Part B-1

1. Excellence

1.1 Quality and pertinence of the project's research and innovation objectives (and the extent to which they are ambitious, and go beyond the state of the art)

Introduction

Active matter, denoting collections of actively moving particles, is an emerging subject of study at the interface between soft matter physics and biology. It has been attracting increasing interest over the past few decades due to its intriguing properties and applicability in a broad range of length scales, from animals to tissues and cells.[1–4] Its study can deepen our understanding of processes such as tissue formation and cancer growth. The knowledge of active matter has also uncovered promising applications in many fields, such as medicine and robotics.[5,6]

Active matter is constantly driven out of equilibrium due to the energy injection at single particle scale. The consequences of being out of equilibrium are most obvious when active particles are in complex environments, especially under confinement. For example, bacteria in a microchannel under flow tend to swim against the flow direction, known as the upstream swimming phenomenon; [7,8] dense actin filaments driven by molecular motor in a microchannel form coherent flow spontaneously;[9] the "pressure" exerted by active particles on their surrounding walls highly depends on the precise particle-wall interactions.[10]

Having these non-equilibrium features, active matter has the potential to advance technologies of great impact in material and healthcare industries. For example, engineering the self-organization of active matter can help synthesize materials with unprecedented micro- and nano- structure; deep understanding of the behavior of active particles in real-life settings can lead to novel drug delivery technologies and bioremediation solutions. However, to achieve the full of active matter, several imperative challenges need to be addressed, among which **determining the behavior of active particles in complex environments** is most challenging and potentially fruitful.

The challenge comes from the many-body nature and complex particle-particle and particle-wall interactions of active matter, which prevents the behavior of active particles from being solved exactly. Much effort has been devoted to borrowing tools from thermodynamics and using a statistical approach to understand active matter.[1,11,12] In particular, the idea of "**effective temperature**" has been adopted successfully by a vast literature, by considering the steady state of active particles as hot passive colloids.[13–16] However, when particle-particle and particle-wall interactions become important, non-equilibrium phenomena such as clustering and collective motions occur, leading to the breakdown of the "quasi-equilibrium" approximation.[9,17,18] Another macroscopic observable borrowed from equilibrium thermodynamics, **pressure**, has also been shown to behave differently from equilibrium systems due to its sensitivity to specific particle-wall interactions and wall shapes.[10,19–21] As a result, a thermodynamic description of active matter systems is still premature and need further elaboration, especially in the presence of confining walls.

Over the past three decades, many theoretical models have been proposed for active matter systems, such as the Toner-Tu model and the polar active gel model.[22] ~~We have a good chance of solving the behavior of active matter using these models.~~ However, further development of them relies on definitive comparison between theory and experiment, in order to determine the details of the models, as well as to what extent the models are applicable. Therefore, to bridge the gap between theoretical models and real-life applications involving active matter and complex environment, a set of experiment, where "environment parameters" can be systematically tuned, is crucial.

In this proposal, I suggest a simple yet flexible model system to study the behavior of active matter system in confined environments. Specifically, I will encapsulate bacteria in the aqueous shell of an oil/water/oil

double emulsion (Fig. XX). In the preliminary work, the inner droplet is hexadecane and the outer droplet is bacteria suspended in water. Due to the density mismatch and buoyancy, the inner droplet is pushed to the top of the outer droplet. Bacteria, the model active matter, are confined between the two droplets. The double emulsion system naturally imposes the simplest form of curved confining walls: a spherical shell. A microcapillary device is used to produce uniform double emulsions with well defined core-shell geometry (Fig. XX).[23,24] The ability to control the flow rates independently allows production of confining walls with a wide range of curvature, the key parameter of the confinement. The inner droplet, on the other hand, serves as a probe which allows us to extract information of the active bath in the aqueous shell.

The motion of the inner droplet is inherently 3D, posing challenges to conventional microscopies. Here, I propose to use the Lagrangian Tracking System developed in Prof. Eric Clement's lab at PMMH-ESPCI to image the 3D motion.[25] The rotated confocal microscope at Gulliver-ESPCI will be used for more time resolved vertical motions (Fig. XX). ~~Is there a proper citation for confocal?~~

Combining the microfluidic technique and the advanced microscopy at ESPCI, I will be able to collect valuable data for the simple model system of active matter under confinement. These data will then be compared with theoretical models developed by our external collaborator Prof. Rodrigo Soto at the University of Chile. The preliminary model based on a Langevin-type equation has qualitatively captured the saturation value of the mean square displacement (MSD) of inner droplets. More experimental data will facilitate further development of the model, and eventually close the gap between theory and application.

Methodology (a conceptual framework for research!)

