Introduction to Colloid Physics

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Boulder Summer School
Soft Matter Physics

http://www.seas.harvard.edu/projects/weitzlab

Dispersed particles

- Dispersed system
  - Particles in continuous fluid phase

Dispersed Particle	**Dispersion**
Solid	Colloid
Fluid	Emulsion
Gas	Foam

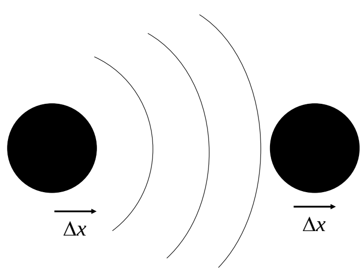
Colloidal particles

- Colloidal particles are ubiquitous
- Biology
  - Viruses, macromolecules, organelles
  - Probe particles for bioassays
  - Quantum dots for fluorescent assays
  - Spores, bacteria
- Processing
  - Paints, coatings, materials control
  - Ceramics

Colloidal particles

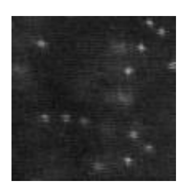
- Key → control rheology
- Solid particles behave like continuous fluid
- Process solids, while flow like fluids
- *eg* Paints and coatings
  - Spread paint like a fluid
  - Solidify into a solid coating

Continuous phase fluid



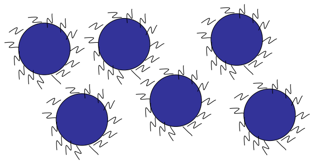
Hydrodynamic interactions

Continuous phase fluid



- Thermalization with fluid
- Equilibrates particles
- Brownian motion

Colloidal Particles



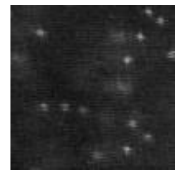
Stability:
Short range repulsion
Sometimes a slight charge

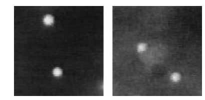
Colloid Particles are:

•Big
•~ a ~ 1 micron
•Can "see" them

Slow
• $\tau \sim a^2/D$ ~ ms to sec
•Follow individual particle dynamics

Colloidal particles undergoing Brownian motion

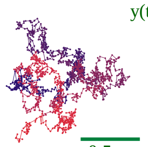


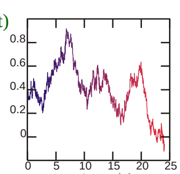


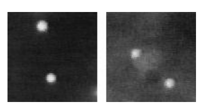
Thermal motion ensures particles are always equilibrated with the fluid
They can explore phase space

Brownian Motion

(2 μm particles, **dilute** sample)

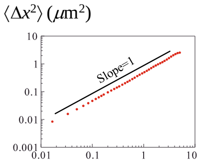




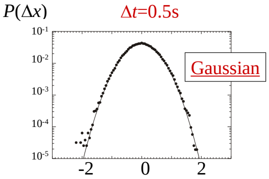


Diffusion

Mean square displacement:



Displacement distribution function:



Leads to normal diffusion: $\langle \Delta x^2 \rangle = 2Dt$ $\quad D = \dfrac{k_B T}{6\pi\eta a}$

Particle size a
viscosity η

Colloidal particles

- Ignore hydrodynamic interactions
  - Thermalize system
  - Important only for dynamics
  - No effect on static properties
- Consider just two-body interactions between particles

Colloidal particles

- Properties set by particle density
- Concentration of particles low compared to normal material
- Typical solid: ~10^{27} atoms/ m^3 (1 / nm^3)
- Colloids: ~10^{18} particles/ m^3 (1 / μm^3)
- Latent heat of phase transitions too small to measure
- Very low pressure: $\Pi = nk_BT$
- $\Pi \sim 4\text{x}10^{-21} / 10^{-18} = 4\text{x}10^{-3}$ Pa

Soft Solids

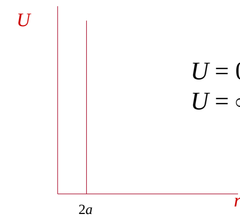
Easily deformable → Low Elastic Constant: $\frac{\text{Energy}}{\text{Volume}}$

Hard Materials	$\frac{\text{eV}}{\dot{\text{A}}^3}$	GPa
Soft Materials	$\frac{k_B T}{\mu\text{m}^3}$	1 Pa

Soft materials invariably have a larger length scale

Colloidal Interactions

Hard-sphere interactions



$$U = 0 \quad r > 2a$$
$$U = \infty \quad r \le 2a$$

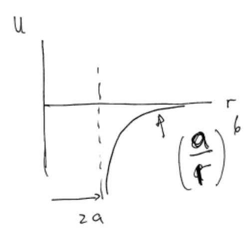
Only excluded volume

Colloidal Interactions

- van der Waals interactions
- Dispersion interactions
  - Dipole-induced dipole interactions
- Depend on polarizability of material
  - Require different materials
  - Always present for particles in a fluid

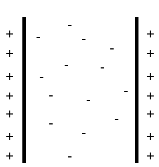
van der Waals interactions

$$U_A = -\frac{A_{\text{pmp}}}{6}\left[\frac{2a^2}{R^2 - 4a^2} + \frac{2a^2}{R^2} + \ln\left(\frac{R^2 - 4a^2}{R^2}\right)\right]$$



- Repulsive
- Short-ranged
- Dipole-dipole $1/r^6$

Stabilizing interactions



Colloidal Interactions - Stabilization

- Screened Coulomb interaction

$$U_R = 2\pi\varepsilon\psi_0^2 a(2a/R)\exp[-\kappa(R - 2a)]$$

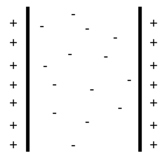
Surface potential

Inverse screening length

$$\kappa = (\varepsilon k_B T / 2z^2 e^2 n_b)^{-1/2}$$

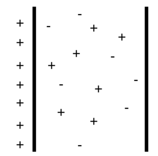
Ion density

Stabilizing interactions



Disjoining pressure:
Can’t compress ions

Destabilizing interactions



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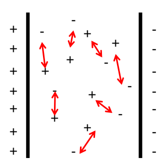
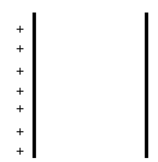


