Magnetic rotational spectroscopy : a novel active microrheology technique for colloids and gels

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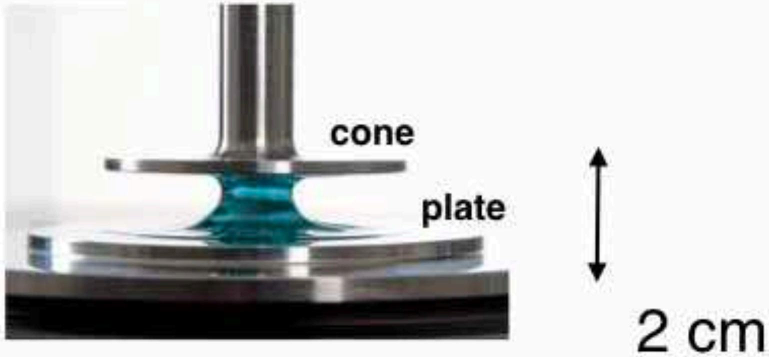
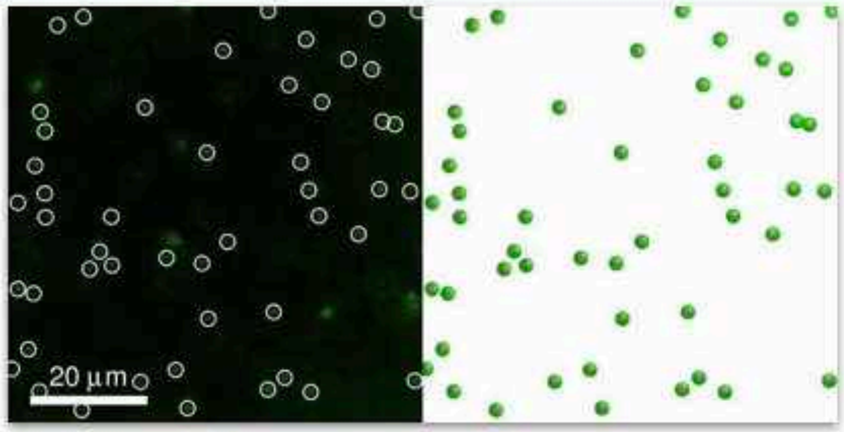
Matière et Systèmes Complexes, Université Paris-Cité, France