Aims – Literature reivews – Research questions – Methods – Resources – Ethics – Outcomes

1.2 Soundness of the proposed methodology (including interdisciplinary approaches, consideration of the gender dimension and other diversity aspects if relevant for the research project, and the quality of open science practices, including sharing and management of research outputs and engagement of citizens, civil society and end users, where appropriate)

AIM Our proposed research aims to develop a theoretical model that accounts for the dynamics of particles in swimming bacterial bath under different confining curvature. Taking advantage of the flexibility of the double emulsion experimental system, we can obtain data over a wide range of parameters (curvature, concentration, etc.) which can facilitate the development of the theoretical model. The ultimate goal of this research is to have a model that is readily applicable to real-life problems that concerning active matter and boundary curvatures, such as cargo transport in blood vessels and tumors, as well as the removal of plaque and clot.

LITERATURE REVIEWS The non-equilibrium nature of active matter is best evidenced in its interaction with confining walls. Over the past two decades, much effort has been devoted to illustrating how confinement influences transport[26], rheology[27–30], pressure[20] spatial distribution[31–33] and collective motion[9,17,34–41] of active matter. Curved confining walls, which are ubiquitous in biological systems, show rich and intriguing confinement effect on active matter.[20,34–37,39,40] Inspired by the collective motion of confined driven filaments[41], Woodhouse and Goldstein constructed a theoretical model, demonstrating that the combination of circular confinement and activity allows for the emergence of stable self-organized rotational streaming.[35] Such circular confinement was then realized by emulsions and elastomer chambers, where single vortical flows were observed.[37,39,40] Ravnik and Yeomans studied the dynamics of active nematics under cylindrical confinement using simulation based on continuum equations. They showed that the collective vortical flows not only emerge along the cylinder axis (as shown by Woodhouse and others), but also within the plane of the cylinder.[34] Fily and co-workers developed a statistical theory for non-aligning, non-interacting active particles to study spatial distributions under strong confinement. They

showed that in such confinement, particle concentrations at boundaries were proportional to the local curvature.[36] Nikola and co-workers showed that not only the collective motion, but also the shear stress exerted by active particles on confining walls, using particle-based theory and simulation.[20] All these previous works have highlighted the strong correlation between the structures of confining walls and the behavior of active matter systems. Such a correlation offers a possibility of manipulating active matter by carefully designing the confinement structures.

RESEARCH QUESTIONS Knowledge of confinement effect on active matter is of key importance to solve real-life challenges with active matter. A few investigations on the role of confining wall curvature were conducted: curvature-dependent pressure[10,20] and curvature-dependent boundary distribution[37] were studied theoretically and numerically; curvature-dependent flow coherence was studied with both experiment and a hydrodynamic model.[37] The fact that experimental data are very scarce has been limiting the advancement of the field. We identify two major problems that are limiting us from obtaining abundant experimental data: (i) the protocols of producing confined active matter are either tedious or less controlled; (ii) the inherent 3D motion poses challenges on conventional microscopy.

Our proposed research overcomes these limitations by: (i) introducing microcapillary devices to produce double emulsions with well-controlled geometries; (ii) state-of-the-art microscopy techniques to capture 3D motions. Equipped with these techniques, we set out to investigate the following research questions:

RQ1. What is the effective temperature of an active bath in the dilute limit, where particle-particle interactions are not important? Is it the same as in the bulk? Is it curvature-dependent?

RQ2. What is the effective temperature of an active bath in the dense limit, where particle-particle interactions are important and collective motion emerges? Is it the same as in the bulk? Is it curvature-dependent?

RQ3. What are the motions of non-spherical objects like in confined active bath? Would there be novel self-organization phenomena if several particles are put together? Microparticle shape has been shown to be very crucial in therapeutical applications (Refs 218, 219 in Ghosh 2020).

METHODS I have briefly described the techniques we are going to employ. Figure out how detailed it need to be and then write.

RESOURCES/ETHICS May not apply.

OUTCOMES The

Intergration of methods and disciplines to pursue the objectives

Gender dimension and other diversity aspects

Open science practices

Research data management and management of other research outputs

1.3 Quality of the supervision, training and of the two-way transfer of knowledge between the researcher and the host

Two-way transfer of knowledge between the researcher and the host organisation

There is a great potential for transfer of knowledge between me, the host laboratories at the PMMH and Gulliver labs in ESPCI and our external collaborators at University of Chile. A post-doctoral stay under Prof.

Eric Clement's supervision will be a great opportunity to acquire new knowledge and to produce an interdisciplinary and impactful study.

The proposed research focuses on the behavior of active matter under confinement. My experience of studying the diffusion, rheology and collective motions of bacterial suspensions forms a solid foundation to carry out this research. Additionally, I can share with the host a mutant strain of E. coli whose motility can be controlled by light. I genetically engineered the mutant strain during my PhD at the University of Minnesota, and I believe it can lead to a more versatile experimental system and more concrete outcome of this research project.

The hosts, the Clement, Lindner and Lopez-Leon groups at ESPCI, form an ideal combination of knowledge and techniques that are necessary for conducting the proposed research. Prof. Eric Clement and his group are world leading experimentalists on the study of active fluids, with special expertise in the behavior of active particles in complex environments. His lab is equipped with the state-of-the-art Lagrangian 3D tracking system, which makes resolving 3D motions possible. Prof. Anke Lindner is an internationally acknowledged specialist in the interactions between anisotropic particles and flow. Her knowledge will be valuable, especially when we study the motion of non-spherical particles in active baths. Prof. Teresa Lopez-Leon is an expert on microfluidic devices. She has the technique of producing double emulsions readily available for the proposed research.