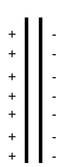
Counter ions can be neutralized

Destabilizing interactions



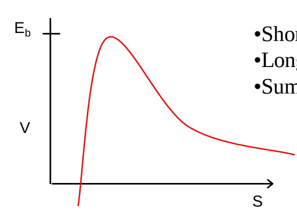
Counter ions escape

Destabilizing interactions



Attractive interaction
Not symmetric with repulsive interaction

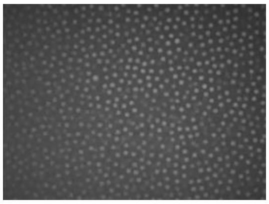
Colloidal interactions – stabilizing



- Short range attraction
- Long range repulsion
- Sum: Stabilizing barrier

$E_b > k_B T$ → Colloid stable against aggregation

Repulsive Spheres

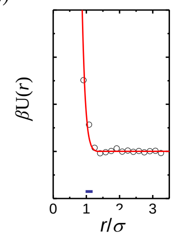


Repulsive interactions

Repulsive Spheres

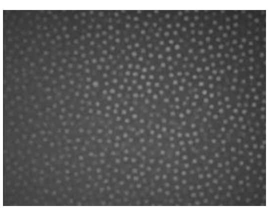
$$g(r) \propto \exp[-\beta u(r)]$$
$$\Downarrow$$
$$U = -k_B T \ln(g(r))$$

$$\beta^{-1} \equiv k_B T$$

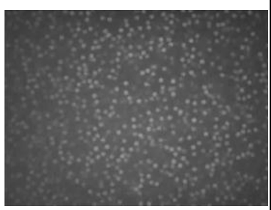


Screen charges

No Salt



Salt



Screen charges

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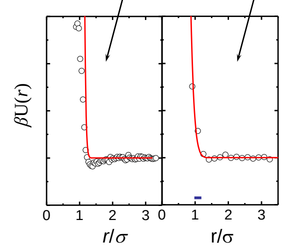
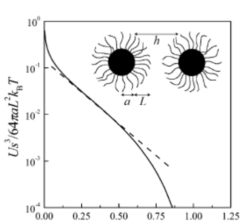


Steric Interactions

- Repulsive interaction
- Due to elasticity polymer brush
- Osmotic effect

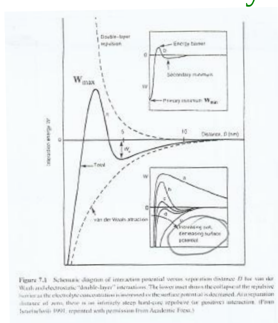


•Depends on thickness of brush
•Can be much less than *a*
•Thin brush → hard-sphere like

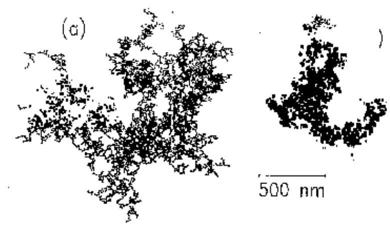
Colloidal interactions – destabilizing

- Add electrolyte → screen repulsion
- Reduce steric repulsion
- Always have van der Waals attraction
  - Colloids are inherently unstable
- Can also induce controlled attraction

Colloidal Stability



Colloidal Aggregation



Colloidal Gold

COLLOIDAL GOLD

TRADITIONAL COLLOID:

- FARADAY (1850's)
- ZSIGMONDY, SMOLUCHOWSKI (AGGREGATION)
- TURKEVITCH (TEM).
- MEDICAL, BIOPHYSICAL USES.
- SERS.

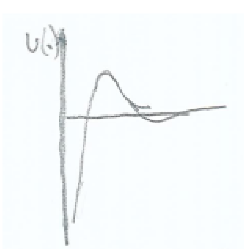
PROPERTIES:

- OPTICAL ABSORPTION RESONANCE:
  WINE RED → BLUE (ON AGGREGATION)
- 75 Å RADIUS
- UNIFORM $\left(\frac{\Delta R}{R} \sim 10\%\right)$
- $\sim 10^{12} / cc \Rightarrow$ SEPARATION ~ 120 RADII
- $D \sim 5 \times 10^{-7}\,\mathrm{cm}^2/\mathrm{sec}$ (DIFFUSIVE MOTION)
- MASS $\sim 10^{-17}$ gm $\rightarrow$ $\sim 10^{-18}$ U.S. $
- 1 GAL. = 5¢ U.S. = PROFIT ON 1 GAL. GAS.

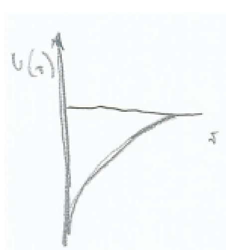
AGGREGATION:

- STABILIZED BY CHARGED IONS ON SURFACE
- ADD NEUTRAL ORGANIC (PYRIDINE)
  - DISPLACE CHARGE
- FORM GOLD-GOLD BONDS, >>*kT*
  - IRREVERSIBLE
  - KINETIC
  - NON-EQUILIBRIUM

Colloidal Stability



Partial Stability
→ Many collisions to stick

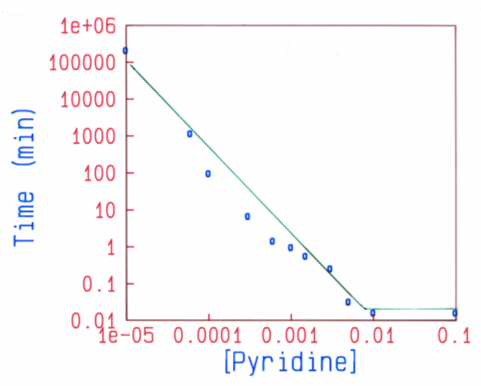


No Stability
→ Sticks every collision

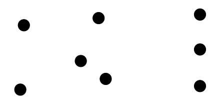
Effect of energy barrier

$$\exp\left\{-\frac{U_{max}}{kT}\right\}$$

$$t_{U_{max}} \sim \frac{R^2}{D_0} \Big/ \exp\left\{-\frac{U_{max}}{kT}\right\}$$



Dilute, stable suspension



R

$$D = \frac{kT}{6\pi\eta R}$$

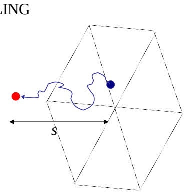
ϕ

Destablize

Irreversible aggregation

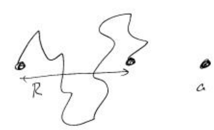
Rate-limiting step: diffusion-induced collision