Rheology *versus* Microrheology

Rheology	Micro-rheology
Rheometer	Microscope
Shearing device	Micron-sized probes



web.mit.edu/savin/Public/



Université Paris Cité

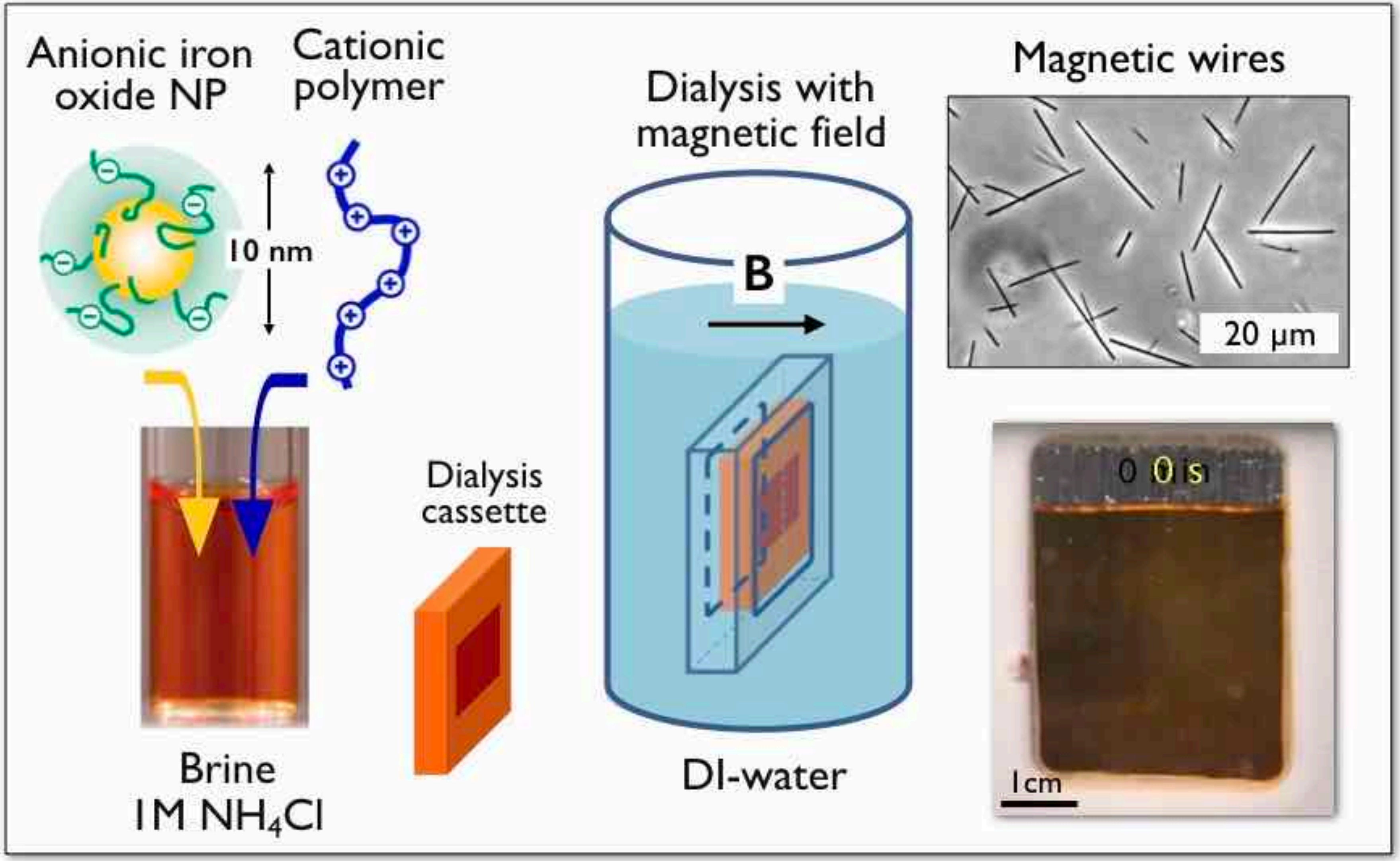
MSC
Matière et Systèmes Complexes

I - The tools

II - Rheological models and validation

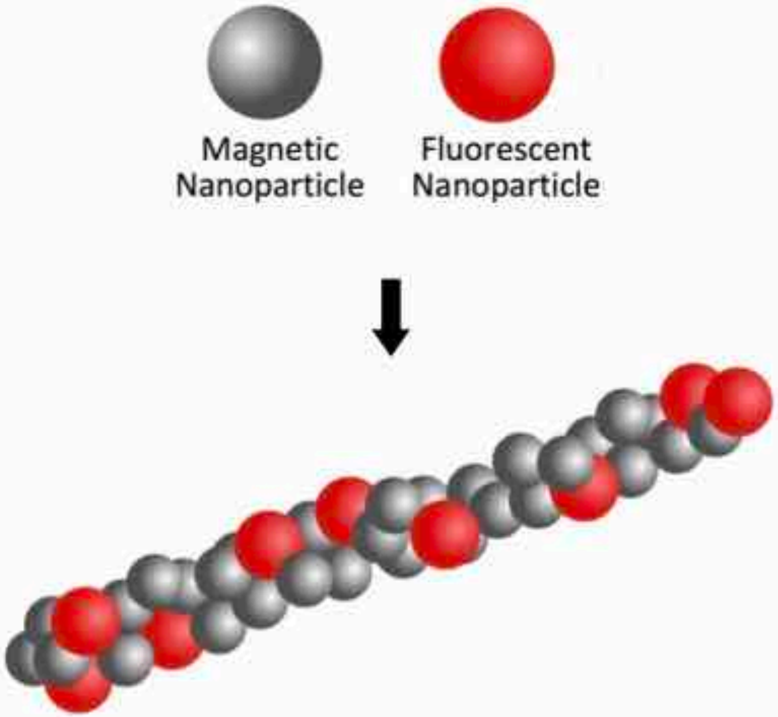
III - Applications to lung fluids

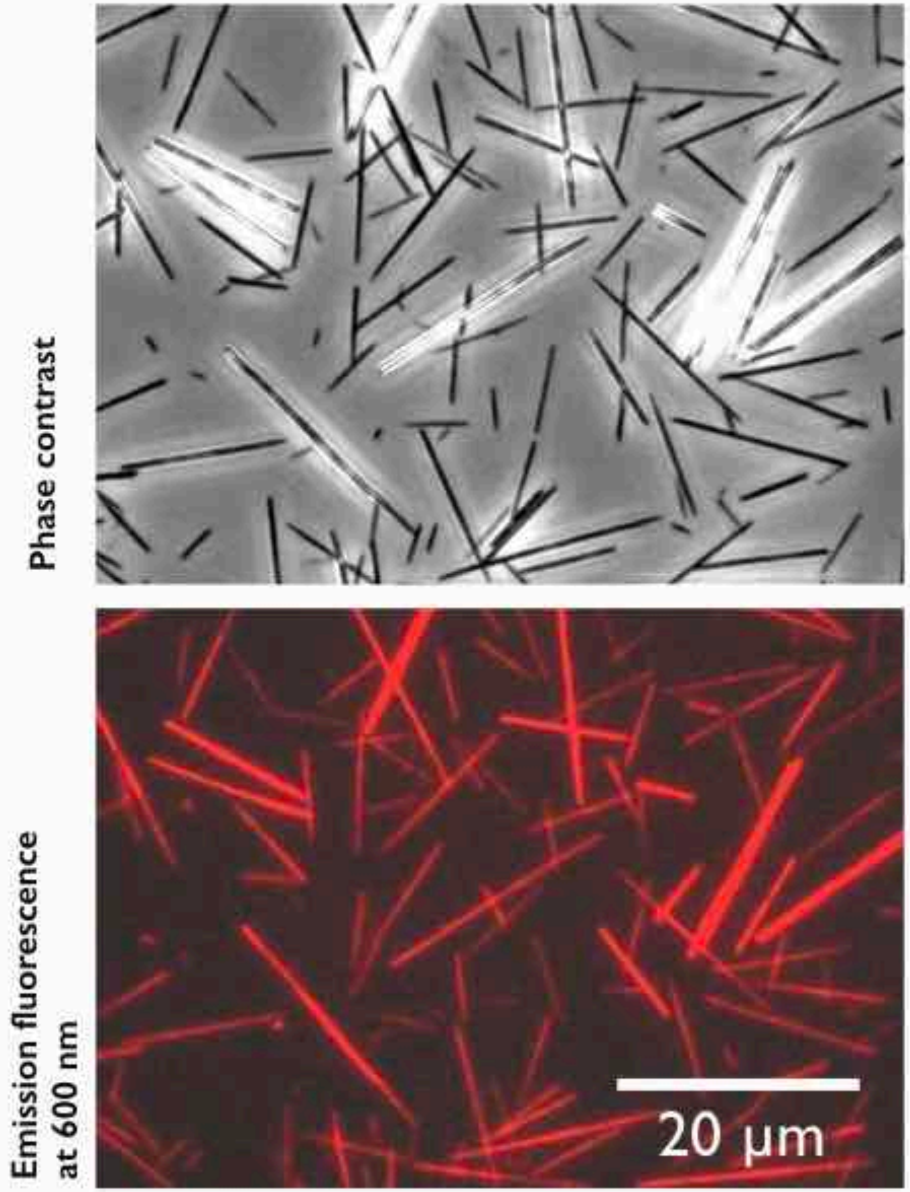
Probe fabrication



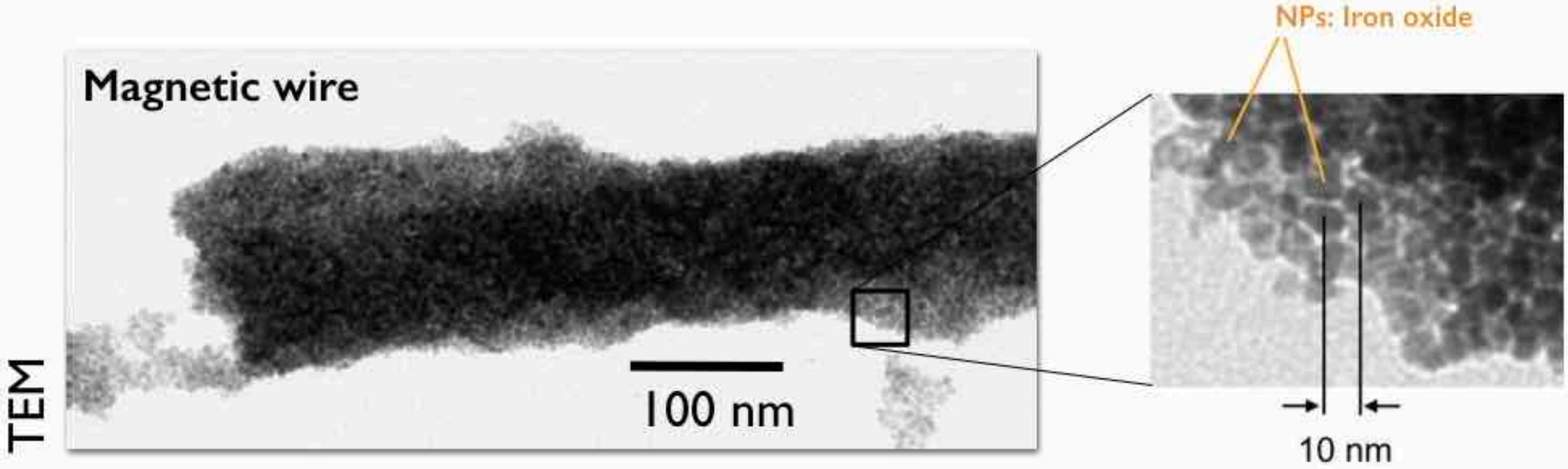
Probe fabrication

Mixing magnetic nanoparticles and fluorescent quantums dots prior to dialysis

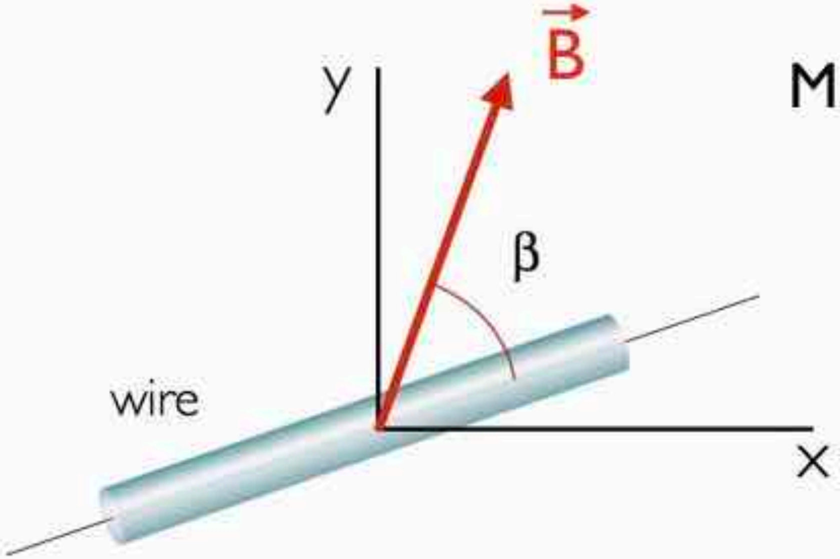




Magnetic properties



Volume fraction of particles
30 vol. %



Magnetic torque

