Active Matter Workshop 2023

VENUE:
CMMA, Meiji University
and via Zoom webinar

DATE:
27 - 28 January, 2023

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

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Program

2023/1/27 Fri.

9:30 - 10:00 **Registration**

10:00 - 10:05 **opening**

Chair: Schnyder, Simon (University of Tokyo)

10:05 - 10:55 [IL] **Murakami, Hisashi** (Kyoto Institute of Technology)
"Mutual anticipation can facilitates self-organization in animal groups"

10:55 - 11:20 **Kaneko, Kojiro** (Kyushu University)
"Self-propelled rods with curved boundaries"

11:20 - 11:45 **Yasuda, Kento** (Kyoto University)
"Most probable path of an active Brownian particle"

11:45 - 13:15 Lunch Break

Chair: Tarama, Sonja (Ritsumeikan University)

13:15 - 14:05 [IL] **Watanabe, Chiho** (Hiroshima University)
"Active droplets design and their behavior"

14:05 - 14:30 **Adachi, Riku** (University of Tokyo)
"Life-like behavior in Autonomous Movements of Oil-droplets and Tetrahymena"

14:30 - 15:00 Break

Chair: Yasuda, Kento (Kyoto University)

15:00 - 15:25 **Feng, Chao** (Kyoto University)
"Direct numerical simulations of a model microswimmer near a liquid-liquid interface"

15:25 - 15:50 **Tarama, Sonja** (Ritsumeikan University)
"Self-organization in crawling cells through mechanic feedback interaction"

15:50 - 16:15 **Schnyder, Simon** (University of Tokyo)
"Competition between cell types under cell cycle regulation with apoptosis"

16:15 - 16:30 Break

Chair: Ryoichi, Yamamoto (Kyoto University)

16:30 - 16:55 **Tarama, Mitsusuke** (Kyushu University)
"Dynamic network structure formation of mesoderm cells in early chick embryo"

16:55 - 17:20 **Ebata, Hiroyuki** (Kyushu University)
"Metabolism-dependent and cytoskeleton-independent rheology of cell cytoplasm"

17:20 - 17:45 Discussion

2023/1/28 Sat.

10:00 - 10:05 **opening of Day 2**

Chair: Tanaka, Shinpei (Hiroshima University)

10:05 - 10:55 [IL] **Sumino, Yutaka** (Tokyo University of Science)
"Dynamics and control of the injection front induced by precipitation formation"

10:55 - 11:20 **Kuroda, Yuta** (Nagoya University)
"Hyperuniformity and Singular Density Correlation in Chiral Active Fluids"

11:20 - 11:45 **Kato, Airi** (Wenzhou Institute, UCAS)
"Rough colloids at interfaces: With scopes of interfacial active matter"

11:45 - 13:15 Lunch Break

Chair: Kato, Airi (Wenzhou Institute, University of Chinese Academy of Sciences)

13:15 - 13:40 **Yamagishi, Minami** (University of Tokyo)
"Dynamics of a quantum active particle based on 2D non-Hermitian quantum walks"

13:40 - 14:05 **Kawamura, Ayase** (Hiroshima University)
"Self-propulsion of 3-Phenylpropionaldehyde Droplet in Homogeneous and Heterogeneous Aqueous Solutions"

14:05 - 14:30 **Tanaka, Shinpei** (Hiroshima University)
"Collective motion of active droplets and how to grasp it"

14:30 - 15:00 General discussion and closing

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Presentation time

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

Contributed presentation: 25 min each including discussions

Abstracts

Day 1
27 Jan., 2023

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17:20 - 17:45 Discussion

Mutual anticipation can facilitates self-organization in animal groups

Hisashi Murakami[1]

[1]Kyoto Institute of Technology

Collective animal groups often seem to behave as if having one body and/or one mind as a whole. Without external controls, a globally ordered state emerges from inter-individuals interactions. Human crowds also show various collective pattern formations similar to other animal groups, such as bird flocks or fish schools. Anticipatory behavior has been considered to play a key role in a wide range of self-organizing living systems. In particular, it is evident that pedestrians anticipate the future positions of their neighbors to seek their paths in dynamical pedestrian flow, unlike distance-dependent repulsive interactions in classical models of human crowds resembling physical particle systems. This anticipatory path-finding behavior results in the deviation of pedestrians from the direct path to their destination. However, the deviation of individual movements in human crowds is poorly understood, even though the path-searching activities of pedestrians seem to influence collective-level behavior directly. Do individuals in human crowds follow a specific search strategy? If so, how is such a strategy influenced by the ability to anticipate of motions of neighbors? Moreover, does this individual anticipatory behavior offer functional benefits to the group? We here show that the deviation derived from the anticipation of motions of neighbors can be statistically described, and how it impacts the global crowd dynamics, via two experiments with fifty-four participant pedestrians. First, we conducted an experiment on lane formation, a striking example of collective patterning in human crowds, where pedestrians waiting at each side of the experimental corridor begin walking towards the opposite side and then spontaneously separate into several lanes with uniform walking directions. We found that during lane formation, the fluctuation of pedestrians from their desired directions (i.e., the direct path to their destination) follows a scale-free movement strategy called a Levy walk process. A Levy walk is a special class of random walks in which many small steps are interspersed with occasional long steps and is theoretically optimal when searching unpredictably distributed resources. This result suggests that lane formation efficiently emerges through an optimal path-seeking strategy by anticipation. To check this suggestion, we conducted the second experiment which was similar to the first experiment; however, we asked some participants to perform walking while texting on the smartphone. Hence, these pedestrians were distracted to anticipate the motions of neighbors. We found that the walking strategy of distracted pedestrians differs from non-distracted ones, influences on motions of other pedestrians as well, and decreases the degree of collective pattern formation (lane formation). Moreover, both the distracted pedestrians and the non-distracted ones had difficulties navigating. These results imply mutual anticipation facilitates the efficient transition to emergent pattern formation. Interestingly, also in other animal groups, anticipatory behavior is known as crucial to perform robust collective behavior: individual noisy movements derived from anticipating or negotiating neighbors, which seem to collapse the global order, can facilitate interactions with various neighbors and contribute to dynamic collective behavior. Our findings suggest that mutual anticipation is an underlying mechanism across a wide range of animal groups and is a key factor to develop the collective mind analogy.

References

1. H Murakami, C Feliciani, Y Nishiyama, K Nishinari, "Mutual anticipation can contribute to self-organization in human crowds", *Science Advances* **7**, eabe7758 (2021)
2. H Murakami, C Feliciani, K Nishinari “Lévy walk process in self-organization of pedestrian crowds”, *Journal of the Royal Society Interface* **16 (153)**, 20180939 (2019)
3. H Murakami, T Niizato, T Tomaru, Y Nishiyama, YP Gunji “Inherent noise appears as a Lévy walk in fish schools”, *Scientific Reports* **5**, 10605 (2015)

Self-propelled rods with curved boundaries

Kojiro Kaneko, **Jun-ichi Fukuda**

Department of Physics, Faculty of Science, Kyushu Univ.

