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Collective motion and dynamic self-assembly of colloid motors

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ABSTRACT

Collectively dynamic self-assembly arising from the living mobility is the fundamental process of lives. Inspired by collective behaviors of living systems, collective motion and self-assembly of synthetic colloid motors have been brought into focus due to high performance and emerging phenomena beyond the power of single colloid motor. Here, we summarize the recent progress on the collectively dynamic self-assembly systems of synthetic colloid motors sorted by various triggers of self-propulsion and external fields (such as chemicals, light, electric fields, and acoustic fields), ranging from the propulsion to stimuli of collective self-assembly. The typical physical phenomena are presented, including phase separation, clustering, and giant number fluctuations. The collectively dynamic self-assembly of colloid motors are expected to provide unlimited opportunities to various applications with continuous innovation both in the design of synthetic colloid motors and the modulation of collectively dynamic self-assembly.

1. Introduction

Collective assembly is essential and common for normal biological processes of living organisms, such as the schooling of fishes, the flocking of birds, the cooperation of ants, and the swirl motion of bacteria [1•,2–4]. Fig. 1 shows the collective assembly of moving natural individuals in both macroscopic and microscopic scales. These biological collective assemblies include moving lives and the communications in between. Resembling to the natural collective systems, artificial collective assemblies consist of the moving synthetic units and the interactions among them.

Self-propelled synthetic colloid motors (also referred as active colloids, micro-/nanomotors, or micro-/nanomachines) are micro-/nanoscale devices that are capable of converting chemical or other energies in their surrounding environments into movement in fluids [5,6•,7]. Recently, studies on single motors show various propulsions powered by chemical reaction [8–10], light [11,12], electric fields [13], acoustic fields [14], and magnetic fields [15,16], as well as diverse applications in biomedical [17,18], sensing [18,19], and environmental fields [9].

One of the significant features of colloid motors is the capability to perform collective self-assembly. Collective assembly means the collective behavior induced by the dynamic self-assembly of micro-/nanoobjects, acting at an out-of-equilibrium state with energy dissipation and stimuli-responsive ability. The typical collective behaviors of colloid motors include schooling and dispersing, dynamic clustering, predator–prey behavior, and collectively directional migrations. Different from static assembly of passive particles that would reach a thermodynamic equilibrium state finally, the collective dynamic assembly of the colloid motors requires constant energy input, and would present nonequilibrium dynamics [20,21]. Studies of collective self-assembly comprise not only the movement behavior and propulsion mechanism of the colloid motors, but also the interactions between these colloid motors and the remarkable physical phenomena of the collective systems. The interactions of colloid motors in collective self-assembly could be modulated by various energy sources which may be different from the powers that propel the motors. The collective self-assembly of the colloid motors may promote the advances in understanding natural collective systems, constructing novel active materials and developing biomedical applications [22–28].

Considering that the input triggers play an important role in the propulsion and collective motion, collective self-assembly of colloid motors can be discussed according to the triggers of collective behaviors. Recent reviews have been focused more on the collective self-assembly systems of colloid motors with a certain propulsion manner [29–31]. Here, we would like to systematically discuss the remarkable phenomena in collective behaviors of colloid motors and overview recent progress on collective assemblies of synthetic colloid motors that are either based on self-propulsion and collision, or triggered by external physical stimuli (Fig. 2). By summarizing the typical physical phenomena and process, we aim to discuss the related aspects with regard to the collective motions, propulsion mechanisms, and fundamental physics in the collective assembly of colloid motors.

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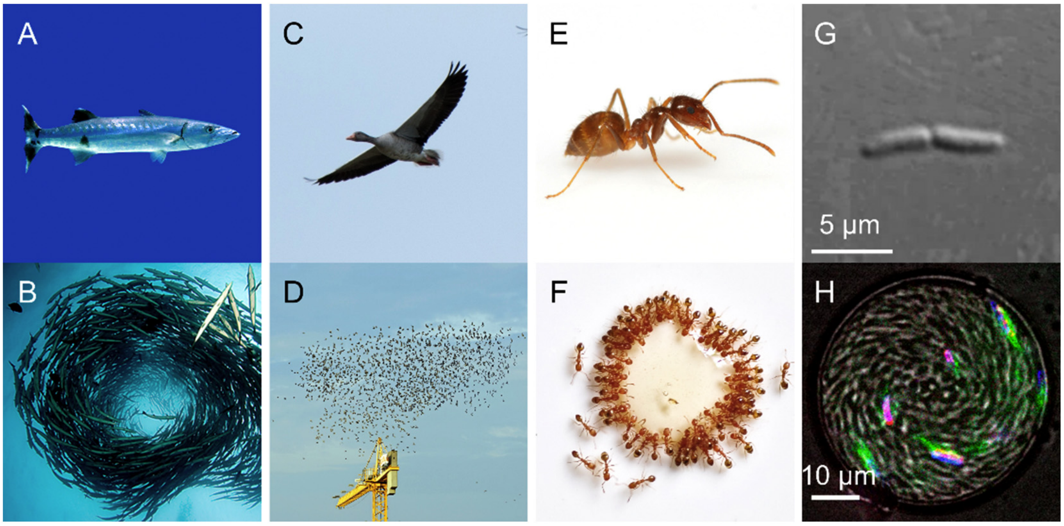

