Swarming behavior of microtubules driven by dyneins

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Self-propelled particle


![Diagram](image-url)

- 180 mm
- pentanol
- aqueous phase (2.3 vol%)
- water
- oil
Main questions

* How to gain momentum without external force
* How to break symmetry
* Collective phenomena of active matters
Swarming behavior of active particles

Swarming behavior through a short range interaction

\[ x_i^{j+1} = x_i^j + (e_x \cos \theta_i^j + e_y \sin \theta_i^j) \Delta t \]
\[ \theta_i^{j+1} = \langle \theta_k^j \rangle + \xi_i \]

There is only short-range interaction about the direction of motion.

Universal Characteristics!

Nonequilibrium phase transition

Giant Fluctuation


Experimental evidence

J. Deseigne, et al., 2010.  
V. Schaller, A.Bausch, 2010.
Deformable self-propelled particles should have memory.

Vicsek model does **NOT** have memory

\[ x_i^{j+1} = x_i^j + (e_x \cos \theta_i^j + e_y \sin \theta_i^j) \Delta t \]
\[ \theta_i^{j+1} = \langle \theta_i^j \rangle + \xi_i^{j+1} \]

No memory (correlation)

Deformable self-propelled particles should have memory.

- What is the role of memory of motion?

Mathematical model

\[ \dot{x}_i = v_0 (e_x \cos \theta_i + e_y \sin \theta_i) \]
\[ \dot{\theta}_i = \omega_i + \frac{\alpha}{n_i(t)} \sum_{|x_i-x_j|<l} \sin 2(\theta_j - \theta_i) \]
\[ \dot{\omega}_i = -\frac{1}{\tau} (\omega_i - \omega_0) + \xi_i(t) \]

\(\langle \xi(t) \rangle = 0, \langle \xi(t)\xi(t') \rangle = \sigma^2 \delta(t-t') \)
\(\langle \omega^2 \rangle = \sigma^2 \tau / 2 \)

\(v_0 = 8.75 \, \mu m/s, \omega_0 = -0.00624 \, \text{rad/s}, l = 15.0 \, \mu m, \alpha = 0.0583 \, \text{rad/s},\)
\(\langle \omega^2 \rangle = 2.48 \times 10^{-4} \, \text{rad}^2/\text{s}^2\)
Order parameter

1. Nematic order parameter

\[ S = \langle \exp 2i\theta_i \rangle \]

If all particles align parallel or anti-parallel (nematic order), \( S=1 \).

If there is no global nematic order, \( S=0 \).

2. Density fluctuation

\[ u^2(n)/n_a \]

\( u^2 \) is the variance of density in a 60 \( \mu m^2 \times 60 \mu m^2 \) region. \( n_a \) is the average number of particles in the same region.

If the density is not uniform, this value is large.
Phase diagram
Phase diagram
Phase diagram

Phase diagram

Vortex lattice
Microtubule

- No polymerization and depolymerization (stabilized with taxol)
- Microtubules were labeled with Cy3.
Dynein-c

Inner-arm dynein purified from Chlamydomonas flagella
• ATP concentration was 1 mM.
• In vitro motility assay consisted of dynein grafted to glass surface and to microtubules.
• Density of dyneins was 750-2,500/µm².
• Average speed of a microtubule was 8.75 µm/s.
Interaction of microtubules

Microtubule aligns parallel or anti-parallel through collision

(Short-range nematic interaction)
Difference between dyneins and kinesins

- Most microtubules does not change the direction.
Trajectory of an isolated microtubule

- Smooth trajectory (finite correlation time of direction of motion)
- $\frac{\omega_i}{v_0}$ is the curvature of trajectory.
• Correlation length along the trajectory was 542 ± 4 μm (>> microtubule length (10 μm))!
• Average curvature was -7.1 × 10^{-4} μm^{-1} (clockwise rotation).
• Standard deviation of curvature was 1.8 × 10^{-3} μm^{-1}.
• Density was 40 μg/ml (5 MT in 100 μm²).
• The size of a vortex was 443 ± 64 μm (major axis) (>> microtubule length (10 μm)).
Density Dependence

14.3 μg/ml

28.6 μg/ml

57.2 μg/ml

114.5 μg/ml

100 μm
Situation corresponding to the experiments

$\tau=171 \text{ s}, L=7.68 \text{ mm}, \rho=4.44 \times 10^{-2} \mu\text{m}^2, N=2621440$

Vortex lattice!
Conclusion and remarks

- Using a mathematical model, we found long correlation time of motion and high density leads to vortex lattice of active particles. Only short-range nematic interaction is needed for vortex lattice (not hydrodynamical one (I. H. Riedel, et al., Science (2005))).

- We experimentally confirmed this type of swarming behavior using motility assay consisted of dynein proteins grafted to glass surface and to microtubules.

- The macroscopical meaning of the finite correlation time of the curvature of microtubule’s trajectory are being analyzed.