Dense bacterial suspensions show distinctive vortical motions with an intrinsic length scale. Such emergent dynamics is now called active turbulence and attracts broad attention. When the turbulent dynamics of such suspensions is restricted within some confinement or by some obstacles, bacteria show different behaviors near the boundaries. If these geometrical constraints possess a length scale comparable to the one of turbulent-like motion, they rectify the collective motion of bacteria and yield stably ordered vortices [1,2].

This research aims to uncover the underlying mechanism of this ordered behavior and to understand the effect of complex geometrical constraints on the dynamics of bacteria. Using an agent-based model in an environment with boundaries, we perform coarse-grained molecular dynamics simulations for such situations. We model bacteria as self-propelled rods with excluded volume so that they have anisotropic steric interaction with each other and with boundaries. We implement both internal and external geometrical boundaries to investigate the dynamics of bacteria within a confinement or with obstacles.

In this talk, we will discuss the collective behavior of self-propelled rods when we vary (1) the properties of interactions, (2) the shape of rods, and (3) the geometrical conditions.

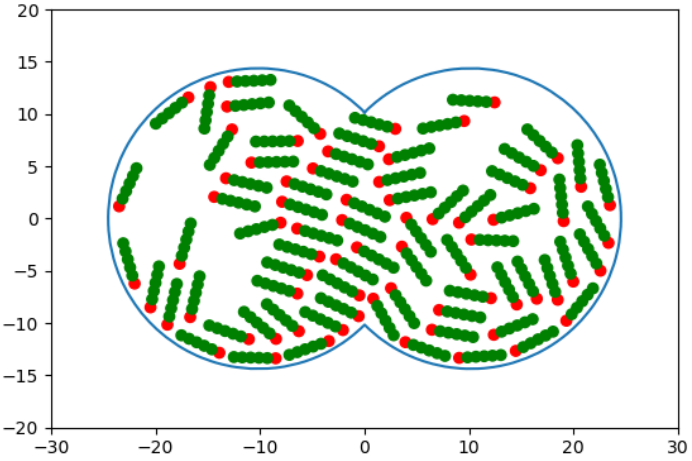

Fig.1： A snapshot of simulation in a doublet well.

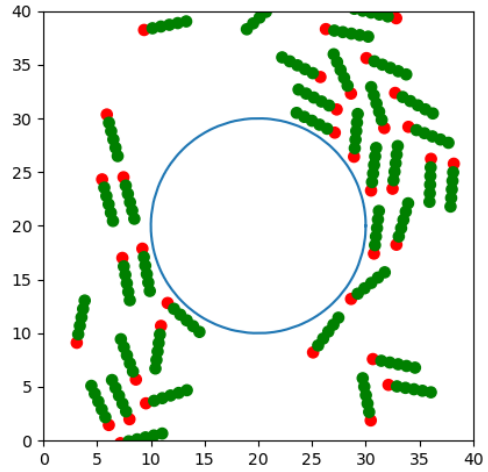

Fig.2： A snapshot of simulation with a circular obstacle.

References

1. Beppu, K., Izri, Z., Gohya, J. *et al.*: “Geometry-driven collective ordering of bacterial vortices”, *Soft Matter* **13**, 5038 (2017).
2. Nishiguchi, D., Aranson, I.S., Snezhko, A. *et al.*: “Engineering bacterial vortex lattice via direct laser lithography”. *Nat. Commun.* **9**, 4486 (2018).

Most probable path of an active Brownian particle

Kento Yasuda, **Kenta Ishimoto**

Research Institute for Mathematical Sciences, Kyoto University

In this study, we investigate the transition path of a free active Brownian particle (ABP) on a two-dimensional plane between two given states. The extremum conditions for the most probable path connecting the two states are derived using the Onsager-Machlup integral and its variational principle. We provide explicit solutions to these extremum conditions and demonstrate their nonuniqueness through an analogy with the pendulum equation indicating possible multiple paths. The pendulum analogy is also employed to characterize the shape of the globally most probable path obtained by explicitly calculating the path probability for multiple solutions. We comprehensively examine a translation process of an ABP to the front as a prototypical example. Interestingly, the numerical and theoretical analyses reveal that the shape of the most probable path changes from an I to a U shape and to the ℓ shape with an increase in the transition process time. The Langevin simulation also confirms this shape transition. We also discuss further method applications for evaluating a transition path in rare events in active matter.

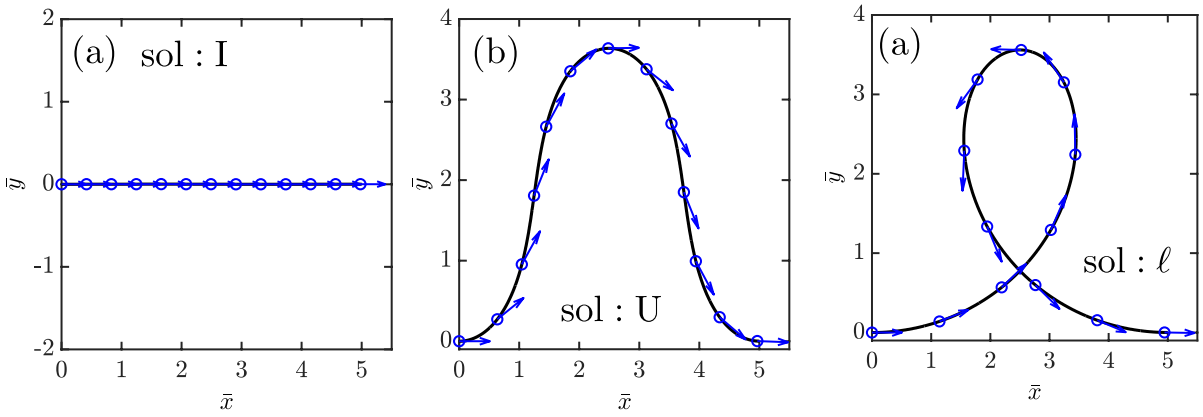

Fig. 1 : Examples of the most probable path of an active Brownian particle.

References
1. K. Yasuda and K. Ishimoto, Phys. Rev. E 106, 064120 (2022).

Active droplets design and their behaviors

Chiho Watanabe[1, 3], **Shinpei Tanaka**[2, 3]

[1]Graduate School of Integrated Sciences for Life,
[2]Graduate School of Advanced Science and Engineering,
[3]School of Integrated Arts and Sciences, Hiroshima University, Hiroshima, Japan

Self-propelled active objects or droplets floating on the water surface, including a camphor boat and ethyl salicylate droplets, have been studied and attracted attention [1,2]. Such active matters are often called Marangoni surfers and their motion is driven by inhomogeneous surface tension around the object of interest. Therefore, how to impose the inhomogeneous surface tension around the object is the key to the design. In this study, we investigated droplets' motion floating on the water where two types of droplets, a surfactant source, and a surfactant sink, created inhomogeneous surface tension around them. Specifically, we used a droplet of 1-decanol which has weak surface activity as a surfactant source, and fluid paraffin as a sink droplet that dissolves 1-decanol. This two-droplet source-sink system can make a minimal "droplet chemotactic" system that can show characteristic co-responsive behavior. A dye, Sudan black B (SB), was added to the 1-decanol droplet for visualization, though we found that the active droplets' trajectory patterns depended on the concentration of SB. At low SB concentration (0.005 wt%), the droplets show binary-star-like motion while at high SB concentration (0.20 wt%), the 1-decanol droplet chases the paraffin droplet. On the other hand, at an intermediate SB concentration (0.05 wt%), the 1-decanol droplet pokes at the paraffin droplet periodically, indicating an oscillatory motion pattern (Figure 1a) [3]. In this talk, we will introduce the behavior of this two-droplet source-sink system as well as other experimental results of different initial configurations of source-sink droplets (Figure 1b).

