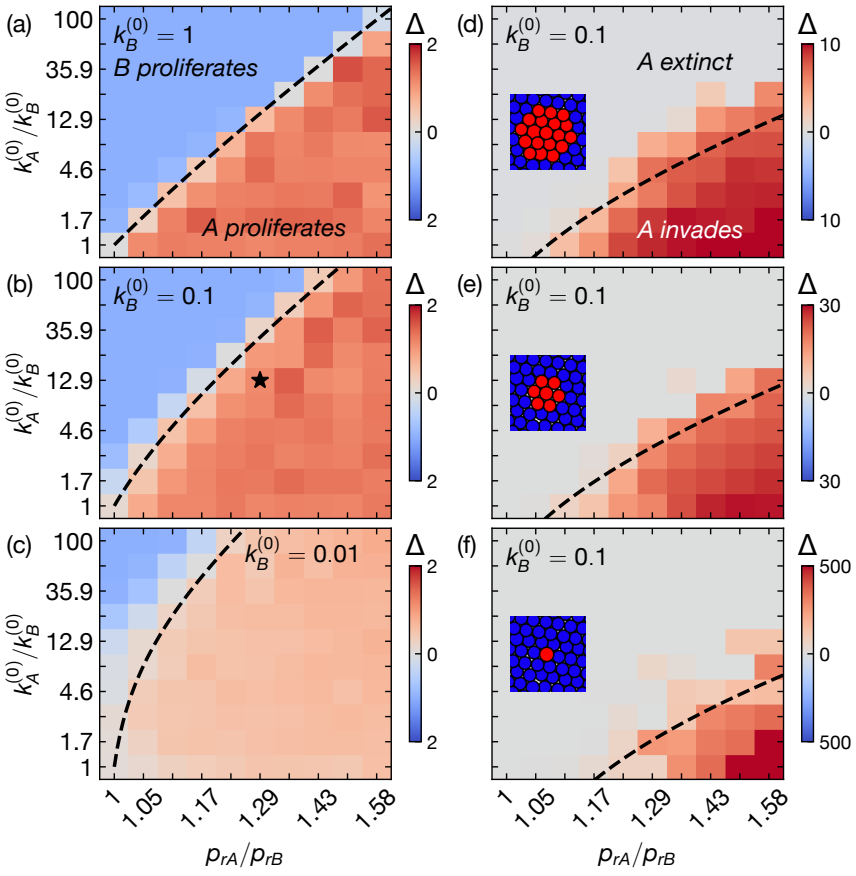
Abstract

Competition between different cell or tissue types is a key process in fields as diverse as bacterial ecology, developmental biology, and tumor growth. Recent studies have revealed that the homeostasis pressure is sufficient to account for the output result in MDCK experiments. However, in vivo, different cell types can also have different rates of programmed cell death (apoptosis). We study how the combination of homeostatic pressure and apoptosis rate can impact the competition process. Using an analytical model and discrete simulation, we explore how cells coexist/outcompete with each other under two initial conditions: a nearly planar interface between two cell types and one in which a small nucleus of one cell type is surrounded by the other.

We explore the "boundary region" where two colonies can coexist. We found that not always the colony with high homeostasis pressure invades the other, which apoptosis rate is also decisive for the competition output. Also, the different dynamics from the two initial conditions indicate the tumor development needs overcome statistical noise and Laplace pressure difference. Our findings shed light on how cancer develops and draw attention to the cell cycle's role.



Phase diagram for cell competition. Colorbars indicate the change in A cell as $\Delta = [N_A(t=100\tau_{div})-N_A(0)]/N_A(0)$ and prediction for the coexistence line, obtained from the continuum theory, is shown as a dashed line in each case. The left panels (a-c) show the outcome from equal initial volumes of A and B in a channel setting. Three different values of $k_B^{(0)}$ are shown. The right panels (d-f) show three different initial conditions containing small initial colonies of A cells ($N_A(0) = 19, 7, 1$ as shown in the insets) in host *B* tissue (0) at $k_B^{(0)} = 0.1$. These are results of simulations in periodic systems of size 30 × 30.

