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Liquid crystal–ferrofluid emulsion systems

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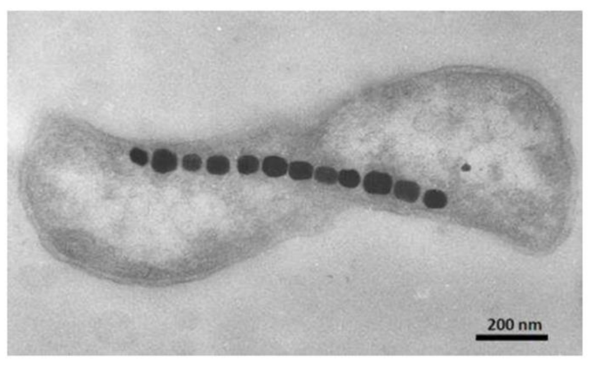
INTRODUCTION & AIM

Objective: To create synthetic magnetotactic bacteria (MTB) mimicking structures using liquid crystals (LCs), ferrofluids and phospholipids.

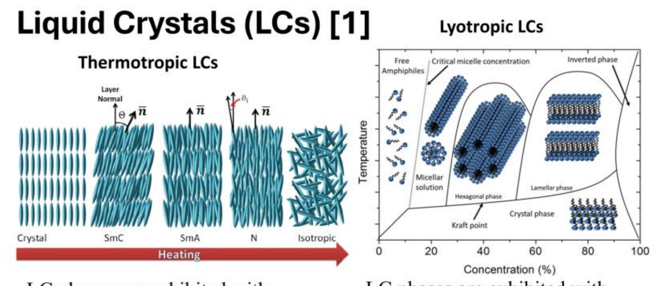
Magnetotactic bacteria (MTB)

- MTB are gram negative aquatic prokaryotic organisms with different morphological types.
- MTB consist of magnetosomes which are membrane-bound organelles containing crystals of iron oxides or iron sulfides.
- Magnetosomes form well-ordered chains and align with Earth's magnetic field



Magnetotactic bacterium. Credit: Imperial College London

Liquid Crystals (LCs) [1]



LC phases are exhibited with change in temperature. LC phases are exhibited with change in concentration.

Ferrofluids

A ferrofluid is a colloidal suspension which consists of magnetite (Fe_3O_4) nanoparticles dispersed in a Newtonian carrier fluid [2].

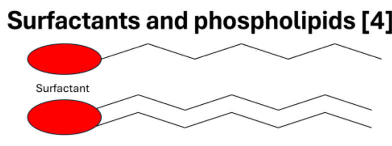
Magnetic force on ferrofluid particles [3]:

$F_B = \mu_0 \int \vec{M} \nabla \vec{H} \, dV$

F_B – force of applied magnetic field
M – mass magnetisation of ferrofluid
μ_0 – magnetic permeability of vacuum
∇H – magnetic field gradient

Spike effect in EFH1 ferrofluid observed under influence of external magnetic field. Ferrofluid nanoparticles are ferromagnetic.

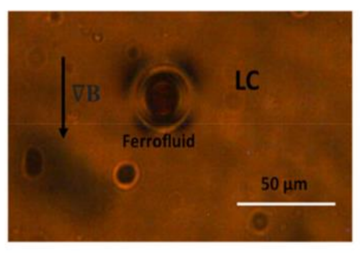
Surfactants and phospholipids [4]

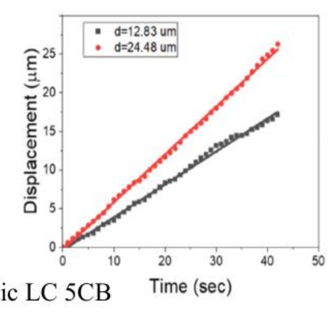


- Surfactants and phospholipids are substances that have the property of adsorbing onto interfaces of systems.
- Chemically, they consist of a hydrophobic part and a hydrophilic part
- They can be used to coat the ferrofluid droplets in the LCs with a membrane