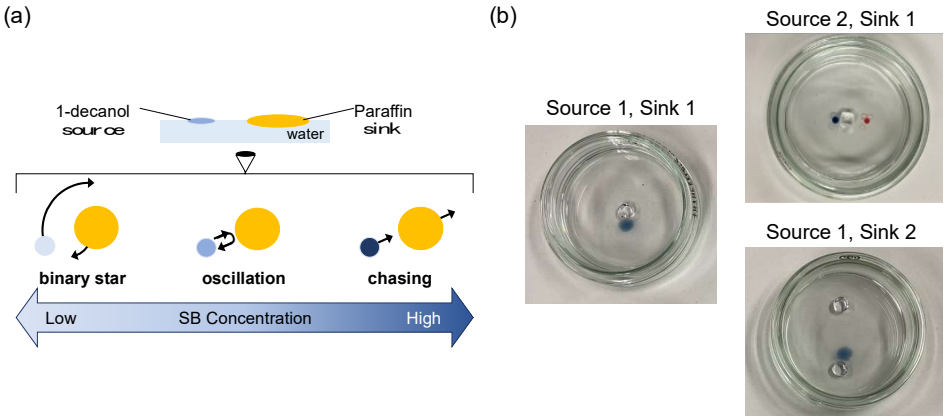

Fig. 1 : (a) An illustration of our experimental set up and the droplets' motion with different dye concentration [3], (b) Examples of source-sink active droplets system.

Acknowledgments
This work was done in collaboration with Dr. Löffler, R.J.G., Prof. Hanczyc, M.M., and Prof. Gorecki, J.

References
1. Fujita, R.; Matsuo, M.; Nakata, S. "Multidimensional Self-Propelled Motion Based on Nonlinear Science" *Front. Phys*. **10**, 854892 (2022).
2. Tanaka, S.; Nakata, S.; Nagayama, M. "A Surfactant Reaction Model for the Reciprocating Motion of a Self-Propelled Droplet" *Soft Matter* **17** (2), 388–396 (2021).
3. Watanabe, C.; Tanaka, S.; Löffler, R.J.G.; Hanczyc, M.M.; Gorecki, J., "Dynamic ordering caused by a source-sink relation between two droplets", *Soft Matter* **18**, 6465 (2022)

Life-like behavior in Autonomous Movements of Oil-droplets and Tetrahymena

Riku Adachi[1], **Hiroki Kojima**[1], **Takashi Ikegami**[1]

[1]Department of General Systems Studies, Graduate School of Arts and Sciences, The University of Tokyo

In considering the transition from non-living to living organisms, it is essential to understand the mechanisms of autonomous movement observed in common between the two. Therefore, in order to discuss the requirements for being "life itself" , it is imperative to compare the motions of the two systems and examine their similarities and differences. To the best of our knowledge, studying "artificial life systems" have been conducted independently in the context of active matter research. Therefore, we scrutinize the spontaneous motion of oil droplets as an example of non-living matter and the spontaneous motion of Tetrahymena as a living organism, and provide an integrated theoretical description of what constitutes life-like behavior.

The experiment setup of the oil droplet consisted of a mixture of ethyl salicylate (ES) and paraffin in a petri dish with an anionic surfactant, Sodium Dodecyl Sulfate (SDS) solution[1]. A droplet whose parameters such as volume and composition ratio (ES: Paraffin) were changed accordingly, and its emerging motion was recorded (Fig.1). While Tetrahymena, a eukaryotic unicellular organism, was confined in a two-dimensional microculture apparatus and observed under a stereomicroscope with sufficient nutrition. Henceforth, the differences in motion were quantitatively evaluated by analyzing the trajectory data obtained from the recordings. As a result, an oil droplet showed characteristic motion patterns (e.g., circular, reciprocal, straight, and chaotic) depending on its volume and composition ratio (Fig.2). In comparison, Tetrahymena was observed moving randomly in the culture medium. According to the energy distribution calculated from the time series of motion, the motion of the oil droplets seems to oscillate around a constant kinetic energy, but Tetrahymena exhibits a characteristic kinetic energy distribution that deviates from the exponential distribution. As the volume of the oil droplet was increased or the ratio of ES was decreased, the distribution function of kinetic energy was found to be closer to that of Tetrahymena.

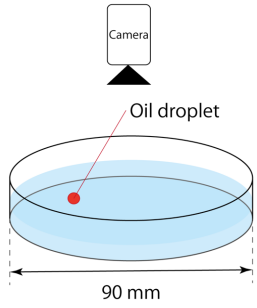

Fig1. Experimental setup

Moreover, we estimated the Lyapunov exponent as a nonlinear analysis and distinguished whether the governing dynamics behind the movement follow a stochastic process or a nonlinear dynamical process. Those results imply that the origin of fluctuations in the motion of non-living (oil droplets) and living (Tetrahymena) systems were different. Oil droplets, which are susceptive to the external surface tension field generated by chemical gradient, exhibited partially chaotic motion; still, the influence of noise (or, say, high dimensional chaos) was dominant for Tetrahymena. This may be because of the increments of the contribution of the degree of freedom for the deformation of the droplet itself as the volume of an oil droplet increases or the ratio of ES decreases. On the other hand, does Tetrahymena own "autonomy" that intrinsically determines life and non-life system in the form of noise-like complex behavior? These issues will be discussed on the day.

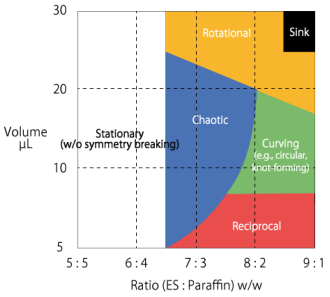

Fig2. Phase diagram

Acknowledgements
This work was financially supported by the World-leading Innovative Study for Frontiers of Mathematical Sciences and Physics (WINGS-FMSP), Graduate School of Mathematical Sciences, The University of Tokyo.

References

1. Tanaka, Shinpei, Yoshimi Sogabe, and Satoshi Nakata. "Spontaneous change in trajectory patterns of a self-propelled oil droplet at the air-surfactant solution interface." *Physical Review E* 91.3 (2015): 032406.