Our collaborator Prof. Rodrigo Soto is an expert in modelling active matter systems. Working together, we expect that our experimental measurements will help determine important parameters in his model. In turn, his model will point out future directions of experiment. Combining experimental and theoretical approaches will provide not only a sound interpretation of experimental data, but also a theory that can be applied to real-life challenges.

Planned training activities for the researcher (scientific aspects, management organisation, horizontal and key transferable skills...)

...

1.4 Quality and appropriateness of the researcher's professional experience, competences and skills

I obtained my PhD degree with my thesis entitled "Novel properties and collective phenomena of active fluids". During my PhD from 2015 to 2021 under the supervision of Prof. Xiang Cheng at the University of Minnesota, I studied the diffusion, rheology and collective motion of active matter experimentally. During these investigations, I have acquired expertise of various experimental techniques, including confocal microscopy, microfluidics, genetic engineering, particle synthesis and image analysis. These studies have led to 3 publications in international peer reviewed journals, with additional papers under preparation.
The proposed research topic matches well with my experience and skill set. I will be able to quickly adapt my expertise to the new work environment. In the mean time, the supervision from world leading scientists and being able to use the state-of-the-art equipments will benefit my career development enormously.

2. Impact

2.1 Credibility of the measures to enhance the career perspectives and employability of the researcher and contribution to his/her skills development

- project management;

2.2 Suitability and quality of the measures to maximise expected outcomes and impacts, as set out in the dissemination and exploitation plan, including communication activities

- conferences; outreach activities;

2.3. The magnitude and importance of the project's contribution to the expected scientific, societal and economic impacts

- ...

3. Quality and Efficiency of the Implementation

3.1 Quality and effectiveness of the work plan, assessment of risks and appropriateness of the effort assigned to work packages

Work package number	1	Start month	1	End month	10
Work package title	Dilute temperature				
Objectives	Measure the "effective temperature" of confined dilute active bath				
Description	- Demonstrate the capabilities of the proposed methods: producing double emulsions with microfluidic device, recording 3D motion of inner droplets with Lagrangian 3D tracking system and confocal microscopy - Set up an experimental protocol - Collect inner droplet images systematically in various geometries - Write programs to extract the trajectories from images				
Methodology					
Deliverables					Month
	D1.1	Conference – APS DFD meeting USA, November 2022			
	D1.2				
	D1.3				

Work package number	2	Start month	8	End month	20
Work package title	Concentrated temperature				
Objectives	Measure the "effective temperature" of confined concentrated active bath				
Description	- Measure effective temperature at a range of different bacterial concentrations, spanning from random swimming to collective motion, at fixed geometry - Collect inner droplet images systematically in various geometries				
Methodology					
Deliverables					Month
	D2.1				
	D2.2				
	D2.3				

Work package number	3	Start month	18	End month	24
Work package title	Anisotropic object				
Objectives	Measure the dynamics of anisotropic particles in active bath				
Description	- Fabricate anisotropic particles using 3D printer -				
Methodology					
Deliverables					Month
	D3.1				

	D3.2		
	D3.3		

3.2 Quality and capacity of the host institutions and participating organisations, including hosting arrangements

Insert here text for your proposal

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Part B-2

(*No overall page limit applied*)

4. CV of the researcher

Insert here text for your proposal

5. Capacity of the Participating Organisation(s)

5.1 Template table: *Overview of Participating Organisations*

Organisation role	PIC	Legal Entity Short Name	Academic organisation (Y/N)	Country	Name of Supervisor
Beneficiary					
Associated partner linked to a beneficiary (if applicable)					
Associated partner for outgoing phase (mandatory for GF)					
Associated partner for secondment (optional)					
Associated partner for non-academic placement (optional)					
Other: _____					

5.2 Template table: *Capacity of the Participating Organisations*

Choose one of: ⁘ *Beneficiary (compulsory)* ⁘ *Associated partner linked to a beneficiary (if applicable)* ⁘ *Associated partner for outgoing phase (compulsory for GF only)* ⁘ *Associated partner for secondment (optional)* ⁘ *Associated partner for non-academic placement (optional)*
[Full name + Legal Entity Short Name + Country]

General description	
Role and profile of supervisor	
Key research facilities, Infrastructure and Equipment	
Previous and current involvement in EU-funded research and training programmes/actions/projects	

6. Additional ethics information

Insert here text for your proposal
(NB: Only if you have additional information that could not be included in the ethics self-assessment)

7. Additional information on security screening

Insert here text for your proposal
(NB: Only if you answered yes to one of the questions in the security issues table, with the exception of "Does this activity involved HE associated and/or third countries?")

8. Letter(s) of commitment from associated partners (host for outgoing phase of Global Fellowship or non-academic placement host)

Insert here text for your proposal

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