METHOD

Ferrofluid droplets in LCs





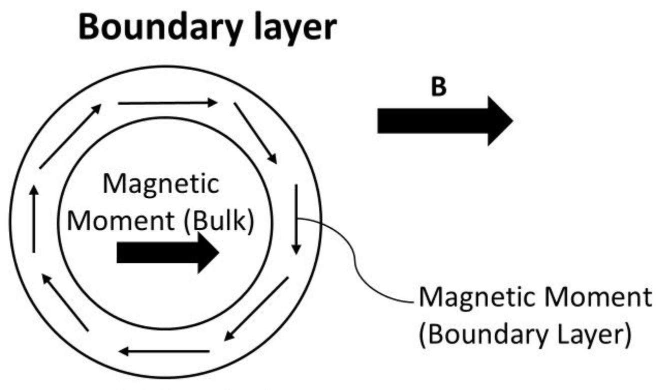
Ferrofluid droplet in thermotropic nematic LC 5CB

Stokes' law [3]:

$$\gamma = \frac{2r^2 M_{vol} \cdot \nabla B}{9 v_{eq}}$$

γ – viscosity of LC
r – effective radius of ferrofluid droplet (radius of droplet minus boundary layer thickness)
M_{vol} – volume magnetisation of ferrofluid

Boundary layer

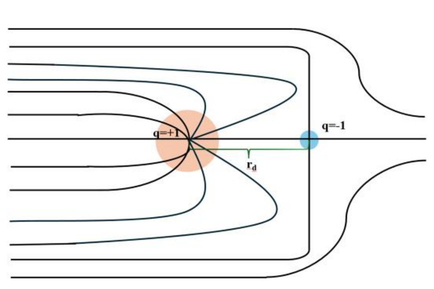


Ferrofluid boundary layer

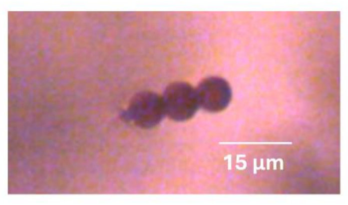
Boundary layer is independent of droplet size and anchoring condition and only depends on the nature of emulsion.

Measured Values for 5CB [5]
$\gamma_{parallel} = 45 \pm 1$ mPa s
$\gamma_{perpendicular} = 129 \pm 4$ mPa s

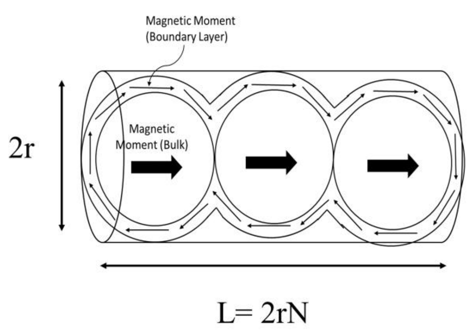
Droplet chains in 5CB



Hyperbolic hedgehog defect q=-1 (blue) in the vicinity of a microparticle/droplet acting as a q=+1 defect (orange).



Ferrofluid droplet chain in 5CB



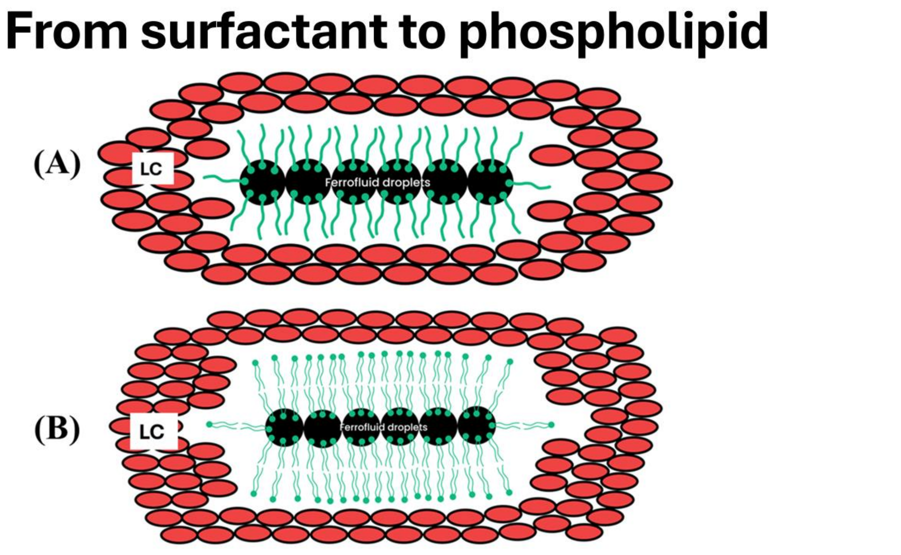
Ferrofluid droplet chain boundary layer. The ferrofluid droplet chain is approximated as a cylinder.