DIFFUSION-INDUCED COLLISIONS.
HOW LONG DOES THIS TAKE?
- DIFFUSION EQUATION
- SCALING



$s \sim c^{-1/3}$

1. $\tau \sim \frac{s^2}{D} \sim \frac{1}{DC^{2/3}}$ **WRONG!**



Volume : $s a^2$

contour length : s = # steps × step length

$= \left(\frac{R}{a}\right)^2 a$

$= \frac{R^2}{a}$

Volume : $R^2 a$

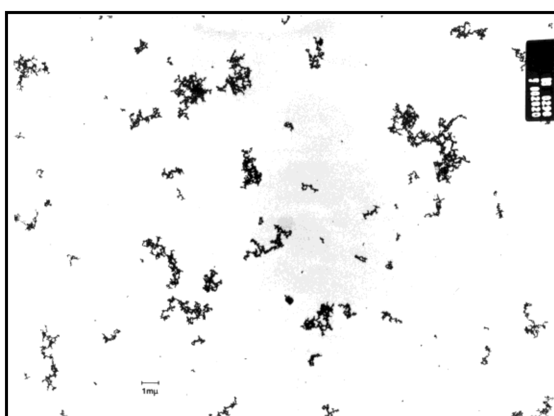
time : $\frac{R^2}{D}$

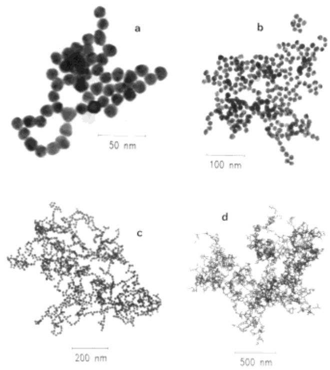
volume / time = Da

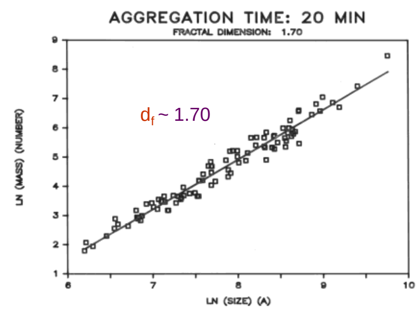
Volume required = $\frac{1}{c}$

$t = \frac{1}{caD}$

Rate : $\tau^{-1} = caD$







FRACTAL:

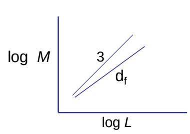
- SELF-SIMILAR

  NO CHARACTERISTIC LENGTH SCALE

$$M \sim R^{d_f}$$

d_f: FRACTAL DIMENSION

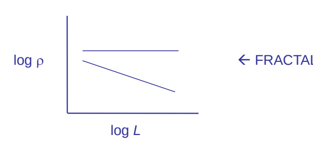
NON-INTEGRAL



$d_f < d$

DENSITY: DECREASES WITH SIZE

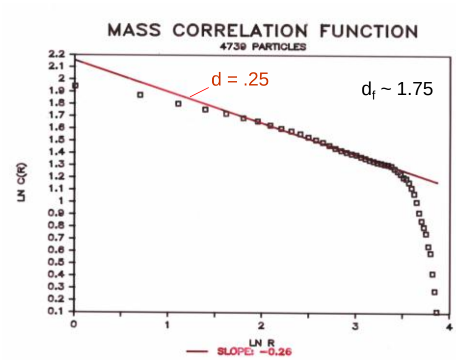
$$\rho = \frac{M}{V} = \frac{L^{d_f}}{L^d} = L^{d_f - d}$$



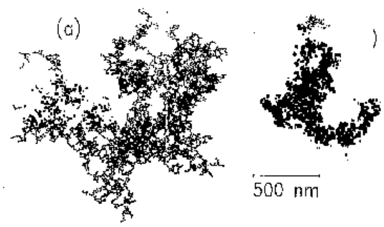
MASS CORRELATIONS:

3d: $c(r) \sim \frac{1}{r^{3-d_{f3}}}$

2d: $c(r) \sim \frac{1}{r^{2-d_f}}$

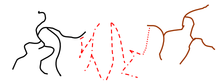


Colloidal Aggregation

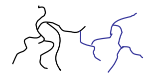


Colloidal Gold

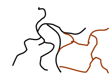
DIFFUSION – REACTION – LIMITED AGGREGATION



DIFFUSE MOTION



DIFFUSION-LIMITED
STICKS WHERE IT FIRST TOUCHES



REACTION-LIMITED
MUST COLLIDE MANY TIMES
DIFFUSIVE MOTION NOT IMPORTANT.

DIMENSIONS:

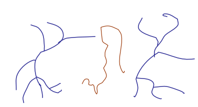
d: Euclidean dimension of space
d = 3 real space
d = 2 surface

d_f: Fractal dimension
Amount of volume occupied by a space filling object is $M \sim R^{d_f}$

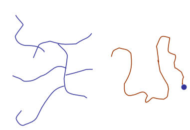
d_t: Trajectory dimension
Fractal dimension of trajectory

Random walk:	$d_t = 2$
Ballistic motion:	$d_t = 1$
No motion	$d_t = 0$

DIFFUSION-LIMITED CLUSTER AGGREGATION



$d_f^1 + d_f^2 + d_t = 1.75 + 1.75 + 2 > 3.$



$d_f^1 + d_f^2 + d_t = 1.75 + 0 + 2 > 3.$

NO INTERPENETRATION
BUT CLUSTERS STICK WITH OTHER CLUSTERS

$\therefore d_f \sim 1.8$ in 3-d.

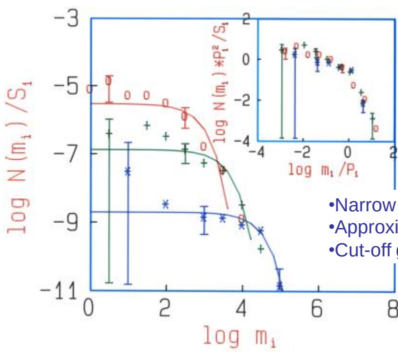
Time evolution: Smoluchowski Equations

$$\frac{dN(m_i)}{dt} = \frac{1}{2}\sum_{j=1}^{i-1} K_{j,i-j} N(m_j) N(m_{i-j}) - \sum_{j=1}^{\infty} K_{i,j} N(m_i) N(m_j),$$