Direct numerical simulations of a model microswimmer near a liquid-liquid interface

Chao Feng[1], **John J. Molina**[1], **Matthew S. Turner**[2], **and Ryoichi Yamamoto**[1]

[1] Department of Chemical Engineering, Kyoto University, Kyoto 615-8510, Japan

[2] Department of Physics, University of Warwick, Coventry CV4 7AL, UK

Transport of material across liquid interfaces is ubiquitous for living cells and is also a crucial step in drug delivery and in many industrial processes. Here, we present numerical simulations of the hydrodynamic flows associated with a single microswimmer embedded in a binary fluid mixture. The two fluids demix, separated by a penetrable and deformable interface that we assume to be initially prepared in its planar ground state. We find that the microswimmer can either penetrate the interface, move parallel to it, or bounce back off it. We analyze how the trajectory depends on the swimmer type (pusher/puller) and the angle of incidence with respect to the interface. Our simulations are performed in a system with periodic boundary conditions, corresponding to an infinite array of fluid interfaces. A puller reaches a steady state in which it either swims parallel to the interface or selects a perpendicular orientation, repeatedly penetrating through the interface. In contrast, a pusher follows a bouncing trajectory between two interfaces. We discuss several examples in biology in which swimmers penetrate soft interfaces. Our paper can be seen as a highly simplified model of such processes.

We also investigated the effect of the fluid viscosity ratio on the movement patterns of microswimmers. We find that swimmers systematically reorientate towards the region containing the lower viscosity fluid. Ultimately this is expected to drive the swimmers to behave as if they are more inclined to swim in low viscosity fluids. Furthermore, in addition to the types of swimming already reported in the isoviscous system, i.e. bouncing, sliding and penetrating, we observed a hovering motion, in which strong pullers swim parallel to the interface with a certain distance, which is consistent with the dynamics of such swimmers near the solid wall.

Self-organization in crawling cells through mechanic feedback interaction

S. Tarama[1], M. Tarama[2]

[1]College of Life Sciences, Department of Bioinformatics, Ritsumeikan University
[2]Department of Physics, Kyushu University

Communication between cells is essential for correct tissue formation and morphogenesis. Here, we theoretically investigate the ability of actively crawling cells to coordinate their motion through mechano-sensing. The basic model considers the cell crawling motion as a cycle of cell elongation and contraction, accompanied by a modification of the friction with the underlying substrate through adhesion to and de-adhesion from it. Due to different surface frictions in the adhered and de-adhered states, the cell is able to effectively push itself forward during its motile cycle. A feedback is then introduced between the experienced force resulting from neighbouring cells pushing against the cell, and its internal dynamics. As a result, the speed at which the motile cycle advances as well as the magnitude of the cell elongation during the cycle changes depending on the experienced force. For positive feedback, cells tend to follow the external force, resulting in a smaller elongation length and higher (lower) progression rates in the shrinking (elongating) stage of the cycle. Contrarily, for negative feedback, cells try to counteract the external force, resulting in a longer elongation length and higher (lower) progression rates in the elongating (shrinking) stage of the cycle. The resulting multi-cell dynamics for the one-dimensional case reveals a multitude of dynamical modes, including synchronization and travelling wave formation, depending on the feedback strength. These results are a first step to understanding how self-organization of cells may occur in biological systems based on mechanical sensing, with the larger goal of understanding cell dynamics up to the tissue scale, including morphogenesis and organ formation.

References

1. M. Tarama, R. Yamamoto: Mechanics of Cell Crawling by Means of Force-free Cyclic Motion, *JPSJ* **87**, 044803 (2018)

Competition between cell types under cell cycle regulation with apoptosis

Jintao Li[1], **Simon K. Schnyder**[1,2], **Matthew S. Turner**[3,1], **Ryoichi Yamamoto**[1]

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[2] Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
[3] Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

Mechanics-based models for cellular tissues often assume that cell growth and division directly depend on physical variables such as pressure. However, biologists understand these processes as fundamentally being controlled by the cell cycle. While both approaches have had successes, they have so far not been properly unified. In a first step, we developed a hybrid model for tissue growth that combines a regulatory cell cycle with a physical model [1]. We study this model using particle-based simulations and within a continuum analysis in order to investigate the expansion of non-motile colonies in quasi-1D channels and on 2D substrates. The model reproduces a range of features that we relate to experimental observations. We also study the competition of two colonies with different rates of programmed cell death (apoptosis) and characteristic cell-cycle control pressures [2]. Synchronisation of cell division/apoptosis events can emerge, causing oscillations in cell number, pressure and cell-cycle activity over timescales corresponding to several division times.

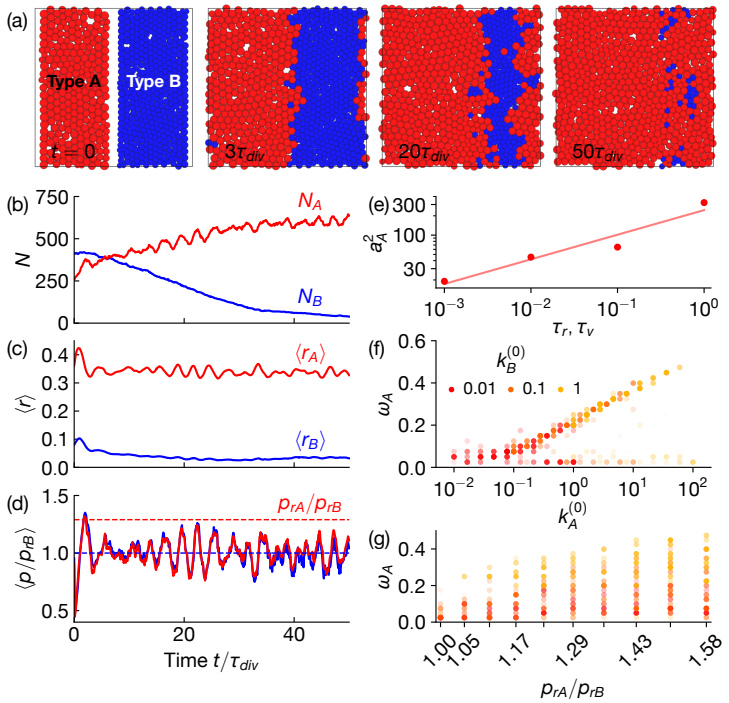

Fig. 1: (a) Simulation snapshots showing the invasion of A cells (red) at the expense of B (blue). Evolution of (b) cell number N, (c) cell cycle activity r and (d) the cell-type-averaged pressure p. Note the emergence of synchronisation in birth/death, manifested in oscillations in these mechanochemical variables. (e) peak value of the squared mode amplitude in the power spectrum as a function of the cell cycle times $\tau_r = \tau_v$. (f,g) Shows the corresponding peak (power) frequency.

References

1. Li, J., Schnyder, S. K., Turner, M. S. & Yamamoto, R.: "Role of the Cell Cycle in Collective Cell Dynamics", *Phys. Rev. X* **11**, 031025 (2021).
2. Li, J., Schnyder, S. K., Turner, M. S. & Yamamoto, R.: "Competition between cell types under cell cycle regulation with apoptosis", *Phys. Rev. R* **4**, 033156 (2022).