$$\Gamma_{Mag} = \frac{1}{2\mu_0} V \Delta\chi B^2 sin\,(2\beta)$$

Wire volume

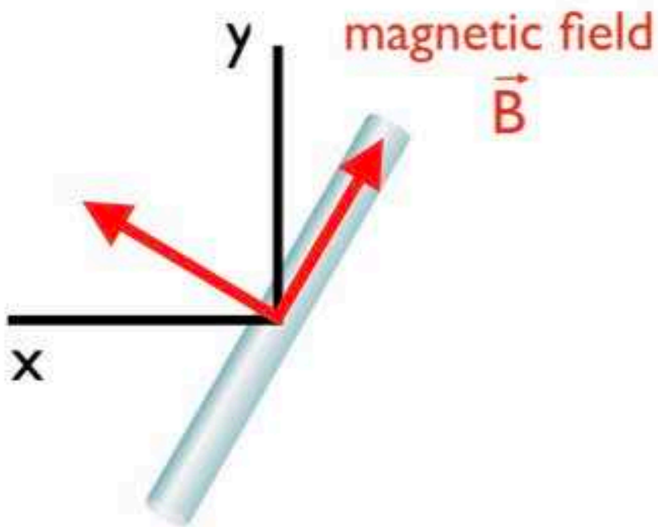
Susceptibility anisotropy

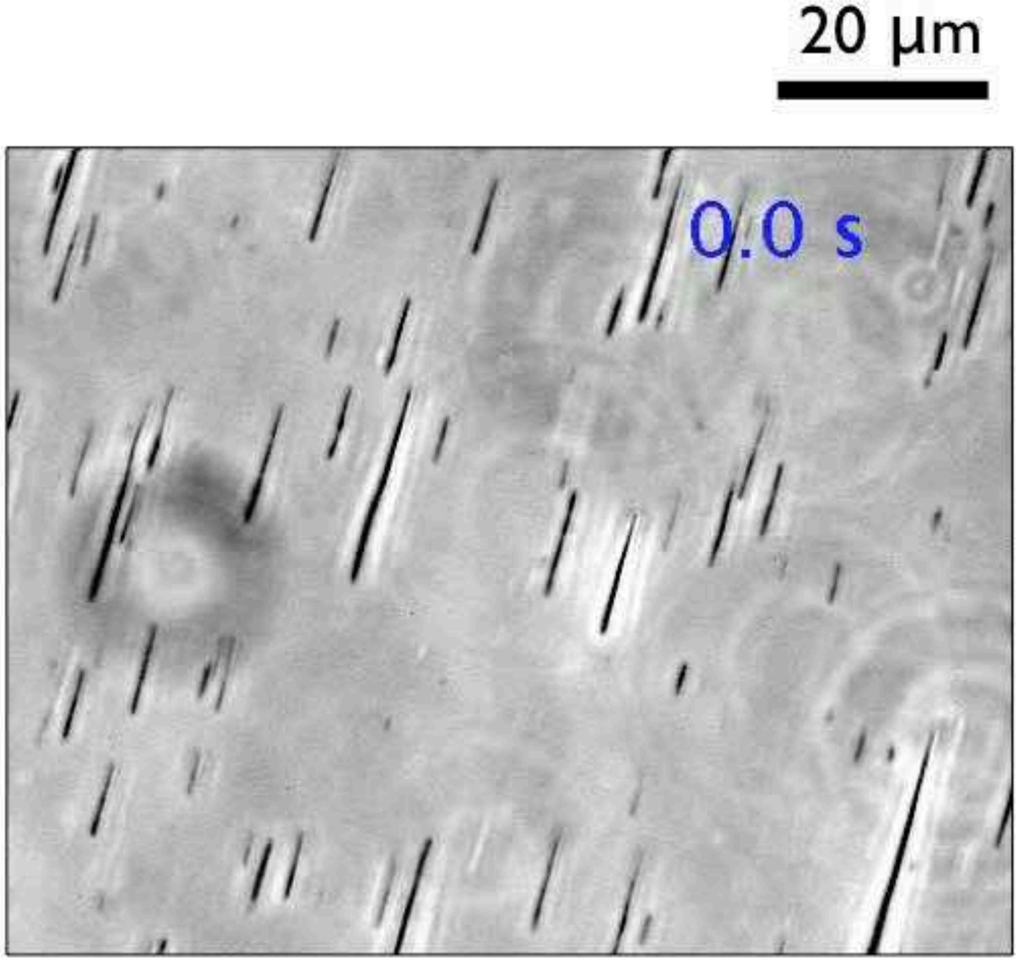
Magnetic field

J. Fresnais, J.-F. Berret et al., Adv. Mater. ***20****, 3877 (2008)*

Magnetic properties

90°-flip of the magnetic field



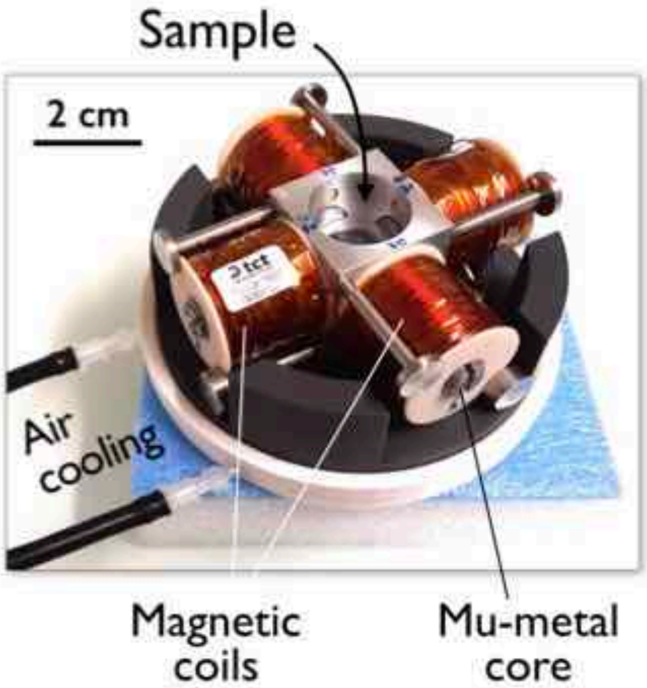


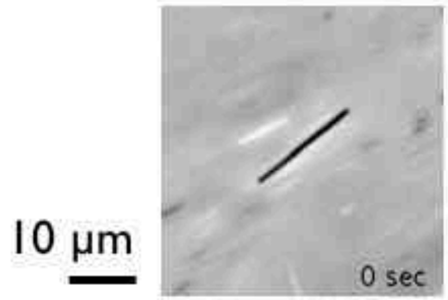
- The wires are superparamagnetic
- Their response to a field depends on the length and diameter

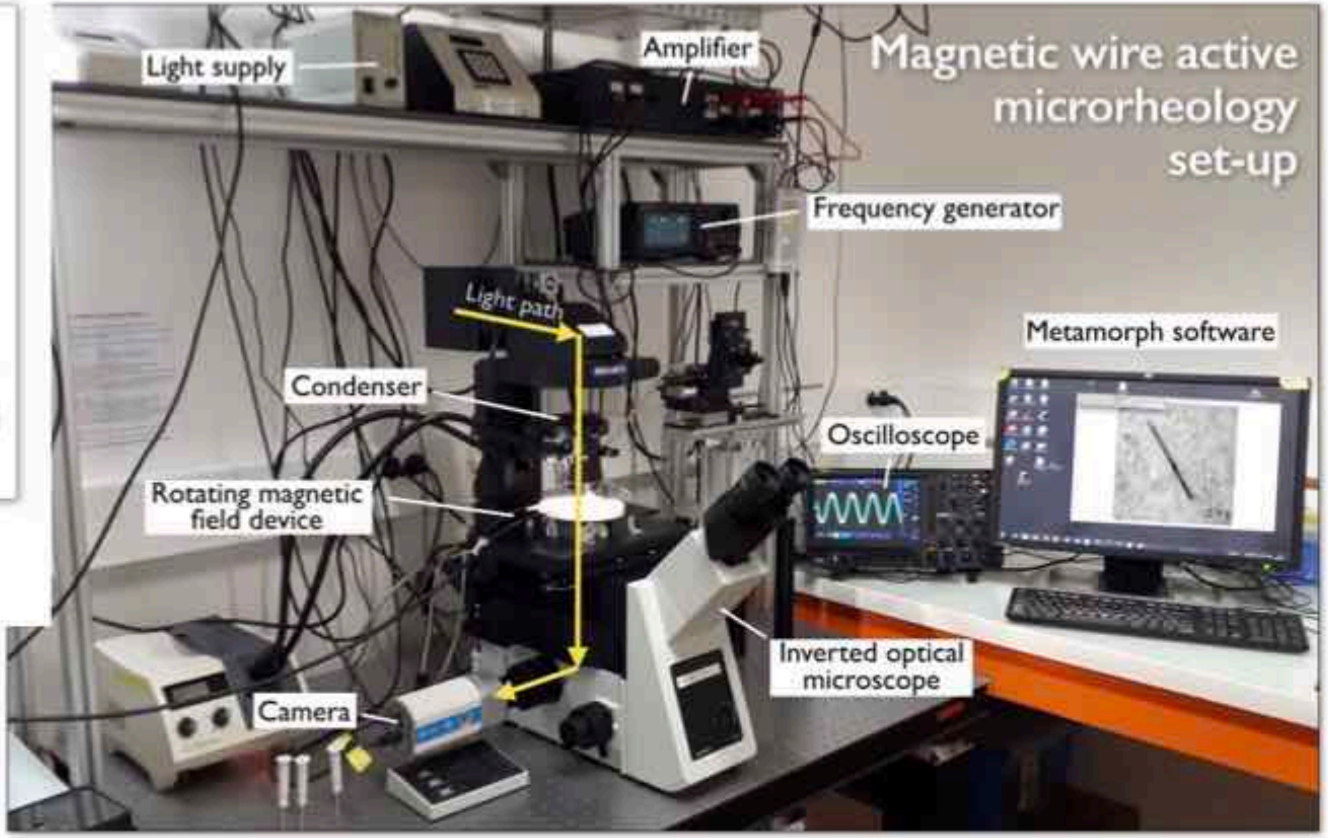
Experimental set-up

Magnetic Rotational Spectroscopy*

In MRS, micron-sized wires are submitted to a **rotational magnetic field** (1 - 50 mT) as a function of the **frequency** (10^{-4} - 100 Hz)