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Shaping dynamic and static patterns in artificial cells by modulating reaction-diffusion coupling of Min system

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Reaction-diffusion coupling (RDc) is a mechanism to determine the spatiotemporal pattern of biomolecules in cells. It induces two types of self-assembly: dynamic and static patterns. Here, we investigated the selection mechanism of these spatiotemporal patterns by using Min waves reconstituted in artificial cells. Min wave is a regulator of bacterial cell division plane, which emerged by the RDc of MinD and MinE. We revealed that the balance of membrane binding and dissociation from the membrane of MinD determines the mode selection between traveling wave and standing wave of the Min wave. We showed that the transition of the wave modes can be regulated by controlling this balance (Fig. 1). Furthermore, by modulating the reaction network of Min wave, we created Turing patterns (static patterns) within artificial cells. The number of spots of Turing patterns increased depending on the spatial size, and single spots were observed in smaller space. The Turing patterns created here may explain the mechanism of molecular arrangement in living cells.

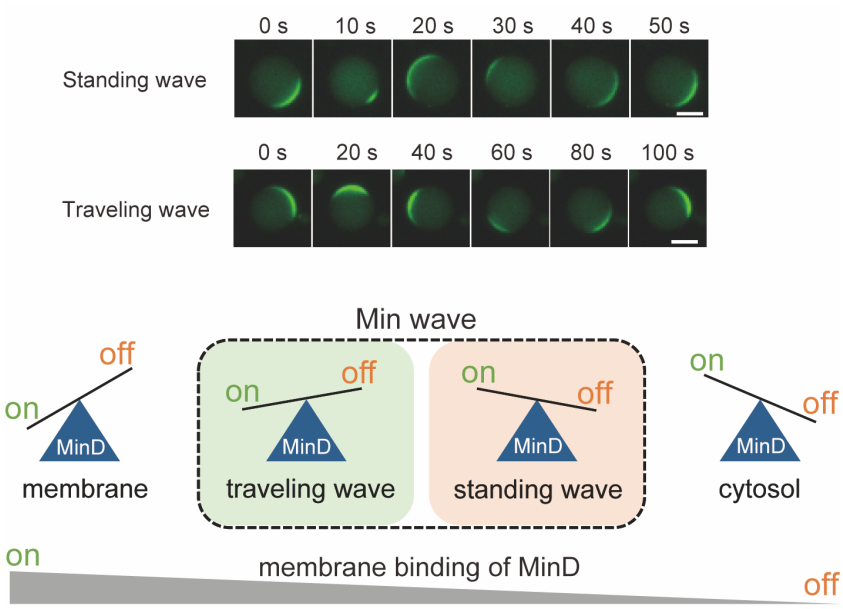

Fig. 1 Two modes of Min waves and summary of mode selection mechanism

The emergence of aggregation phenomena in a microscopic model of labor force migration

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Aggregation phenomena, which have been investigated thoroughly in biology and chemistry, are also common to society. In this talk, we propose a mathematical model to describe the migration of economic agents using Active Brownian particles and show by agent-based simulations that the workforce clusters out of a random initial state. We also find that the model exhibits two well-known empirical laws in social sciences called Zipf's and Okun's laws. Given that one can derive an extended Keller-Segel system from the microscopic model, our results are a significant indication that the aggregation of labor force is accounted for by the same process as chemotaxis and is associated with blow-up phenomena in the PDE system.

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Defining a Quantum Active Particle Using Non-Hermitian Quantum Walk

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We present a model of quantum active particles using non-Hermitian quantum walks. Although there are a number of works on active matter, most of them are conducted in classical systems. Since neither the energy nor the momentum is conserved, it is challenging to express active-matter dynamics in terms of a quantum Hamiltonian. In the present work, we propose a quantum walk as a suitable tool to define an active particle in a quantum system.

Schweitzer *et al.* [1] studied the motion of a Brownian particle with the ability to take up energy from the environment, to store it inside the particle, and to convert the internal energy into the kinetic energy. In order to describe these processes, they added a new term expressing the internal energy of the particle $e(t)$ on the right-hand side of the Langevin equation as follows:

$$m\dot{\boldsymbol{v}} + \gamma_0 \boldsymbol{v} + \boldsymbol{\nabla} U(\boldsymbol{r}) = d_2 e(t)\boldsymbol{v} + \mathcal{F}(t). \tag{1}$$

Here, m, $\boldsymbol{v}$, and $\boldsymbol{\nabla} U$ denote the mass, velocity, and the potential of the particle, respectively, while γ_0 denotes the friction coefficient. The stochastic force $\mathcal{F}(t)$ satisfies the following equations:

$$\langle \mathcal{F}(t) \rangle = 0; \quad \langle \mathcal{F}(t)\mathcal{F}(t') \rangle = 2S\delta(t - t'), \tag{2}$$

and $e(t)$ denotes the internal energy of the particle which evolves according to the following equation:

$$\frac{\mathrm{d}}{\mathrm{d}t} e(t) = q(\boldsymbol{r}) - ce(t) - d_2 v^2 e(t), \quad v^2 = \boldsymbol{v} \cdot \boldsymbol{v}. \tag{3}$$