Dynamic network structure formation of mesoderm cells in early chick embryo

Mitsusuke Tarama

Department of Physics, Kyushu University

Self-organisation of various cellular structures is of fundamental importance in morphogenesis during development of biological organisms. In this talk, I introduce the network structure of mesoderm cells that was found in the early chick embryo. During the development of the chick embryo, the mesoderm cells that appear through invagination at the primitive streak migrate collectively in the lateral direction between the epiblast (outer layer) and the endoderm (inner layer). While moving collectively, the mesoderm cells self-organise into a network structure, where spaces void of cells filled with extracellular liquid are surrounded by cells that are connected to each other. The network of mesoderm cells undergoes reconnection dynamically.

I developed a theoretical model of self-propelling cells of elongated shape to understand the origin of the dynamic network structure formation. By introducing a short-range attractive interaction with a repulsive core between cells, the model cells reproduced the network structure for intermediate strengths of the attractive interaction. The results were compared with the experiment quantitatively by using persistent homology. In addition, we studied the effect of the elongated shape and the self-propulsion on the structure formation. Moreover, we also investigated how the self-organised structure changes as the development proceeds.

References

1. Y. Nakaya, M. Tarama, et al., “Migrating mesoderm cells self-organize into a dynamic meshwork structure during chick gastrulation”, bioRxiv 2022.09.08.507227 (2022).

Metabolism-dependent and cytoskeleton-independent rheology of cell cytoplasm

Hiroyuki Ebata[1], **Daisuke Mizuno**[1]

[1]Department of physics, faculty of science, Kyushu University

Intracellular space among cell cytoskeleton is crowded with bio-macromolecules, which can lead to glassy or jamming behavior. When metabolic activity was suppressed, the bacterial cytoplasm showed the glassy dynamics, such as nonergodicity, caging, and dynamic heterogeneity [1]. Viscosity of cell extracts increased with super-exponential function and practically diverged as the concentration of solid contents approached physiological value [2]. On the other hand, cytoplasm of living cell maintained fluidity with similar concentrations [2]. These results suggest that the cell cytoplasm is fluidized by the forces generated by motor-proteins and mechano-enzymes. Previous studies have measured the rheology of cell cytoplasm that contained not only interstitial fluid with dense bio-macromolecules but also polymer networks, that is cytoskeleton. Therefore, in order to elucidate the mechanism of fluidization of the glassy cytoplasm, it is necessary to clarify the rheological properties of the cytoplasm in cells with impaired cytoskeletal development.

We conducted active microrheology in HeLa cells to measure the complex shear viscoelastic modulus $G(\omega) = G'(\omega) - iG"(\omega)$. To figure out the effect of the cytoskeletal development, we used cells on soft gels, cells with cytoskeletal inhibitors, and genetically deficient cells. As a result, the complex shear viscoelastic modulus of spherical cells on soft gels, cells with inhibited actin skeleton, microtubule inhibited cells, and vimentin deficient cells showed no significant difference with that of untreated HeLa cells. In all conditions, same frequency dependence of the storage and loss moduli $G(\omega) \propto (-i\omega)^{0.5}$ was obtained (Fig. 1), which is characteristic for dense colloidal systems near the jamming transition point. On the other hand, when ATP was depleted by the drug and the metabolic activity was severely suppressed, storage modulus significantly increased at low frequency, which caused a constant plateau as $G(\omega) = G_0 + A(-i\omega)^{0.5}$. Thus, the linear viscoelasticity of the cytoplasm of HeLa cells is almost independent of the cytoskeletal development, while it is strongly influenced by metabolic activity.

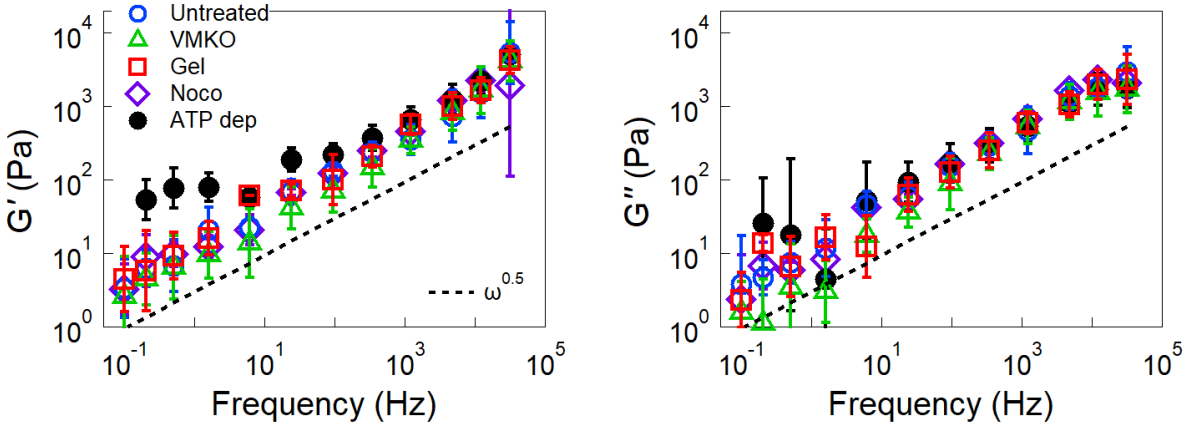

Figure 1 : Frequency dependence of storage modulus *G'* and loss modulus *G"* for the untreated cell, cells with different cytoskeletal structures, and cells with low metabolic activity. Untreated (blue circle): untreated HeLa cells. VMKO (green triangle): vimentin deficient HeLacells. Gel (red squre): cells on soft gels. Noco (purple diamond): microtubule inhibited cells. ATP dep (black circle): ATP depleted cells.

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Day 2
28 Jan., 2023

10:00 - 10:05 **opening of Day 2**

Chair: Tanaka, Shinpei (Hiroshima University)

10:05 - 10:55 [IL] **Sumino, Yutaka** (Tokyo University of Science)
"Dynamics and control of the injection front induced by precipitation formation"

10:55 - 11:20 **Kuroda, Yuta** (Nagoya University)
"Hyperuniformity and Singular Density Correlation in Chiral Active Fluids"

11:20 - 11:45 **Kato, Airi** (Wenzhou Institute, UCAS)
"Rough colloids at interfaces: With scopes of interfacial active matter"

11:45 - 13:15 Lunch Break

Chair: Kato, Airi (Wenzhou Institute, University of Chinese Academy of Sciences)

13:15 - 13:40 **Yamagishi, Minami** (University of Tokyo)
"Dynamics of a quantum active particle based on 2D non-Hermitian quantum walks"

13:40 - 14:05 **Kawamura, Ayase** (Hiroshima University)
"Self-propulsion of 3-Phenylpropionaldehyde Droplet in Homogeneous and Heterogeneous Aqueous Solutions"

14:05 - 14:30 **Tanaka, Shinpei** (Hiroshima University)
"Collective motion of active droplets and how to grasp it"

14:30 - 15:00 General discussion and closing

Dynamics and control of the injection front induced by precipitation formation

Yutaka Sumino, Shunsuke Tanaka, Kojiro Otoguro

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Many engineering processes, such as chemical grouting and enhanced oil recovery, involve an injection of fluid into soil that has a confined geometry. Similar dynamics of fluid in soil play relevant roles in the geological process, including earthquakes. Varieties of study on such dynamics of the fluid is conducted using a simple experimental model. A famous example is viscous fingering produced through Saffman-Taylor instability. Special attention should be paid to precipitation formation accompanied by the above engineering and geological processes. The generated precipitation hinders fluid motion and creates a complex pattern. The observation of the dynamics of the injection front *in situ*, as well as its control, would be relevant to physical problems.