Drag force of chains [6]:

$$F_{drag} = \frac{4\pi\gamma v_{eq}\left(\frac{L_{eff}}{2}\right)}{\ln\left(\frac{L_{eff}}{r_{eff}}\right) - 0.72}$$

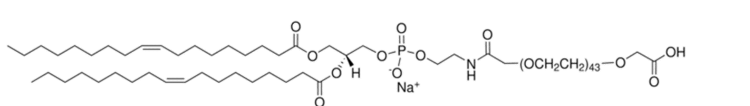
F_{drag} – drag force
L_{eff} – effective length of the ferrofluid droplet chain (length of the chain minus twice boundary layer thickness)
r_{eff} – average effective radius of droplets in chain (average radius minus boundary layer)
γ – viscosity
v_{eq} – equilibrium velocity

From surfactant to phospholipid



(A) A ferrofluid droplet chain coated with a surfactant in 5CB. Here, the hydrophilic headgroup (green sphere) adsorbs into the ferrofluid while the hydrophobic tail is in the LC. (B) A ferrofluid droplet chain coated with a lipid bilayer in 5CB. Here, a bilayer is formed by the lipid molecules with the hydrophilic part in the ferrofluid and the hydrophobic part in the LC.

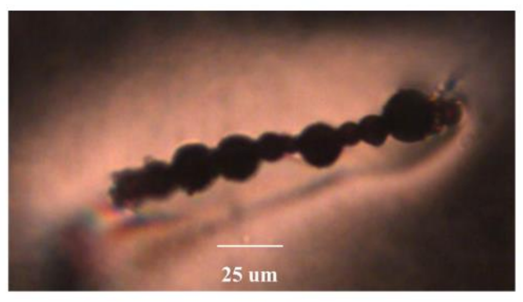
Most efficient phospholipid



DOPE-PEG (2000) Carboxylic acid sodium salt (Zwitterionic lipid)

RESULTS & DISCUSSION

Synthetic structure

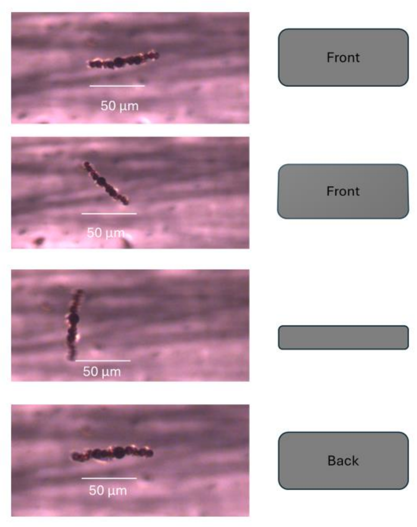


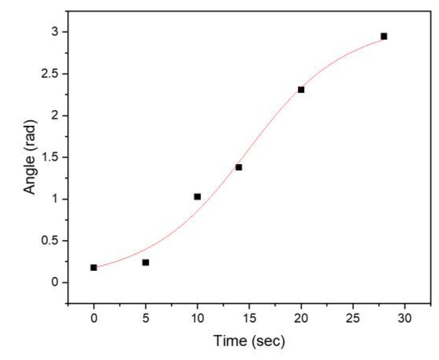
Ferrofluid droplet chain coated with lipid bilayer in 5CB

- 5CB mixed with DOPE-PEG(2000) Carboxylic acid sodium salt (zwitterionic lipid) dispersed in chloroform.
- Chloroform is evaporated by freeze-drying.
- Water-based ferrofluid WHKS1S12 is dispersed in mixture by mild vortexing.
- Emulsion is filled into Hele-Shaw cell (with planar alignment) and observed under POM.