Scaling solutions

Cluster mass distribution

Diffusion-limited aggregation



- •Narrow distribution
- •Approximately constant
- •Cut-off grows in time

Cluster mass distribution

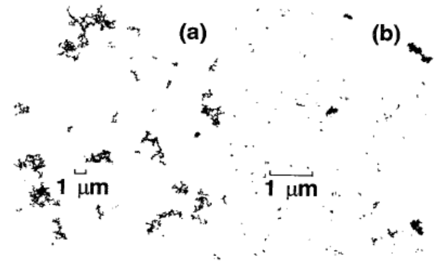
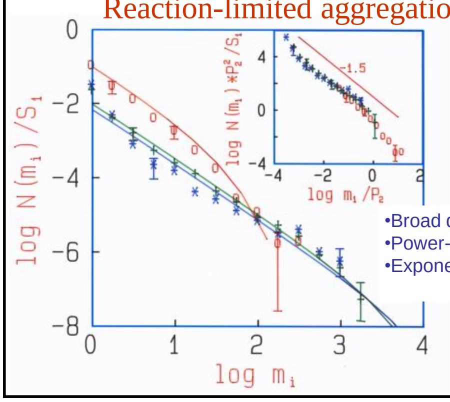


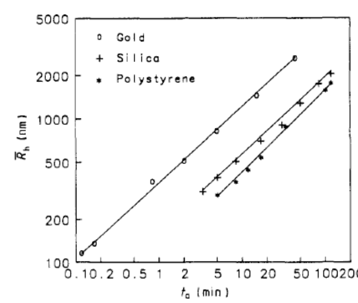
FIG. 1. Typical TEM images of clusters formed by (a) diffusion-limited aggregation and (b) reaction-limited aggregation. The aggregate's fractal dimensions and the cluster-mass distributions are clearly different for the two regimes.

Reaction-limited aggregation



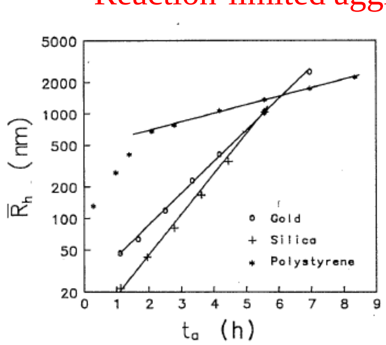
- •Broad distribution
- •Power-lay
- •Exponential growth in time

Diffusion-limited aggregation



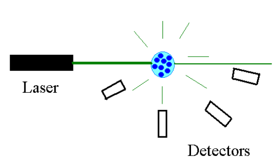
Linear growth in time

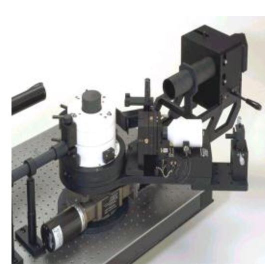
Reaction-limited aggregation



Exponential growth in time

Light Scattering





Static Scattering: Structure

Scattered field from single particle

$$E_m(q) = A_m e^{i\vec{q}\cdot\vec{r}_m} e^{-i\omega t}$$

Scattered intensity per particle — Phase factor — Frequency of light

Measure the scattered intensity from collection of particles

$$I(q) = \sum_{m,n} E_m E_n^* = \sum_{m,n} A_m A_n e^{i\vec{q}\cdot(\vec{r}_m - \vec{r}_n)} = P(q) S(q)$$

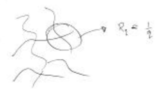
Form factor — Structure factor

- Measure *q* dependence of scattering
- Probes spatial Fourier Transform of density correlations

Scattering from fractals

$$I(q) \simeq N_q(R_q)\, m_q^2$$

$$= \frac{M_T}{m_q} m_q^2$$



$$\simeq M_T\, m_q$$

$$\simeq M_T\, R_q^{d_f}$$

$$N(R_q) = \frac{M_T}{M_q} \qquad = \frac{M_T}{q^{d_f}}$$

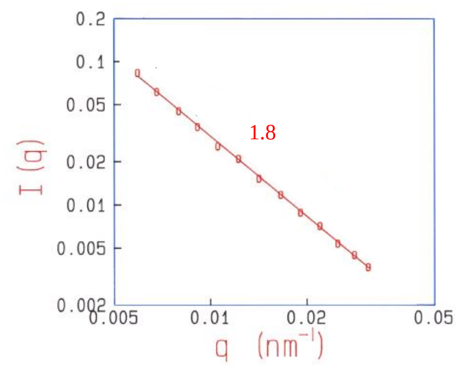
MASS CORRELATIONS:

$$I(q) = \sum_M N(M) I_M(q)$$

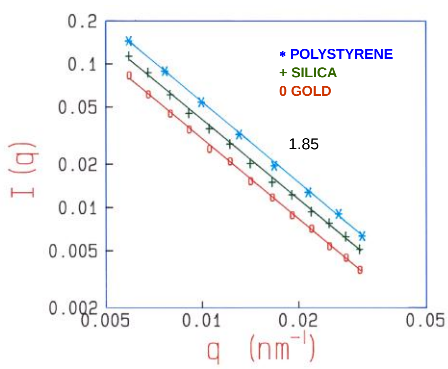
$$I_M(q) = AM^2 S(qR_g).$$

$$S(qR_g) = \begin{cases} 1 & \text{for } qR_g \ll 1 \\ (qR_g)^{-d_f} & \text{for } qR_g \gg 1. \end{cases}$$

Static scattering from diffusion-limited aggregates



DIFFUSION-LIMITED COLLOID AGGREGATION

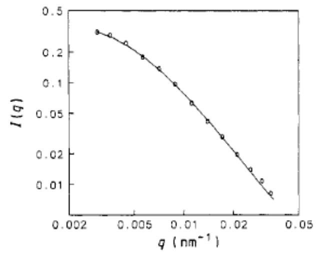


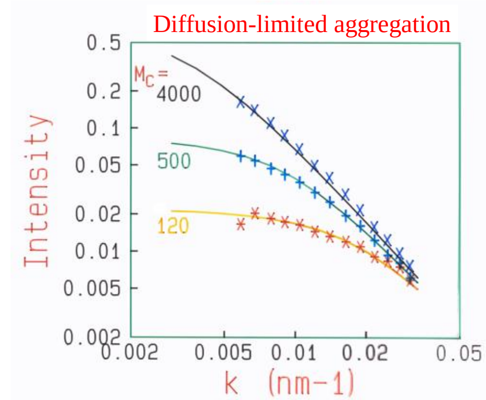
Fisher-Burford

$$S(qR_g) = \left(1 + \frac{1}{3}\frac{2}{d_f}(qR_g)^2\right)^{-d_f/2}$$

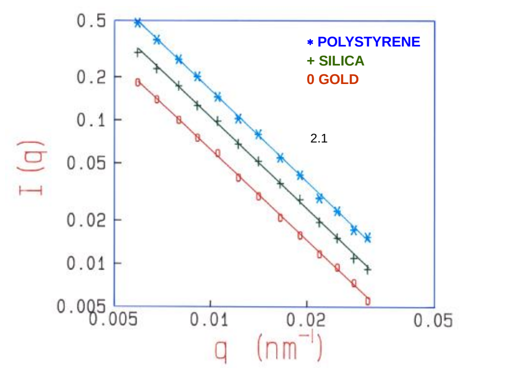
$$qR_g \ll 1 : \quad S(qR_g) = 1 - \frac{1}{3}(qR_g)^2$$