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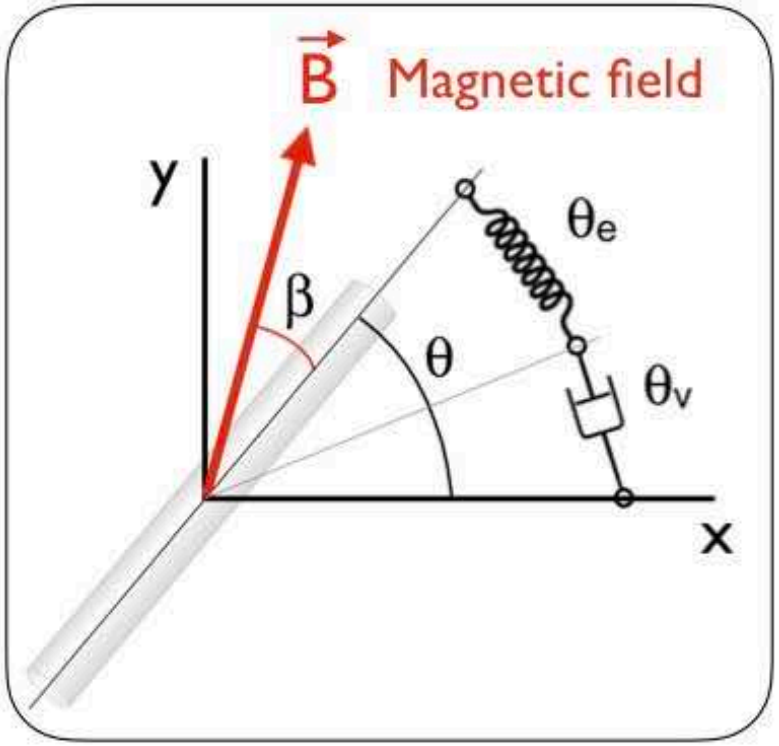
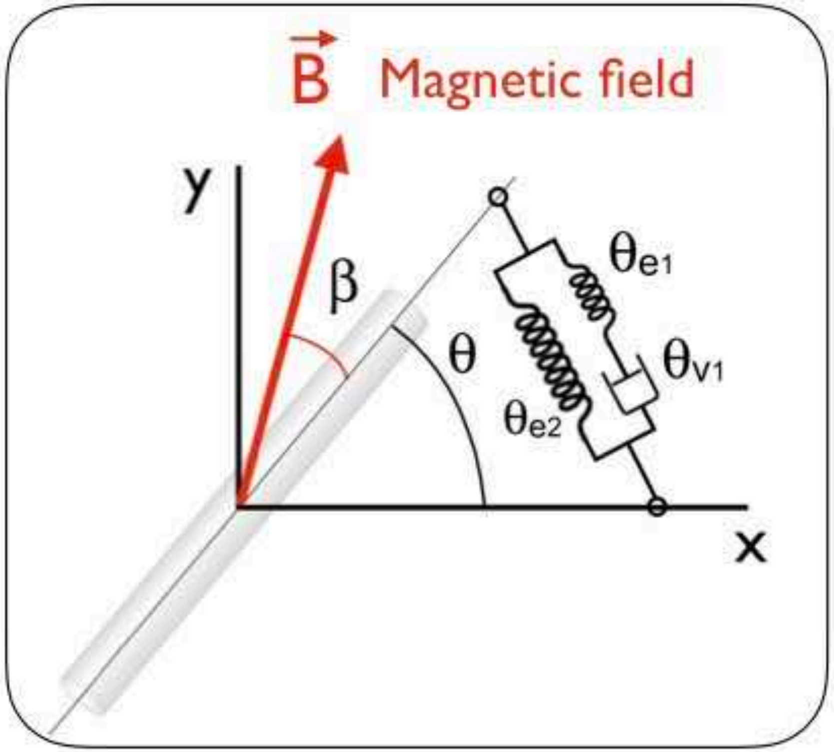
Viscoelastic models

Maxwell model



→ Viscoelastic liquids

Standard Linear Solid model

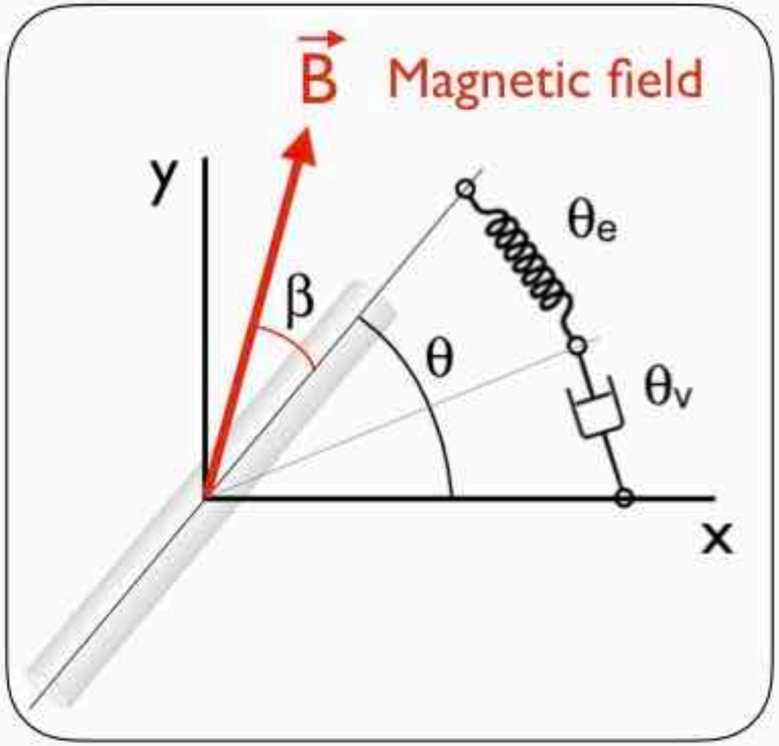


→ Soft Solids

The rotation behavior depends on the rheological properties of the fluid/material surrounding the wire

Viscoelastic models

Maxwell model



Analogy with classical rheology using stress, strain and shear rate

- Magnetic torque

$$\Gamma_{Mag}(B) = \frac{\Delta\chi V}{2\mu_0} B^2 \sin 2(\omega t - \theta)$$

- Viscous torque $\Gamma_{Vis} = \frac{\pi\,\eta L^3}{3g(L/D)} \frac{d\theta_v}{dt}$

- Elastic torque $\Gamma_{El} = \frac{\pi G L^3}{3g(L/D)} \theta_{El}$

L wire length
D wire diameter
η static viscosity
G elastic modulus

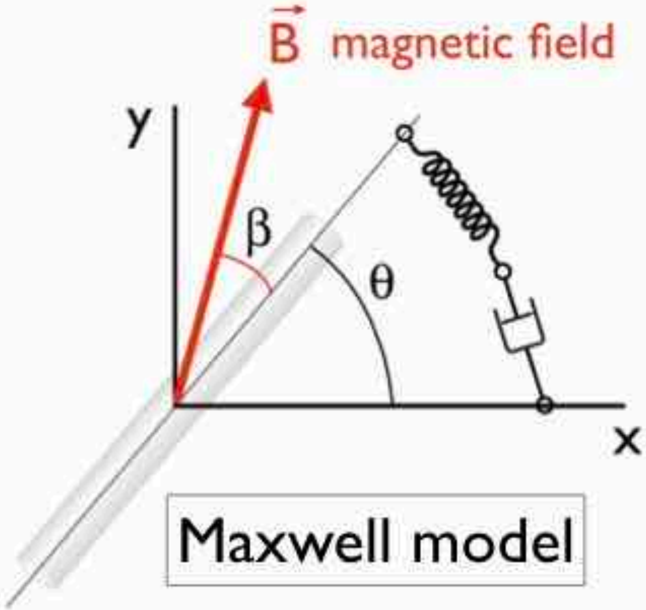
- Differential equation

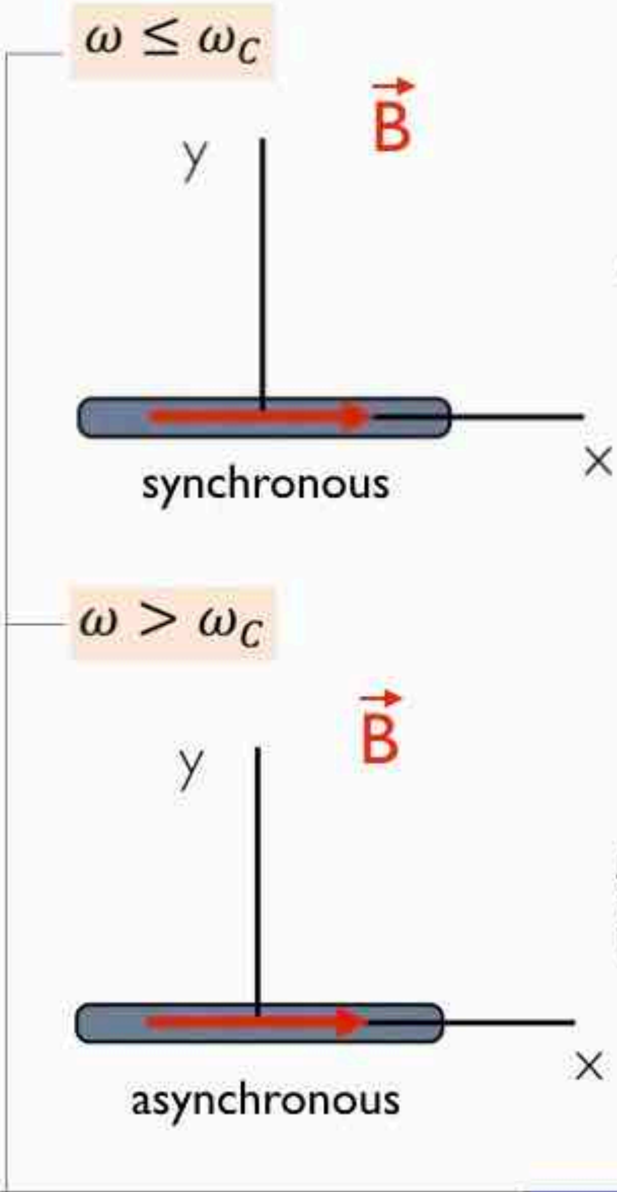
$$\frac{d\theta(t)}{dt} = \frac{\omega_C \sin 2(\omega t - \theta) + \omega\theta_0 \cos 2(\omega t - \theta)}{(1 + \theta_0 \cos 2(\omega t - \theta))} \longrightarrow \theta(t, \omega)$$