For this reason, we built a binary fluid system that produces a precipitate confined in a thin cell. In both our previous study with water glass and cobalt chrolide[1] and CTAB and NaSal[2], the precipitating system shows circular and filament patterns. Figure 1 shows the typical injection dynamics. Here, the top view of transparent parallel cells is shown. The cell was filled with aqueous solution of CTAB whose concentration was kept at 50 mM. The injected solution was an aqueous solution of NaSal whose concentration c was varied. We also varied the injection rate of the inner fluid J. Special attention should be given for the absence of Saffman-Taylor instability due to small viscosity contrast (inner fluid (c = 50 mM, 1.03 m Pa s, Outer fluid: 1.07 mPa s). Upon mixing the inner and outer fluid, worm-like micelles are formed to create a gel-like precipitate. Notably, the number of actively extending filaments, N, saturates around the fixed number proportional to J. Furthermore, we show that the motion of the advancing tip of the filament can be controlled to have a straight motion by the appropriately spaced obstacle in the flow cells. A mathematical model based on a moving boundary adopting the effect of precipitation formation reproduced the straight motion of filaments in structured cells.

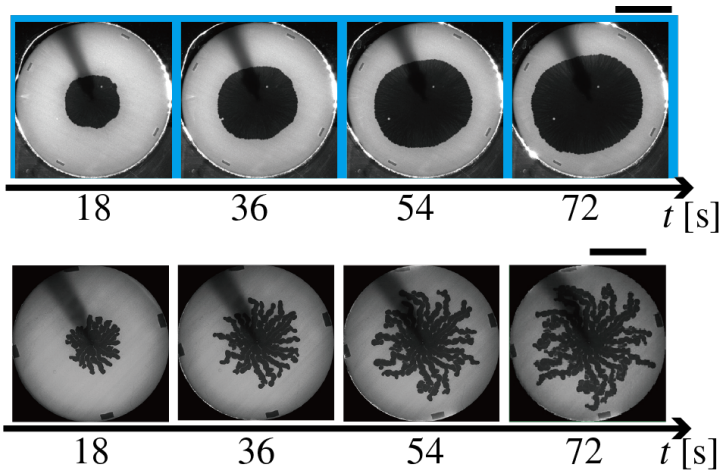

Fig. 1 : The time development of (top) circular pattern, (bottom) filament pattern. Here, injection rate J was fixed as 200 mL/h, and c= (top)50 and (bottom) 200 mM. Scale bar: 50 mm.

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Hyperuniformity and Singular Density Correlation in Chiral Active Fluids

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[1]Department of Physics, Nagoya University

Active matter systems can be classified by the symmetry of the systems. Chiral active matter, where the components perform chiral symmetry-broken motions, is one of the most discussed classes [1]. Here we focus on the density fluctuations in the fluidic state of chiral active matter (hereafter referred to as chiral active fluids). One of the typical hallmarks of active matter is anomalous enhanced density fluctuations at large scales, which are called giant number fluctuations (GNF) [2]. GNF has been observed in various active matter systems, including bacterial suspension, Janus particles, and shaken rods. However, the two-dimensional chiral active fluids exhibit an exactly opposite behavior to GNF, in that the density fluctuations are anomalously suppressed at large scale [3]. This phenomenon is termed hyperuniformity. Hyperuniformity has been reported in several non-equilibrium systems, such as the jamming system and periodically driven colloidal suspension [4]. The hyperuniformity is characterized by the static structure factor $S(q)$, where q is the wavenumber. If this quantity behaves as $S(q) \propto q^{\alpha}$ $(\alpha > 0)$ for small wavenumbers, then the system is said to be hyperuniform.

The hyperuniformity in two-dimensional chiral active fluids was first reported in the numerical study [3]. In Ref. [3], a simple particle model, called the chiral active Brownian particles (cABP), was employed, and it was reported that this system shows hyperuniformity with $\alpha = 2$. Very recently, experimental realizations of this phenomenon were achieved by exploiting the marine algae system [5] and anisotropic-shaped Quincke rollers [6]. Despite intensive studies, however, a microscopic theory that explains hyperuniformity is still lacking. Also, all studies in the past are limited to the two-dimensional system and the three-dimensional case has not been investigated yet.

Here we attempt to understand the density fluctuations in both two- and three-dimensional chiral active fluids theoretically. First, we put forward a microscopic theory for hyperuniformity in the two-dimensional system. An effective hydrodynamic description is derived for cABP. We demonstrate that the obtained hydrodynamic equations yield hyperuniformity with $\alpha = 2$. We also compare our theory with numerical results. Subsequently, we apply the hydrodynamic theory to the three-dimensional system. We theoretically find the density fluctuations show a singularity that reflects the anisotropy of the system. This theoretical prediction is corroborated by a numerical simulation.

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Rough colloids at interfaces: With scopes of interfacial active matter

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Colloidal monolayers—consisting of particles trapped at liquid interfaces energetically—have been known to show various self-assemblies and undergo structural transitions upon compression, depending on particle morphology [1]. This shape dependency is believed to be due to the quadrupole capillary interactions [2]. Smooth rigid spherical colloids have no capillary interaction ideally, which consequences a direct transition from a gas-like state to a solid-like state, where particles are close-packed jamming; they finally collapse abruptly under further compression [1].

Similar to anisotropic colloids, particles with surface roughness feature not only capillary attractions [2] but also frictional contact which leads to the shift of jamming point and the strength of shear thickening [3] in 3D dense suspension. Here we study how roughness affects the interactions and thereby phase behaviors in 2D experimentally and numerically. Experimentally, four surface roughnesses were specifically designed and compared through isotherm measurements upon compression and microscopic observations. We find that, for sufficiently rough systems, a nontrivial intermediate state appears in surface pressure–area isotherms before the close-packed jamming. The intermediate states are attributed to a percolated network (Fig.1, left), caused by roughness-induced capillary attraction. Also, the surface roughness lowers the close-packed jamming points ϕ_J, caused by roughness-induced frictions (Fig.1, center). These behaviors are verified by our Brownian dynamics simulations; we modeled rough particles at the interface as attractive and frictional particles. By constraining the tangential motion of particles in contact, we further simulate interlocking cases. Moreover, the gradual off-plane collapse was observed for very rough particles experimentally, probably owing to the tangential contact force due to the asperities; buckling and collapse can be simulated in future works. The details of this work can access via our preprint [4].

Though the systems of this work are NOT active but quasi-equilibrium, some future directions to active systems will be presented in the talk.