Fig. 1. Collective assembly in nature. (A, B) The individual swimming and swirl schooling of fishes in the ocean. (C, D) The individual fly and flocking migration of birds. (E, F) The individual moving and cooperation of ants. (G, H) The individual motion and homodromous collective motion of bacteria. (A) Adapt from Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Sphyraenidae_-_Sphyraena_barracuda_(Great_barracuda).JPG). (B) Adapt from Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Barracuda_Tornado.jpg). (C) Adapt from Pixabay (https://pixabay.com/en/migratory-birds-geese-wild-geese-508020/). (D) Adapt from Pixabay (https://pixabay.com/en/flock-of-birds-migratory-birds-sky-2150470/). (E) Download from Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Tawny_crazy_ant_(Nylanderia_fulva)_female_worker.jpg). (F) Adapt from Wikimedia Commons Photos in (https://commons.wikimedia.org/wiki/File:Ant_and_honey4.jpg). (A-F) are made available under Creative Commons attribution licenses. (G) Reproduced from Ref. [32], under Creative Commons attribution license. (H) Reproduced with permission from Ref [3]. Copyright (2014) National Academy of Sciences.

2. Phase separation in collective dynamic self-assembly

As the collective dynamic self-assembly of colloid motors rises from the out-of-equilibrium systems, typical phenomena of nonequilibrium systems are expected to emerge remarkably. Before discussing the collective assembly under different triggers, we give a primary introduction of the typical phenomena of collective dynamic self-assembly of colloid motors as the beginning.

Phase separation in non-equilibrium colloid motor systems is caused by collisions out of "collision rule" and happens in a relatively small number of objects (usually a few dozens to a few thousands), distinct from phase separation in equilibrium systems in which the total momentum is preserved and that are only meaningful for very large-size systems (close to infinite) [36]. Hence, the phase separation is a typical signal of non-equilibrium state in the microscopic systems, and implies the transition of colloid motors from disordered, isolated state to ordered (polar or nematic) or clustered state.

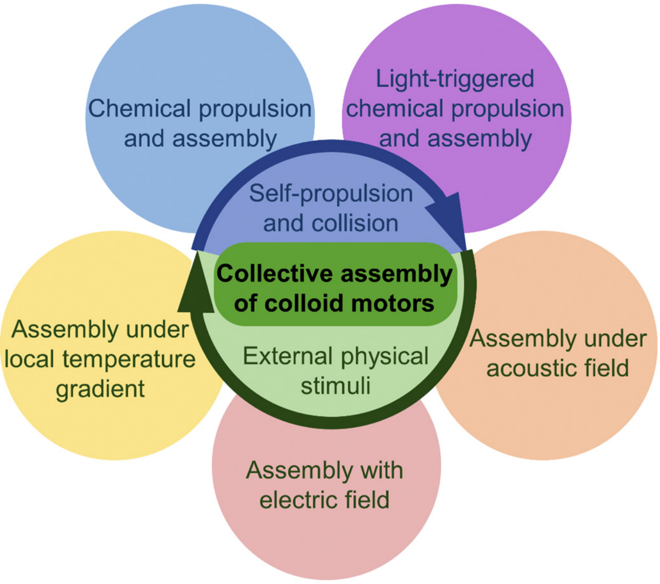

Fig. 2. Schematic illustration of the collective self-assembly of colloid motors triggered by different stimuli.

One of the typical characters of phase separation is cluster formation. Neighboring colloid motors belong to the same cluster, where the word neighboring stands for a pre-defined proximity standard, and thus the behavior of motors in the same cluster is usually highly associated. In a confined geometry, any groups of self-propelled colloid motors with a finite size have a chance to be transformed into clusters. The presence of a boundary or a narrow channel would inevitably lead to the clustering [37,38]. The size distribution of clusters is closely related with the colloid motor's density and velocity, which are also critical factors affecting phase separation [33,39•]. Fig. 3A shows the phase separation of Janus Au-Pt spherical colloid motors due to the chemically induced collision, where the cluster size of the colloid motors grows linearly with the velocity of the colloid motors (Fig. 3B) [33].

Another remarkable feature is giant number fluctuation, a specific form of density variations. The fluctuation of the number of colloid motors (ΔN) in an increasing part of the system scale with the number of units (N) in a given area linearly, which is a property of colloid motor system. For two-dimensional active systems, N can become very large and scale as N^{α}, with an exponent α predicted as 1, which is different from the equilibrium systems where ΔN grows as a square root of N [40–42]. The simulative disks without alignment show the cluster size changes in different particle densities in Fig. 3C, and indicate a packing fraction (critical density) of ~0.4 above which the phase separation happens in this two-dimensional system [34•]. Fig. 3D displays the difference of the ΔN~N relationship at a density below and above the critical fraction. Recently, Lin et al. illustrate the light-activated self-assembly of peanut-shaped colloid motors (Fig. 3E), where a critical density point and giant number fluctuations emerge (Fig. 3F) [35••]. Boundary and topological defects can also affect the collective behaviors [3,43]. These typical phenomena of the collective self-assembly of colloid motors link systems of different propulsion and stimuli with common physical or mathematic characters, and thus provide quantitative measurements to monitor the process of dynamic self-assembly and parameters to alter the systems.