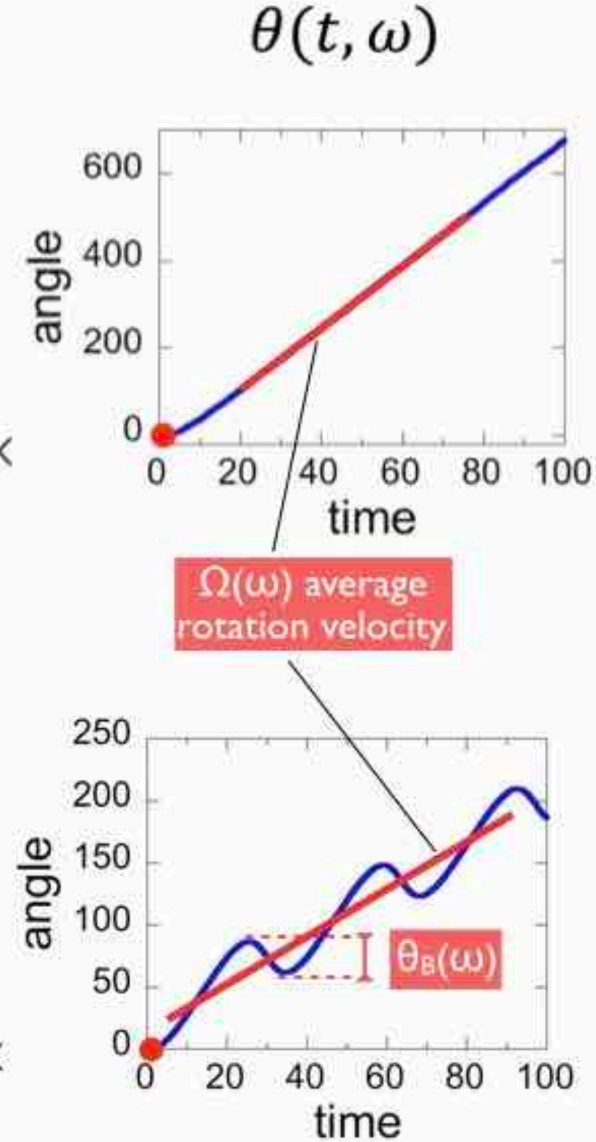
Elastic modulus (θ_0)

Viscosity (ω_C)

Predictions







$$\omega_C = \frac{3}{8\mu_0}\frac{\Delta\chi}{\eta}\frac{B^2}{L^{*2}}$$

$$\lim_{\omega\to\infty}\theta_B = \theta_0 = \frac{3}{4\mu_0}\frac{\Delta\chi}{G}\frac{B^2}{L^{*2}}$$

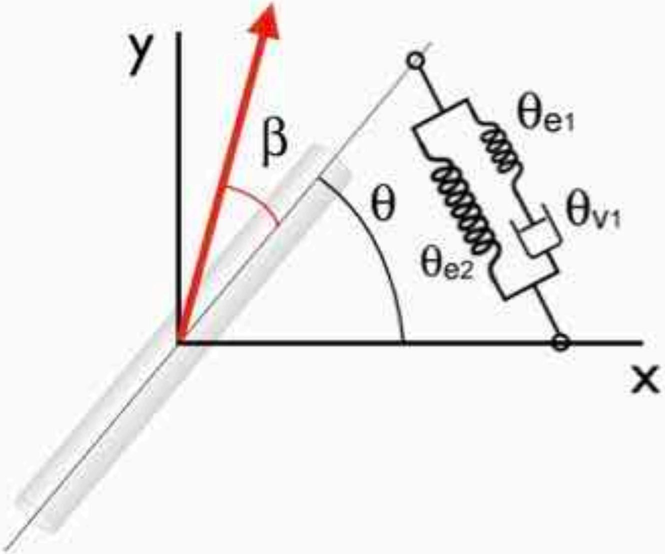
L wire length
D wire diameter
η static viscosity

H magnetic field
$\Delta\chi$ susceptibility anisotropy

L. Chevry, J.-F. Berret et al., Phys. Rev. E 88, 062306 (2013)

Predictions

- Yield stress materials
- Concentrated colloids
- Gels



Standard Linear Solid model

$$\omega_C = \frac{3}{8\mu_0}\frac{\Delta\chi}{\eta}\frac{B^2}{L^{*2}} = 0$$

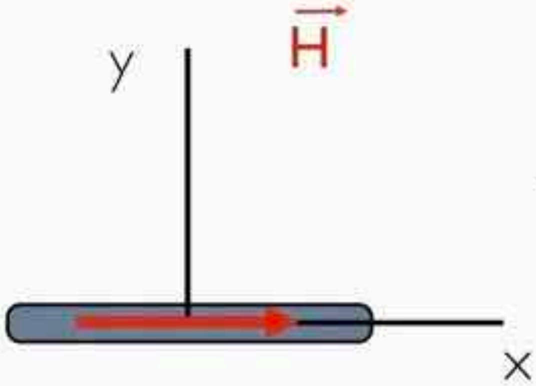
$$\lim_{\omega \to 0} \theta_B(\omega) = \frac{3}{4\mu_0}\frac{\Delta\chi}{G_{eq}}\frac{B^2}{L^{*2}}$$

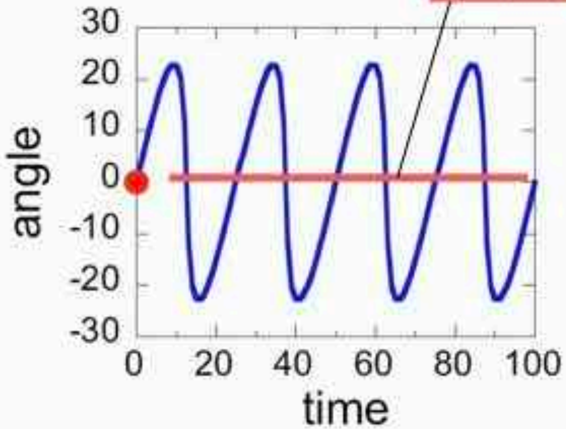
L wire length
D wire diameter
η static viscosity
G elastic modulus

→ a unique regime at all frequencies

Average rotation frequency

$\Omega(\omega)$



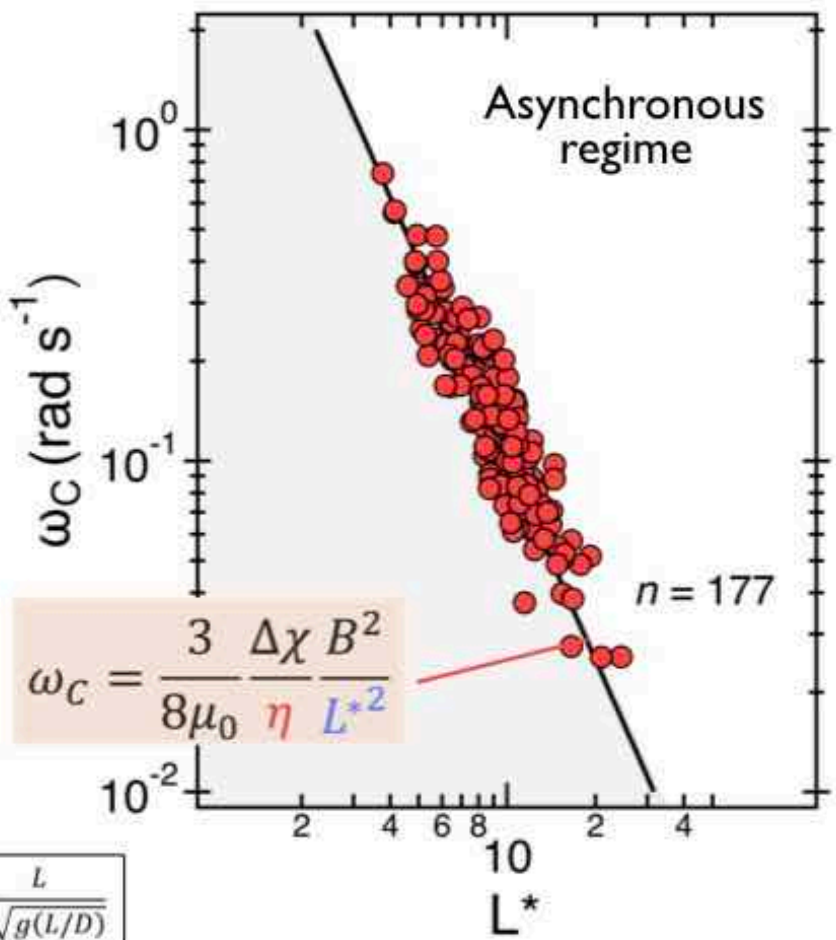


MRS differentiates viscoelastic liquid from soft solids

H. A. Barnes, J. Non-Newtonian Fluid Mech. **81**, 133–178 (1999)

How is the viscosity measured ?