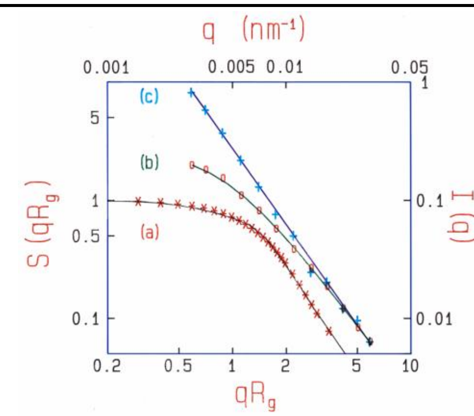
$$qR_g \gg 1 : \quad S(qR_g) \sim (qR_g)^{-d_f}$$



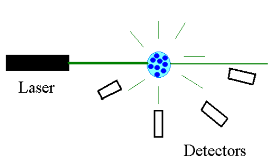


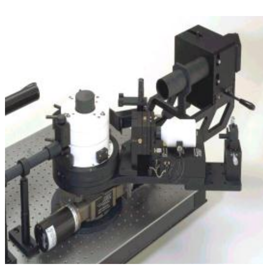
REACTION-LIMITED COLLOID AGGREGATION



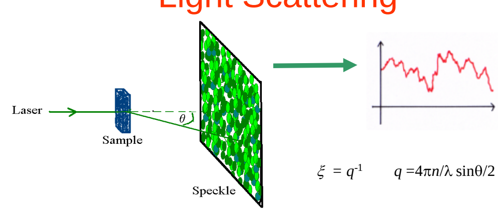


Dynamic Light Scattering





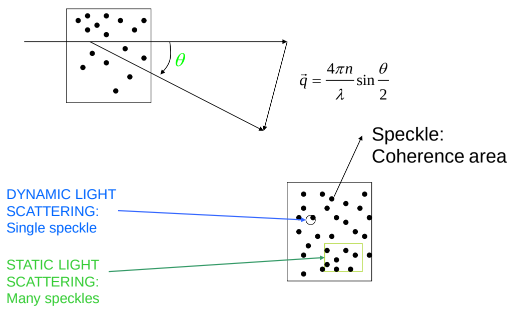
Structure and Dyanmics: Light Scattering



- SLS: $< I >$ vs. q ⟶ probe structure
- DLS: $< I(q,t)I(q,t+\tau) >$ ⟶ probe dynamics $f(q,\tau)$

Light Scattering

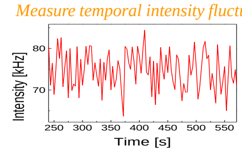
Probes characteristic sizes of colloidal particles



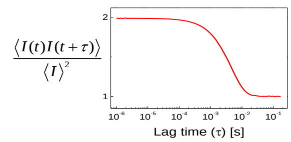
$$\vec{q} = \frac{4\pi n}{\lambda}\sin\frac{\theta}{2}$$

Dynamic Light Scattering

Measure temporal intensity fluctuations



Obtain an intensity autocorrelation function



Dynamic Light Scattering

Measure temporal correlation function of scattered light:
Intermediate structure factor

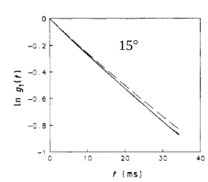
$$f(q,t) \sim \langle E(0)E(t)\rangle$$

$$\langle E(0)E(t)\rangle = \left\langle A^2 \sum_{m,n} e^{i\vec{q}\cdot\{\vec{r}_m(0)-\vec{r}_n(t)\}}\right\rangle$$ Time average over all particles

$$\sim e^{-q^2\langle \Delta r^2(t)\rangle}$$ Correlations only between the same particles
Cumulant expansion: $\Delta r^2(t) \sim Dt$

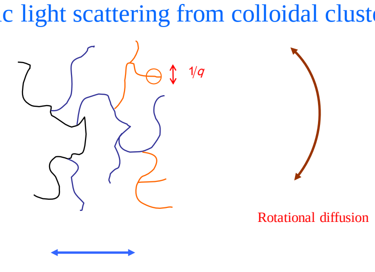
$$\sim e^{-q^2 Dt}$$ Physics: How to change the phase of the field by π
Each particle must move by $\sim\lambda$

Dynamic light scattering from colloidal clusters



Small angle → don't resolve internal motion

Dynamic light scattering from colloidal cluster



$$S(k,t) = \sum_l S_l(k) e^{-Dk^2 t}$$

Dynamic light scattering from colloidal cluster

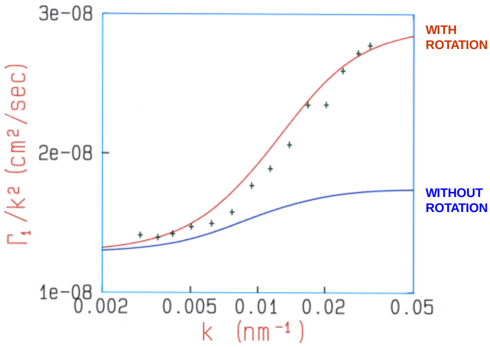
$$S(k,t) = \sum_l S_l(k) e^{-Dk^2 t} e^{-l(l+1)\Theta t}.$$

$$g_1(t) = \frac{1}{I(q)} \sum_M N(M) M^2 \exp(-q^2 Dt) \sum_{l=0}^{\infty} S_l(qR_g) \exp[-l(l+1)\Theta t].$$