Characteristics	Live MTB magnetosomes	Synthetic MTB droplet chains
Composition	Inorganic magnetite crystals	Ferrofluid droplet chains
Size	30-50 nm	10-25 µm
Shape	Cuboctahedral	Spherical

Rotation with magnetic field (synthetic structure)

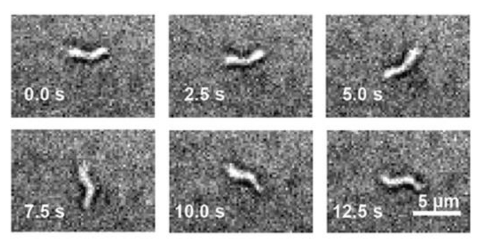


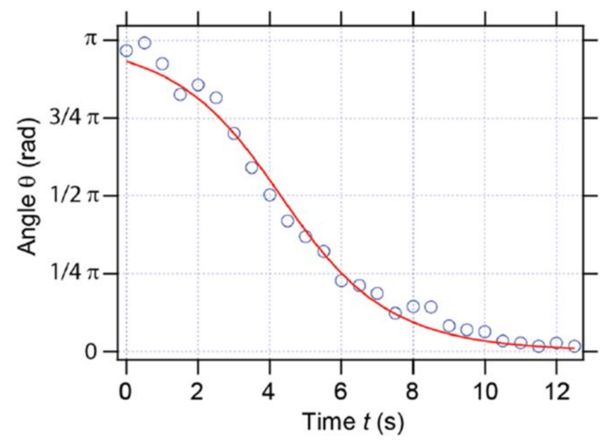


$$\theta(t) = 2\arctan\left[e^{\left(\frac{\mu B}{\gamma_{rot}}t\right)} \tan\left(\frac{\theta_0}{2}\right)\right]$$

$\gamma_{rot} \approx 85$ mPa s [7]

Rotation with magnetic field (live MTB) [8]





CONCLUSION

A synthetic structure which mimics a magnetotactic bacterium has been created using nematic 5CB, water-based ferrofluid and PEGylated lipids.

FUTURE WORK / REFERENCES

1. Dierking, I.; Al-Zangana, S. Lyotropic Liquid Crystal Phases from Anisotropic Nanomaterials. Nanomaterials 2017, 7, 305. https://doi.org/10.3390/nano7100305
2. Abro, K. A. (2021). Role of fractal–fractional derivative on ferromagnetic fluid via fractal Laplace transform: A first problem via fractal–fractional differential operator. European Journal of Mechanics-B/Fluids, 85, 76-81
3. Dierking, I., Yoshida, S., Kelly, T., & Pitcher, W. (2020). Liquid crystal–ferrofluid emulsions. *Soft Matter*, *16*(26), 6021–6031. https://doi.org/10.1039/d0sm00880j
4. Rosen, Milton J. (1989). Surfactants and interfacial phenomena (2nd edition), Wiley and Sons, Inc.
5. Chandrasekar, V., Lu, J.R. and Dierking, I., 2023. Micro-scale viscosity measurements of different thermotropic and lyotropic classes of liquid crystals by using ferrofluid inclusions. Journal of Molecular Liquids, 383, p.122178.
6. Happel, John, and Howard Brenner. 1983. Low Reynolds Number Hydrodynamics : With Special Applications to Particulate Media. 2nd rev. ed. The Hague: Nijhoff.
7. Capar, M.I. and Cebe, E., 2005. Rotational viscosity in liquid crystals: A molecular dynamics study. Chemical physics letters, 407(4-6), pp.454-459.
8. Zahn, C., Keller, S., Toro-Nahuelpan, M., Dorscht, P., Gross, W., Laumann, M., Gekle, S., Zimmermann, W., Schüler, D. and Kress, H., 2017. Measurement of the magnetic moment of single Magnetospirillum gryphiswaldense cells by magnetic tweezers. Scientific Reports, 7(1), p.3558.