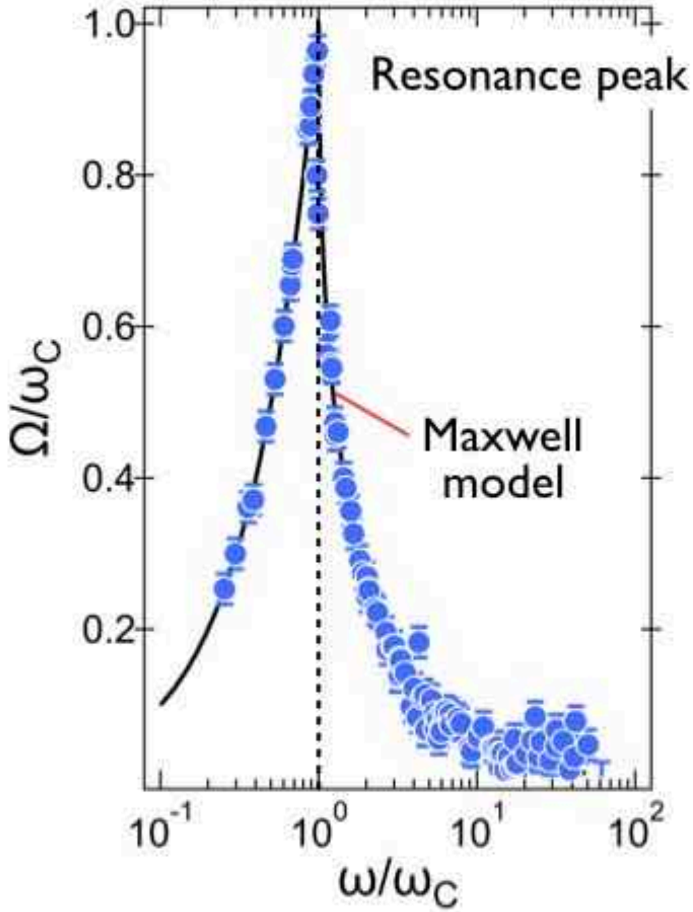
Water-Glycerol



$$\omega_C = \frac{3}{8\mu_0}\frac{\Delta\chi}{\eta}\frac{B^2}{L^{*2}}$$

$$L^* = \frac{L}{D\sqrt{g(L/D)}}$$

Wormlike micelles



Accessible ranges: Viscosity 0.001 - 1000 Pa s - Elastic modulus 0.01 - 100 Pa

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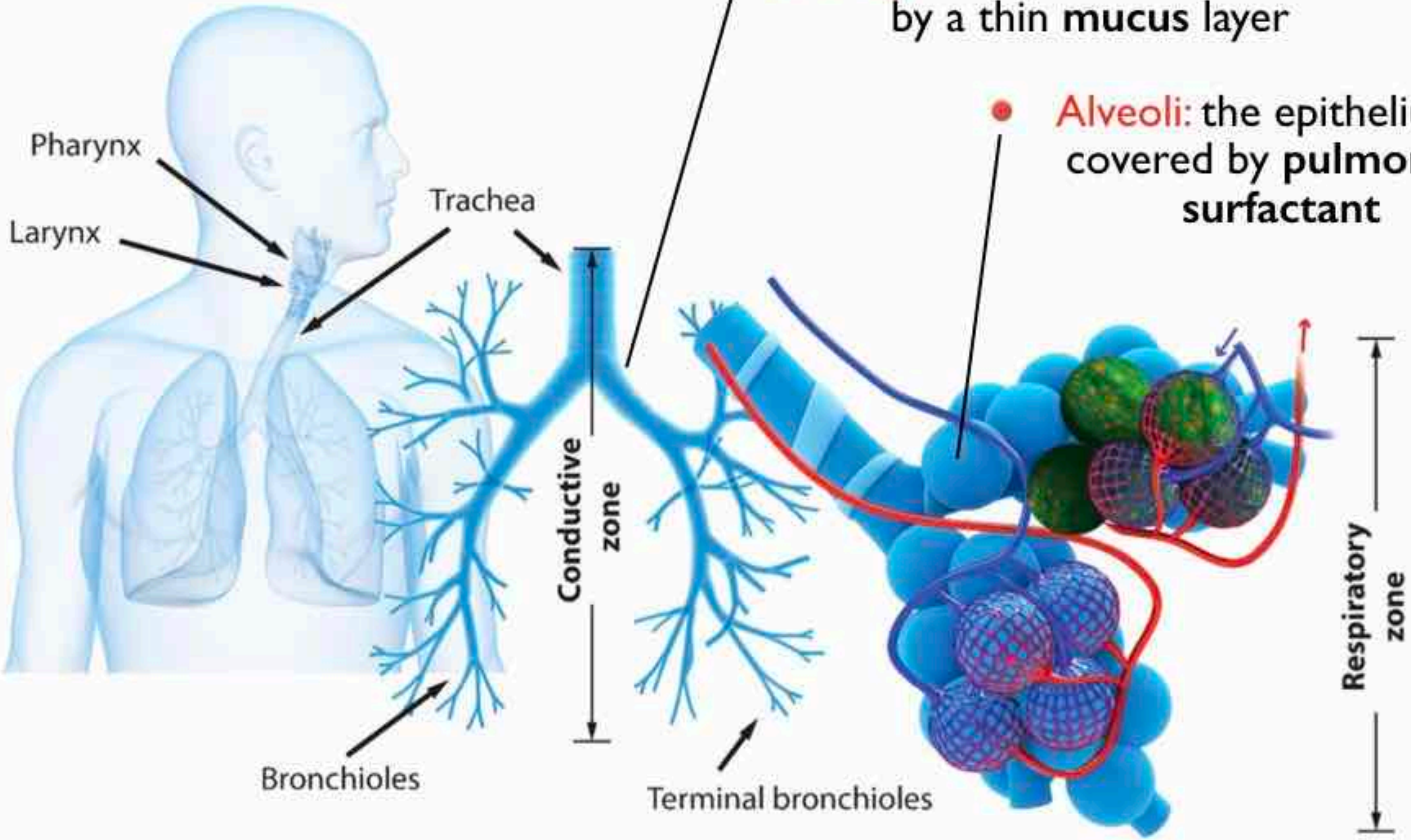
Lung fluids

Respiratory track

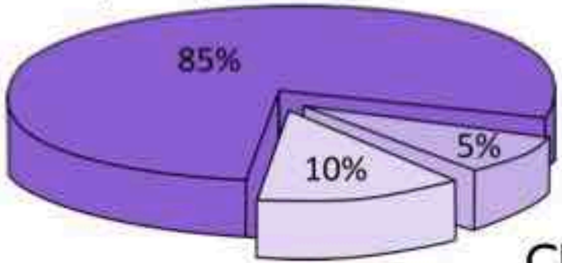
- Bronchi: the epithelium is covered by a thin **mucus** layer
- Alveoli: the epithelium is covered by **pulmonary surfactant**



P. Bajaj et al., ACS Biomater. Sci. Eng. **2,** *473 (2016)*

Pulmonary surfactant

Composition



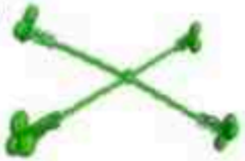
lipid/protein conc. : 40 g L^{-1}

Specific proteins

SP-A

SP-B

SP-D

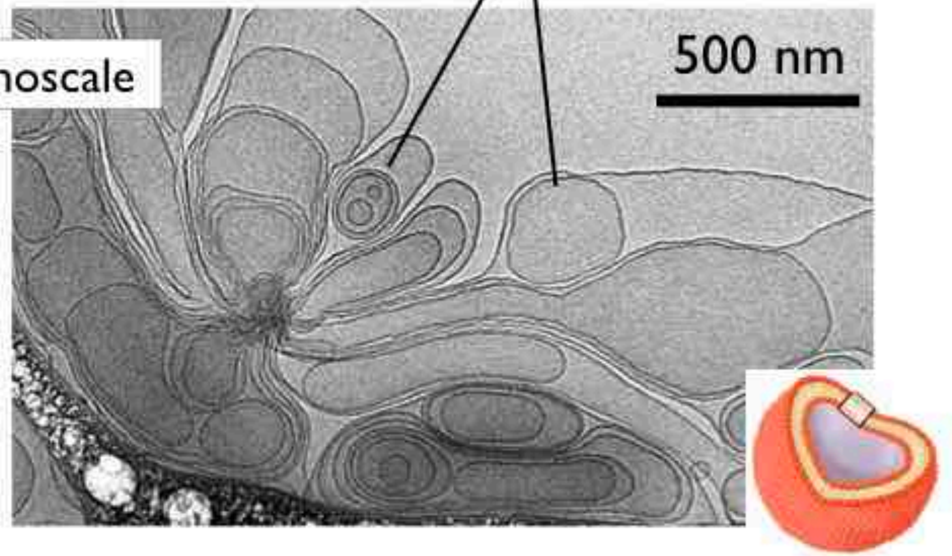


SP-C

Curosurf®

- From Chiesi (Italy)
- Porcine origin
- Administered to premature infants (< 32 weeks)
- **Multivesicular vesicles** (negatively charged)