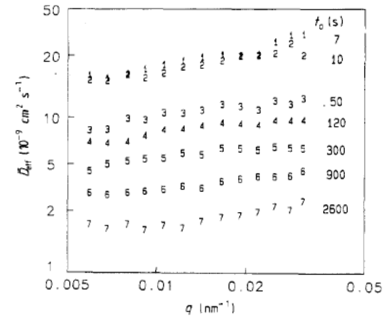
$$g_1(t) = \frac{1}{I(q)} \sum_M N(M) M^2 S(qR_g) \exp(-q^2 D_{\mathrm{eff}} t).$$

$$\bar{D}_{\mathrm{eff}} = \frac{\sum_M N(M) M^2 S(qR_g) D_{\mathrm{eff}}}{\sum_M N(M) M^2 S(qR_g)}.$$

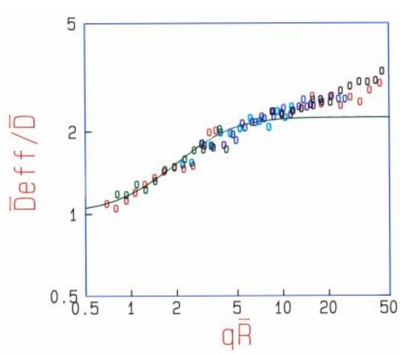
Diffusion-limited colloid aggregation



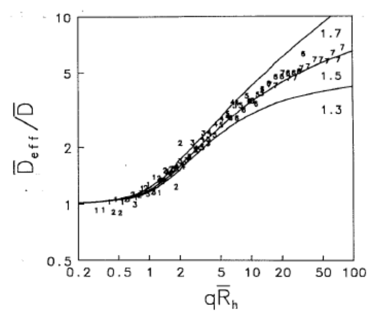
Dynamic light scattering from colloidal clusters
Time evolution



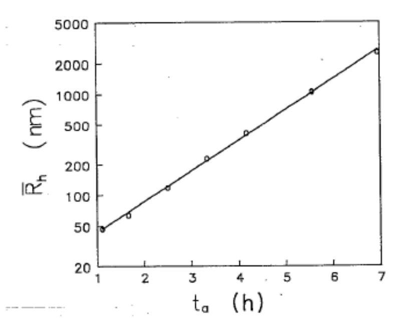
Diffusion-limited colloid aggregation



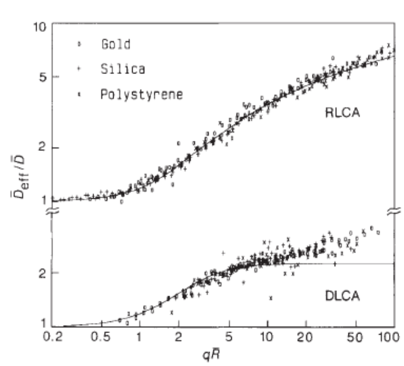
Effective diffusion coefficients for colloidal clusters
Power-law distribution



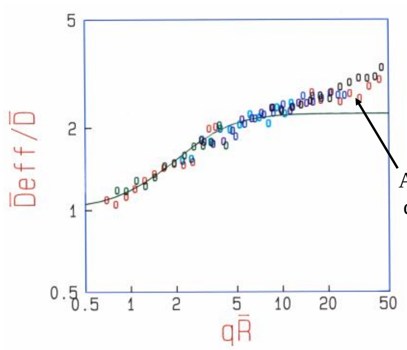
Dynamic light scattering from colloidal clusters
Time evolution → Exponential growth



Universal Behavio

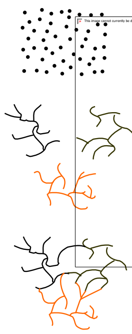


Diffusion-limited colloid aggregation



Additional dynamics

DIFFUSION-LIMITED GELATION



MASS	NUMBER	VOLUME FRACTION
M_0	N_0	Φ_0

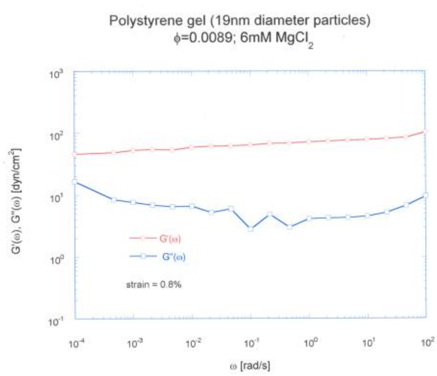
$$M_c \simeq \left(\frac{R_c}{a}\right)^{d_f}$$

$$N_c = \frac{N_o}{M_c} = N_0\left(\frac{R_c}{a}\right)^{-d_f}$$

$$\phi_c = \frac{V_c}{V} N_c = \frac{R_c^3}{V} N_0 \left(\frac{R_c}{a}\right)^{-d_f} = \phi_0\left(\frac{R_c}{a}\right)^{3-d_f}$$

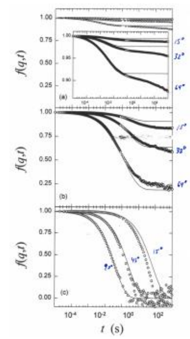
$$\phi_g = \phi_c = 1$$

$$R_c = a\phi_0^{1/3-d_f} \sim \phi.$$



DYNAMIC LIGHT SCATTERING FROM COLLOIDAL GEL

BOUYANCY-MATCHED POLYSTYRENE ***a* = 9.5 nm**



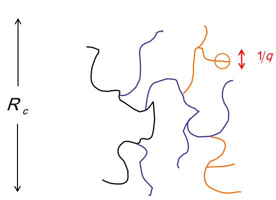
ϕ_0

5.0×10^{-3}

1.5×10^{-3}

1.7×10^{-4}

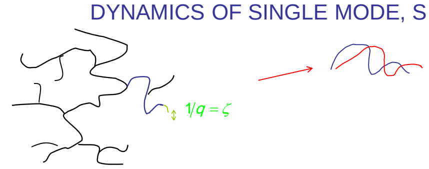
DYNAMICS OF A FRACTAL COLLOIDAL GEL



- CONSIDER BLOB OF SIZE $1/q = R_q$
- MOTION DUE TO FLUCTUATIONS OF ALL OTHER CONNECTED BLOBS
  - INDEPENDENT MODES
  - OVERDAMPED

LARGER BLOBS: LARGER DISPLACEMENT
SLOWER TIMESCALES

DYNAMICS OF SINGLE MODE, S



CONSTRAINED BROWNIAN MOTION $\left\langle \Delta r_\zeta^2(t)\right\rangle_s = \frac{kT}{k(s)n(s)}\left[1-e^{-t/\tau(s)}\right]$