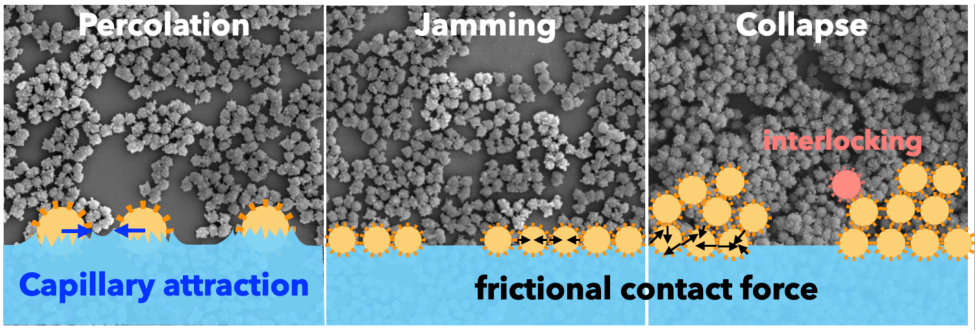

Figure 1 SEM micrographs and schematics of the percolation, jamming, and collapsed monolayer

Acknowledgments
We acknowledge the staffs of the common facilities in WIUCAS. The speaker thanks the organizers who welcome the speaker to talk about our work on non-active systems.

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Dynamics of a quantum active particle based on 2D non-Hermitian quantum walks

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[1]Department of Physics and [2]Institute of Industrial Science, the University of Tokyo
[3]Department of Applied Physics, Hokkaido University

We present a model of quantum active particles using non-Hermitian quantum walks in two dimensions (2D). This talk will be a continuation of the last talk that I gave on the one-dimensional (1D) quantum active particle in Active Matter Workshop 2022 [1].

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. Adachi *et al.* [2] used a non-Hermitian quantum spin system to simulate a "stoquastic" active matter. In contrast to their work with many-body systems, we start with simpler, one-particle systems to allow systems real-time evolution in a fully quantum range. We aim to reproduce similar phenomena that Schweitzer *et al.* [3] numerically found, that is, the dynamics of their (active) Brownian particle changes depending on energy-take-up term.

We believe that the following two points are essential properties for a system to be an active matter: (i) energy nor momentum are not conserved and (ii) kinetic motion depends on particles' internal states. A system without energy conservation is realized with our non-Hermitian Hamiltonian

$$H_{\mathrm{NH}} = \sigma^0 \otimes \tau^0 \otimes \begin{pmatrix} -\varepsilon & -we^{-g} \\ -we^{+g} & +\varepsilon \end{pmatrix},$$

where σ^0 and τ^0 are 2×2 identity matrices for the space spanned by the leftward and rightward states ($|\mathrm{L}\rangle$ and $|\mathrm{R}\rangle$) and the space spanned by the downward and upward state ($|\mathrm{D}\rangle$ and $|\mathrm{U}\rangle$), respectively. We introduce new internal states, the ground state $|\mathrm{G}\rangle$ and the excited state $|\mathrm{E}\rangle$. The non-Hermiticity parameter g promotes transition from $|\mathrm{G}\rangle$ to $|\mathrm{E}\rangle$, and hence the particle takes up energy from the environment. We use different parameter values for $|\mathrm{G}\rangle$ and $|\mathrm{E}\rangle$, which means that the kinetic motion depends on particle's internal state, to realize a system without momentum conservation.

To simulate "Brownian motion" under a harmonic potential in a 2D quantum system, we use quantum walks. The quantum walk (QW) is a quantum analogue of random walk. Instead of stochastic fluctuations of a classical random walker, a quantum walker moves under interference of quantum fluctuations at each site, which deterministically governs the walker's dynamics. We start with proposing a 2D Dirac Hamiltonian [4]

$$H_{\mathrm{D}}^{(2)} \coloneqq (\epsilon\sigma^z p_x + m_x(x)\sigma^y) \otimes \tau^0 \otimes v^0 + \sigma^x \otimes (\epsilon\tau^z p_y + m_y(y)\tau^y) \otimes v^0,$$

which can be mapped to a 2D QW as well as to a Schrödinger Hamiltonian as we will show in the talk. Here, $\{\sigma^x, \sigma^y, \sigma^z\}$ and $\{\tau^x, \tau^y, \tau^z\}$ are the Pauli matrices for the spaces spanned by $\{|\mathrm{L}\rangle, |\mathrm{R}\rangle\}$ and $\{|\mathrm{D}\rangle, |\mathrm{U}\rangle\}$, respectively, and v^0 is a 2×2 identity matrix for the space spanned by $|\mathrm{G}\rangle$ and $|\mathrm{E}\rangle$. We let $m_x(x)$ and $m_y(y)$ denote the mass terms, which are proportional to the parameters $\theta_x(x)$ and $\theta_y(y)$ for the coin operators for QW [5]. The momenta p_x and p_y can be rewritten in the forms of $-\mathrm{i}\,\partial/\partial x$ and $-\mathrm{i}\,\partial/\partial y$, respectively. Figure 1 shows probability distributions after 500 time steps with different values of g. We observe that less amount of wave functions are bound around the center by the potential in the $g = 2$ case than in the $g = 0$ case. This means that more wave functions have gone out, climbing up the potential wall in the $g = 2$ case.

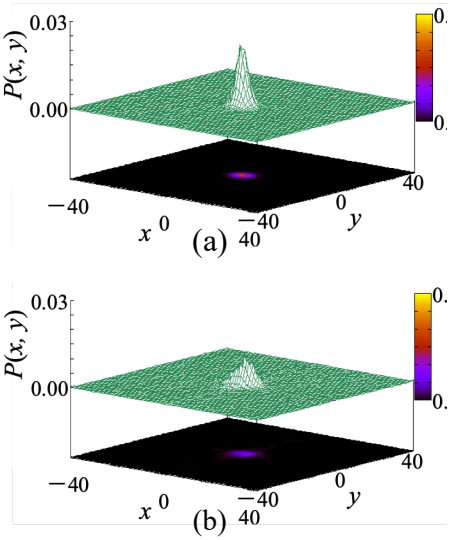

Fig. 1: Probability distribution after 500 time steps of evolution. (a) $g = 0$ and (b) $g = 2$. $\varepsilon = w = a = 0.2$.

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Self-propulsion of 3-Phenylpropionaldehyde Droplet in Homogeneous and Heterogeneous Aqueous Solutions

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In the presence of local interfacial tension gradient at the oil-water or air-water interface, oil droplets can be driven in the water or on the water surface by the flow generated at the interface. We have recently found a new self-propulsive system of 3-Phenylpropionaldehyde (3PPA) droplets, capable of self-propelled both on the surface of Sodium Decyl Sulfate (SDS) aqueous solution and on the glass surface in the solution.

Furthermore, we have also found that the system has the ability to synthesize surfactants when amino acid is added to the solution. The amino acid, histidine (HIS), reacts with 3PPA, an aldehyde, to produce an amphiphilic compound through spontaneous condensation reaction. Although it was expected that the spontaneously generated surfactant propelled droplets, we observed that the produced surfactant could not cause the droplet's motion, even though it decreased the interfacial tension by the same degree as that of the SDS solution. On the other hand, we have noticed that the motion of a 3PPA droplet is significantly changed by the existence of HIS in the SDS solution. In a SDS solution containing HIS, longer duration of propulsion and reciprocation with higher frequency were found to occur compared to a SDS solution without HIS.