Here, $q(\boldsymbol{r})$, c, and $d_2 v^2$ indicate the space-dependent take-up of energy, the rate of internal dissipation of the internal energy, and the rate of conversion of the internal energy into kinetic energy, respectively. The authors revealed that the dynamics of the Brownian particle changes depending on $q(\boldsymbol{r})$.

In order to reproduce the same energy-take-up and energy-conversion processes in a quantum system, we use a non-Hermitian quantum walk. Quantum walk is a quantum analog of the classical random walk. In the simplest case, the quantum walker has two internal states, leftward and rightward, and there are two operators, namely the coin operator which shuffles the two internal states and the shift operator which moves the walker according to the internal states. It is known that the equation of motion of discrete-time quantum walker gives the Dirac equation in the continuum limit. If we set the coin operator as $C = e^{-\mathrm{i}\theta\sigma_y}$, θ corresponds to the mass term in the Dirac equation and hence the walker runs faster with a small value of θ [2].

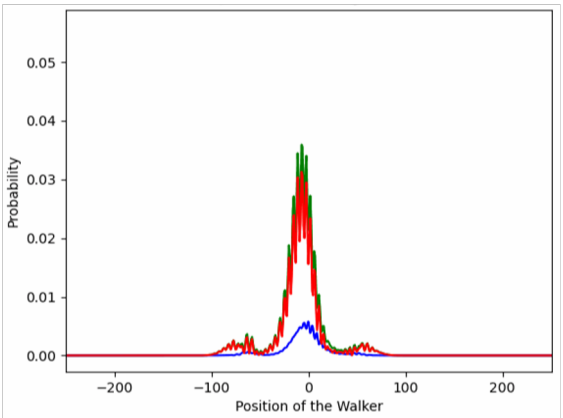

Fig. 1. Probability distribution of the quantum walker after 70 time steps. The vertical and horizontal axes indicate the probability at each site and the position of the walker, respectively. Red and blue curves correspond to the excited and ground states, respectively. Green curve indicates the sum of the probabilities for both states.

In our research, we added the ground and excited states as another internal degree of freedom to describe the same processes as the previous research on a classical system. We thereby introduce an additional operator N for the new space as follows:

$$N = e^{-\mathrm{i}H_{\mathrm{NH}}\Delta t/\hbar}, \quad H_{\mathrm{NH}} = \begin{pmatrix} -\varepsilon & -we^{-g} \\ -we^{g} & \varepsilon \end{pmatrix}. \tag{4}$$

Here, ε, g, and w are real. The off-diagonal elements introduce non-Hermiticity which describes the "take-up" of energy from the environment. Combining the operator N with the coin and shift operators, we introduce a non-Hermitian quantum walk which describes the active particle in a quantum system. Figure 1 shows an example of the dynamics.

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Active matter physics in multicellular dynamics and quantum models

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Experiments in active matter physics naturally involve biological materials, ranging from molecular motors to mammalian cells. Here we use mouse neural progenitor cells, self-propelling bipolar-shaped cells with nematic interactions, to demonstrate how topological concepts can govern the collective dynamics in an active nematic system. We will first show how topological defects generated by the cells themselves make anomalous flow, which eventually leads to cell accumulation and dispersion. Next, we will describe how significant edge flow arises in the stamp culture experiment and discuss how the mechanism is related to topological insulators.

In light of these recent developments in the interface between nonequilibrium physics and condensed matter, we have also been interested in exploring the possible realization of active matter-type phase transitions in quantum many-body systems. We will describe one of our attempts to make a model of “quantum active matter”, where hard-core Bosons undergo phase separation due to non-Hermiticity in the Hamiltonian. We will also show how the quantum phase transitions in this model are mapped to the dynamical phase transitions in a classical system, and explain how dynamical symmetry can help understand the phase diagram.

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The talk will be based on collaboration works with Lisa Yamauchi (RIKEN BDR), Masahito Uwamichi (The University of Tokyo), Tomoya Hayata (Keio University), Tomoki Ozawa (Tohoku University), Kazuaki Takasan (UC Berkeley), and Kyosuke Adachi (RIKEN BDR)