1. SPRING CONSTANT: $k(s) = k_0\left(\frac{s}{a}\right)^{-\beta}$ — SINGLE PARTICLE SPRING CONSTANT

SIZE DEPENDENT

KANTOR-WEBMAN $\beta = 2 + d_B$ → "BOND" DIMENSION

2. TIME CONSTANT: $\tau(s) = \frac{6\pi\eta s}{k(s)}$

VISCOUS DAMPING

3. MAXIMUM AMPLITUDE: $\delta_m^2 = \frac{kT}{k(s)n(s)}$

kT / NORMAL MODE

n(s): DENSITY OF LOCAL MODES

$n(s) = N_c\left(\frac{a}{s}\right)^{d_f}$

DISPLACEMENT OF REGION OF SIZE $\xi = \frac{1}{q}$

- SUM CONTRIBUTIONS OF ALL SIZES, S $\frac{dn(s)}{ds}$
- USE DENSITY OF MODES

$$\langle \Delta r_\xi^2(t) \rangle = 2d_f kt \int_\xi^{R_c} \frac{ds}{sk(s)}\left[1 - e^{-t/\tau(s)}\right]$$

- CAN BE DONE ANALYTICALLY
- FUNCTIONAL FORM IS:

$$\langle \Delta r_\xi^2(t) \rangle = \delta^2 \left[1 - e^{-(t/\tau)^P}\right]$$

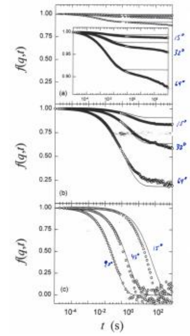
→INITIAL DECAY: STRETCHED EXPONENTIAL

→DECAYS TO A PLATEAU: δ^2

$$f(q,t) = \exp\left\{-q^2 \langle \Delta r^2_{\xi = \frac{1}{q}}(t) \rangle\right\}$$

DYNAMIC LIGHT SCATTERING FROM COLLOIDAL GEL

BOUYANCY-MATCHED POLYSTYRENE ***a* = 9.5 nm**



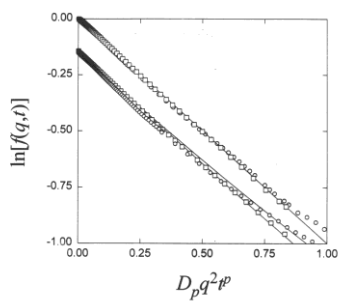
ϕ_0

5.0×10^{-3}

1.5×10^{-3}

1.7×10^{-4}

SCALING STRETCHED EXPONENTIAL



$P = 0.66$

ELASTIC MODULUS OF GEL

DETERMINED DIRECTLY BY δ²

↳ SET BY AVERAGE CLUSTER SIZE

ϕ_0 DEPENDENCE

$\sim \delta^2 \rightarrow \delta^2 k(R_c) \simeq kT$

$$G(\phi_0) = \frac{k(R_c)}{R_c} = k_0 a^\beta R_c^{-1-\beta}$$

$$\Rightarrow \frac{\delta^2}{R_c} \sim \tau$$

BUT $R_c \sim \phi_0^{\frac{1}{d_f - 3}}$

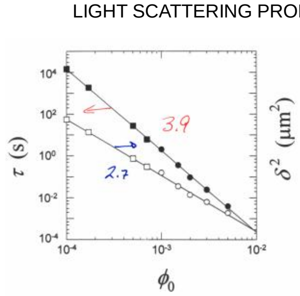
$$G(\phi_0) \sim \phi_0^{\frac{-(1+\beta)}{d_f-3}} \sim \phi_0^{3.7}$$

EXPERIMENT: 3.9

→ MEASURE MODULUS OPTICALLY!

VOLUME FRACTION DEPENDENCE

LIGHT SCATTERING PROBE OF MODULUS



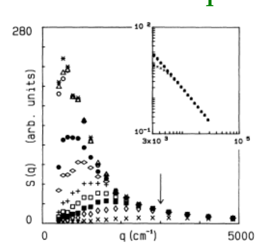
$G \simeq \frac{k_c}{R_c}$

BUT $\tau_c \sim \frac{R_c}{k_c}$

$G \sim \phi^{3.9}$

R_c ONLY LENGTH IN PROBLEM

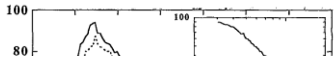
Hints of equilibrium behavior



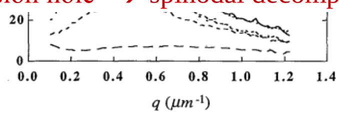
SALS from aggregating colloids

Carpineti & Giglio, *PRL* **68**, 3327 (1992)

Hints of equilibrium behavior



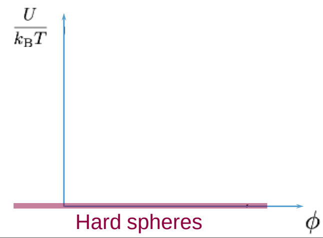
Real-space simulations:
- •Diffusion & aggregation of particles
- •"Diffusion hole" → spinodal decompostion



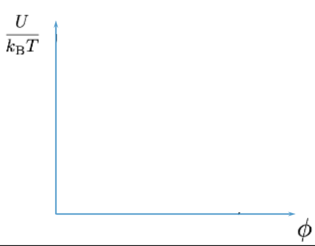
Similar behavior for sticky emulsions

Bibette *et al*, *PRL* **69**, 981 (1992)

State diagram for colloidal particles

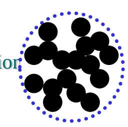


State diagram for colloidal particles

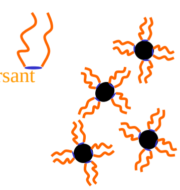


Carbon Black in Oil

Problem:
- •Large Effective Particle Volume Fraction
- •Due to aggregate formation
- •Difficult to control viscosity

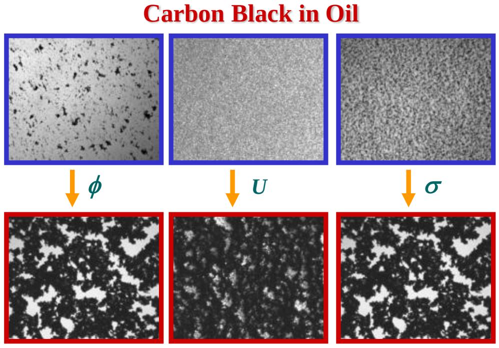


Solution:
- •Add additive package – primarily dispersant
- •Disperse soot particles