In addition to this homogeneous system, we investigated the effect of inhomogeneous distribution of HIS in the SDS solution on the 3PPA droplet. When 3PPA droplets were in a periodic motion on the surface of aqueous SDS solution, HIS powder was added locally to the solution. Figure 1 shows how the motion was altered before and after the addition of HIS. As Figure 1(a) shows, the 3PPA droplet was oscillated periodically before the addition of HIS. After the addition of HIS powder, 3PPA was once attracted to the HIS-rich region immediately (Figure(b)) and exhibited a motion with rapid oscillation thereafter as shown in Figure 1(c).

In the presentation, these self-propulsion phenomena will be discussed in more detail.

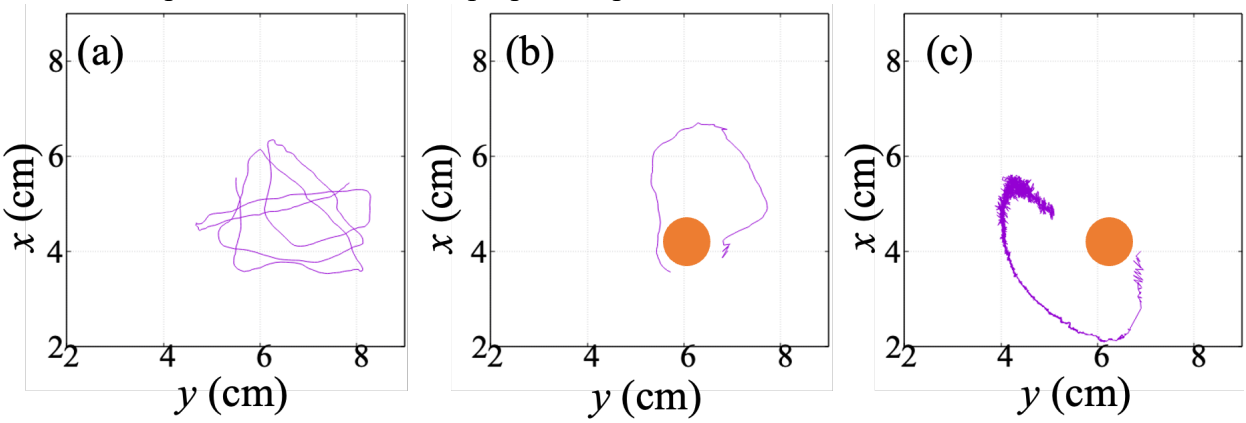

Fig.1 The motion of 3PPA droplet. (a) Before HIS powder was placed on the solution, (b) The 3PPA showed sudden directional change in the middle of the motion as a result of attraction to the inserted HIS powder; HIS powder is represented as orange area. (c) The rapid reciprocations of the 3PPA during the motion after the attraction.

Collective motion of active droplets and how to grasp it

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Alkylsalicylate droplets have been known [1] to exhibit self-propulsion when they are placed on the surface of surfactant solution. Their collective motion is distinctively complex. For example, droplets repeat forming and reforming a circular cluster, collapsing immediately after its formation. Figure 1 shows such a behavior seen in a sample of 10 droplets. The physical mechanisms behind their collective motion are unknown.

We have proposed [1] that a distribution of droplets relative to a droplet and its nearest neighbor could be used to contract motion behavior into a static 2-dimensional map. Figure 2a shows an example of the distribution. A dark region around the origin is where droplets are excluded because a droplet and its nearest neighbor are located at the two centers of the region. Whereas the information about time is lost, the distribution clearly shows where droplets tend to locate around the pair. Moreover, it shows a certain symmetry indicating a dynamic order in the motion behavior.

In this study, we used the distribution as a target to be realized by a simulation model with adjustable parameters. We tested the method with a non-physical toy model having a three-body interaction term introduced as a driving force of particles. The parameters in the model were adjusted so that the distance between the distribution of droplets (Fig. 2a) and that of the particles in simulation (Fig. 2b) became minimum. The resulting motion pattern seen in the simulation (Fig. 2c) was considered to best simulate the motion pattern of droplets. I will discuss in the presentation how much motion patterns are reproduced by a simple toy model adjusted using this method.

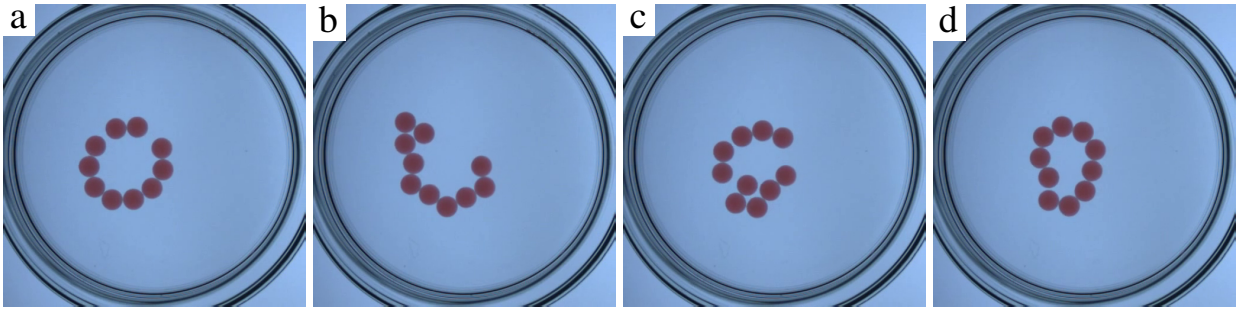

Fig. 1. Collective motion of 10 ethylsalicylate droplets on the surface of sodium dodecyl sulfate solution. Images are shown every 17 s. The Petri dish was 88 mm in diameter.

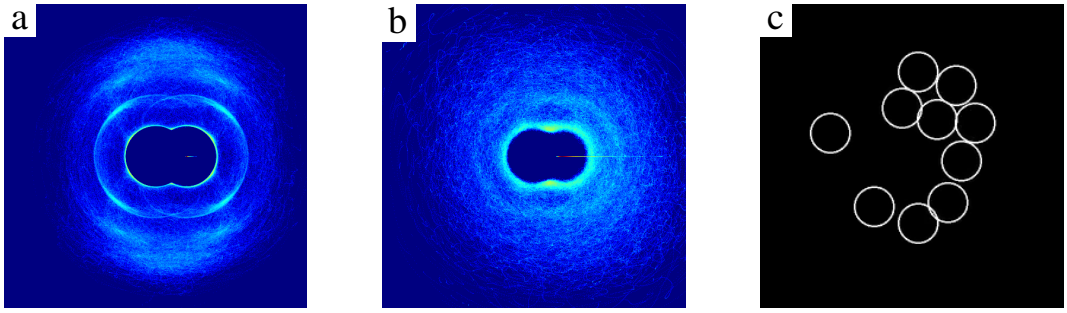

Fig. 2. (a) A distribution of droplets relative to a droplet at the origin and its nearest neighbor pair on the x-axis. (b) The same distribution obtained by a simulation. (c) A snapshot of a simulation.

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