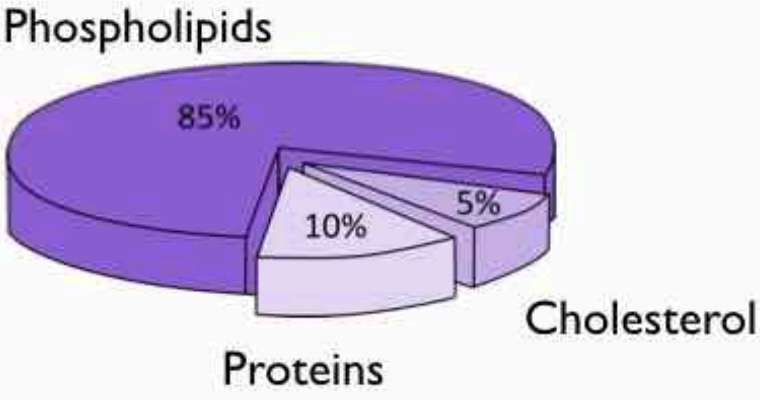
Nanoscale



Phospholipid vesicle

Pulmonary surfactant

Composition

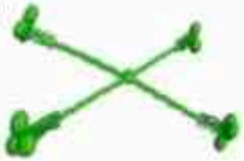


lipid/protein conc. : 40 g L^{-1}

Specific proteins

SP-A


SP-B


SP-D


SP-C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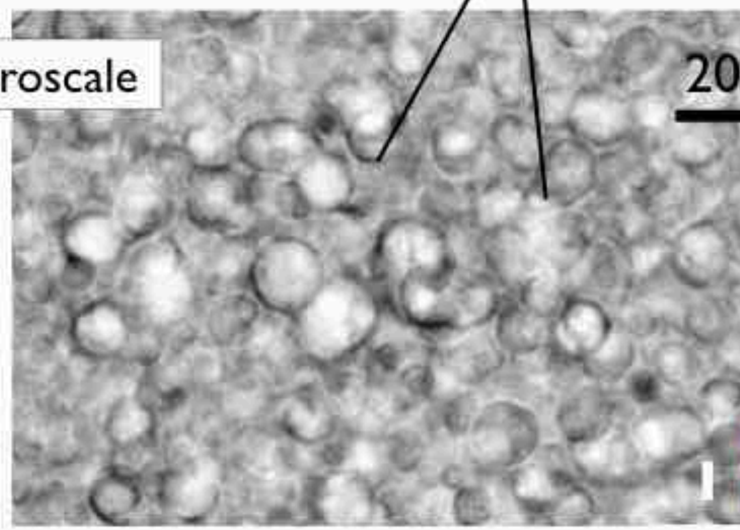
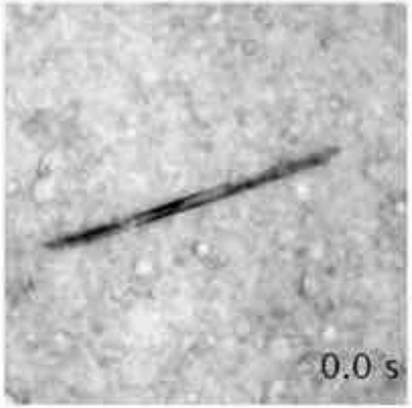
Microscale



Phospholipid vesicle

Curosurf viscosity

Synchronous rotation



20 µm

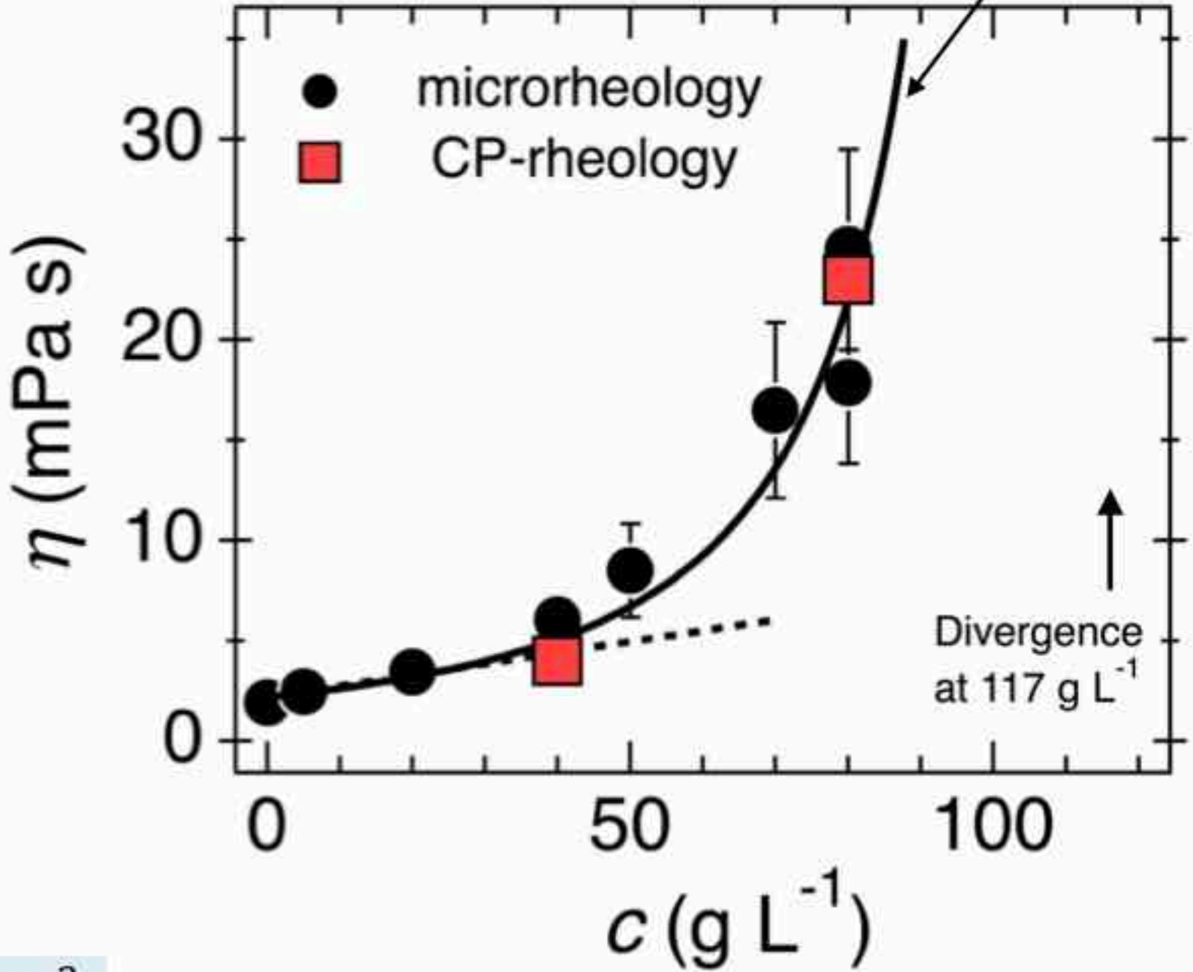
ω_C

Hindered rotation

frequency

Krieger-Dougherty

$$\eta_{K-D}(c) = \eta_S \left(1 - \frac{c}{c_m}\right)^{-2}$$



$$\omega_C = \frac{3}{8} \frac{\mu_0 \Delta\chi}{\eta} \frac{H^2}{L^2}$$

L wire length
D wire diameter
η static viscosity

H magnetic field
$\Delta\chi$ susceptibility anisotropy

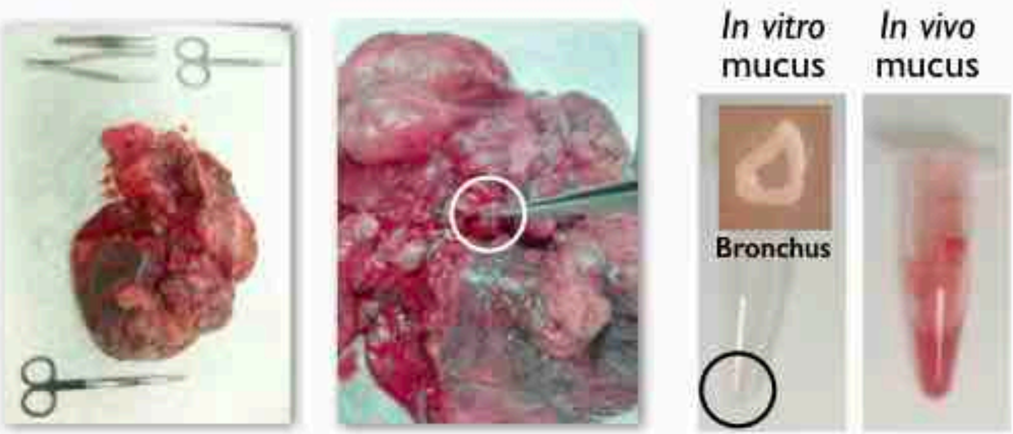
L.P.A. Thai, J.F. Berret et al., Colloids Surf. B: Biointerfaces 178, 337 (2019)

Pulmonary mucus

Healthy *versus* inflamed bronchus

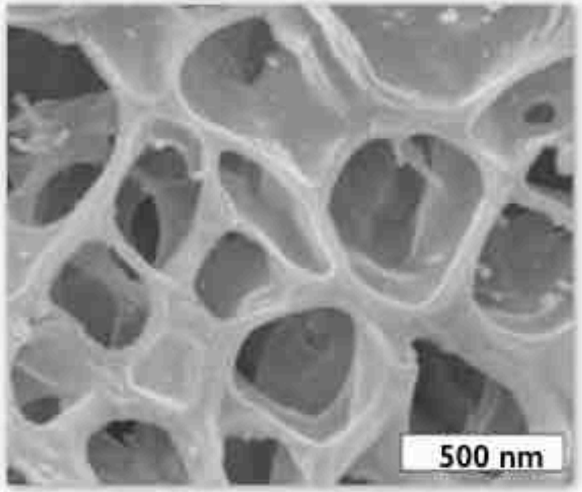
Pr. Xavier Norel
Bichat Hospital (UPC)

Human lungs from the anatomical pathology department at Bichat Hospital



Excised lung **Bronchial tube**

Mucus is a porous viscoelastic gel made from mucin proteins



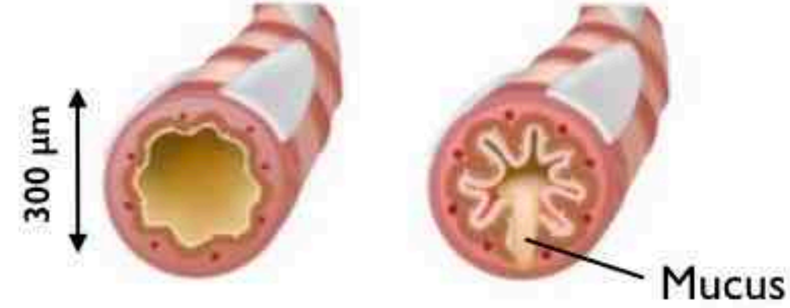
Highlights

- **First determination** of simultaneous viscosity and elasticity on human pulmonary mucus
- Mucus is a weak viscoelastic liquid with low elasticity (few Pa) and very high viscosity (few100 Pa s)

M. Radiom et al., *Soft Matter* 17, 7585 (2021)

Pulmonary mucus

Healthy *versus* inflamed bronchus



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Highlights

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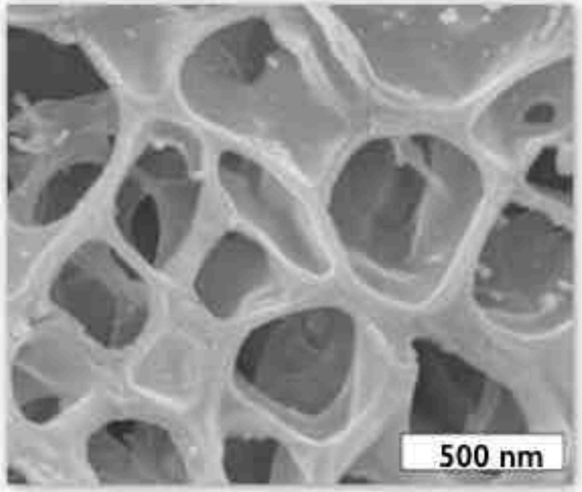
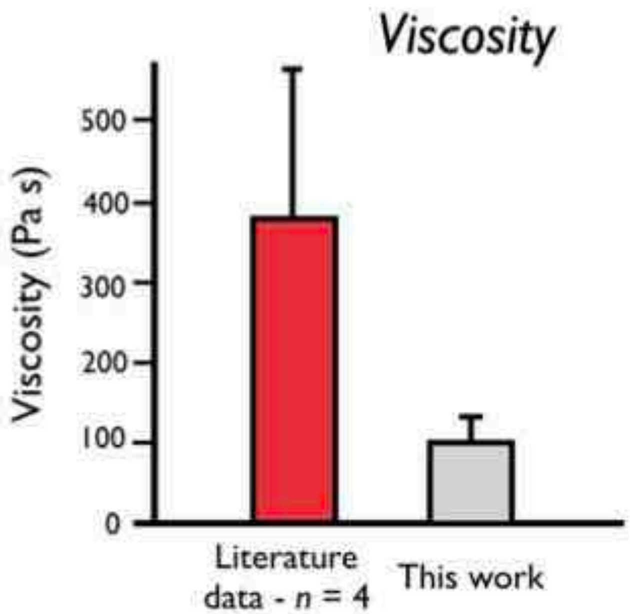
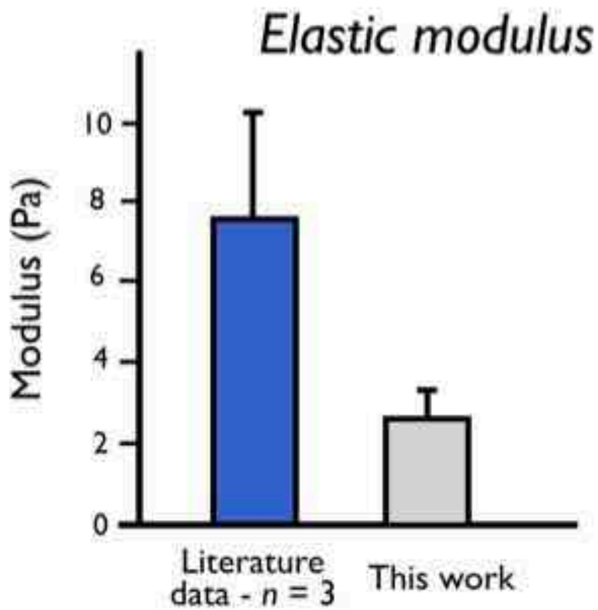






*M. Radiom et al., Soft Matter **17**, 7585 (2021)*

Conclusion

- Magnetic Rotational Spectrometry (MRS) is simple and quantitative
- It measures the rheological properties of complex fluids and materials in the ranges

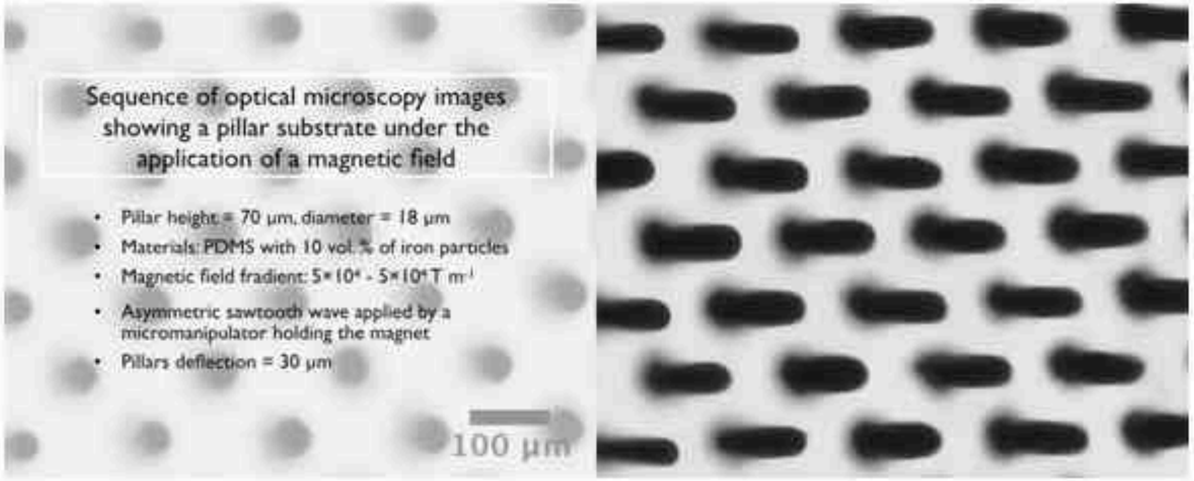
Frequency 10^{-4} - 100 Hz
Viscosity 0.001 - 1000 Pa s
Elastic modulus 0.01 - 100 Pa

- MRS has been applied to wormlike micelles, polysaccharide gels, live mammelian cells, lung fluids and bacterial amiloids
- MRS is doomed to become a classical tool for easy-to-use microrheology

Open postdoc position

24-month POST-DOCTORAL FELLOWSHIP

Lab-on-a-chip model of mucociliary clearance for the treatment of Inflammatory Lung Diseases



Interested? Please contact me at jean-francois.berret@u-paris.fr

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Andrejs Cebers

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Fernando Martínez-Pedrero

Thank you for your attention

The lecture can be found at:
https://www.jean-francois-berret-website-pro.fr