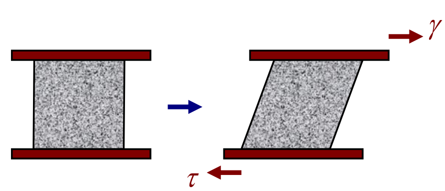


Gelation of Attractive Particles

Carbon Black in Oil



Viscoelasticity of Soft Materials



$\gamma = \gamma_0 e^{i\omega t}$

Solid: $\tau = G\gamma$

Fluid: $\tau = \eta\dot{\gamma}$

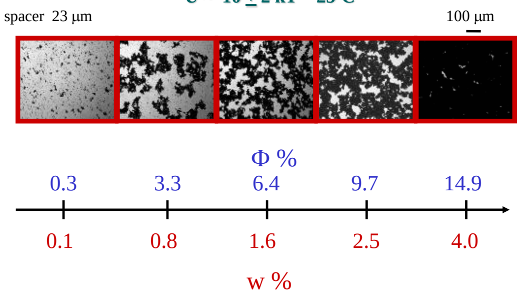
$\longrightarrow \tau = \left[G'(\omega) + iG''(\omega)\right]\gamma$

Elastic Viscous

Effect of Volume Fraction

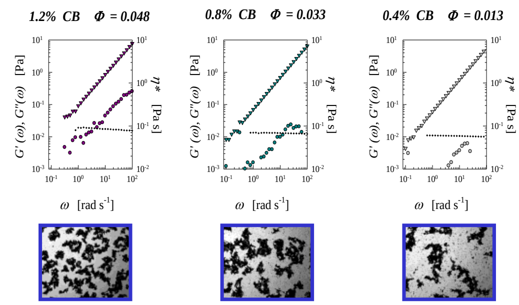
Carbon Black in S150N

U ~ 10 + 2 kT 25°C



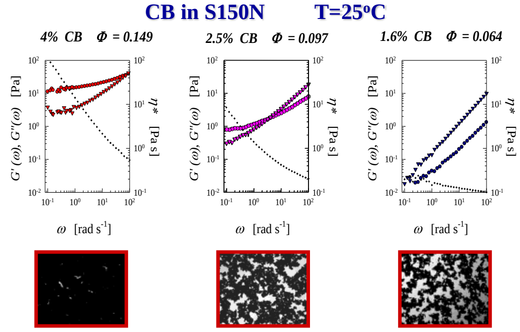
Fluid-Like Behavior

Carbon Black in S150N T=25°C



Solid-Like Behavior

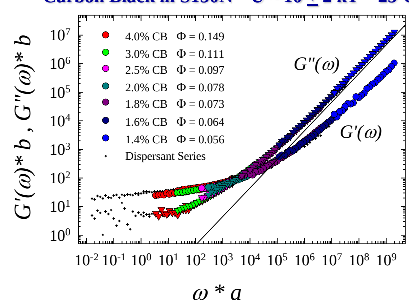
CB in S150N T=25°C



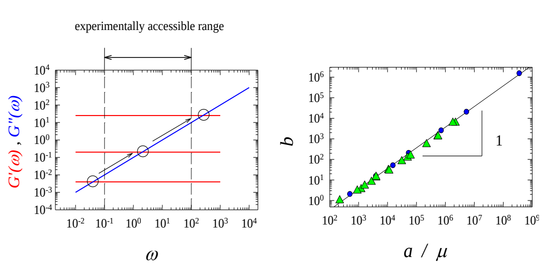
Scaling

ϕ-Dependence

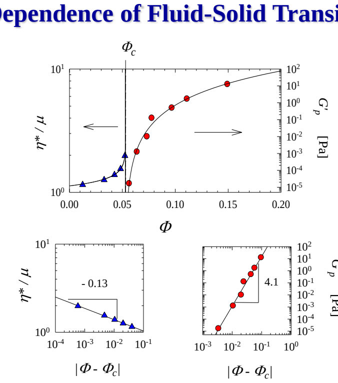
Carbon Black in S150N U ~ 10 + 2 kT 25°C



Scaling along the background-viscosity

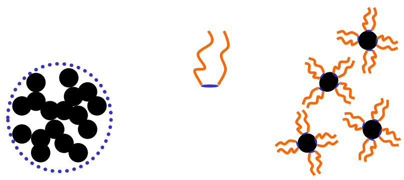


ϕ-Dependence of Fluid-Solid Transition



Effect of Dispersant

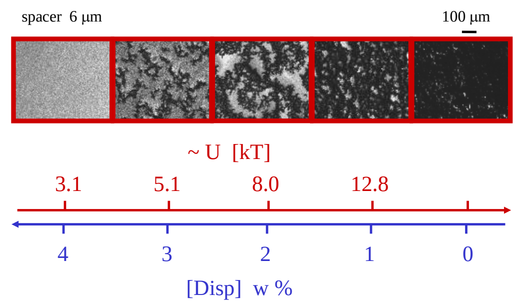
Decrease Interaction Energy
Decrease Aggregation



Amount of Dispersant controls Interaction Energy

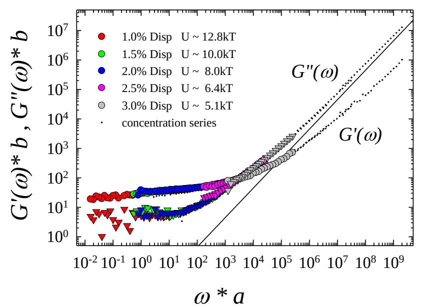
Effect of Dispersant Concentration

Carbon Black in Oil $\phi = 0.14$ 100ºC

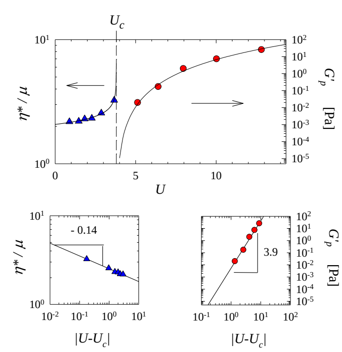


Scaling: *U-Dependence*

Carbon Black in S150N ϕ ~ 0.14 *T*=25ºC

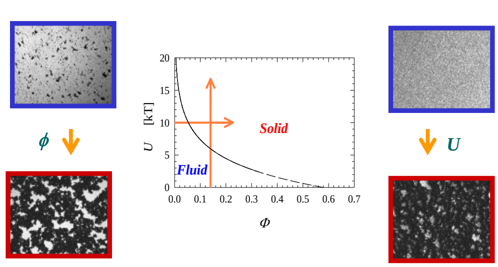


Fluid-Solid Transition *U*-Dependence



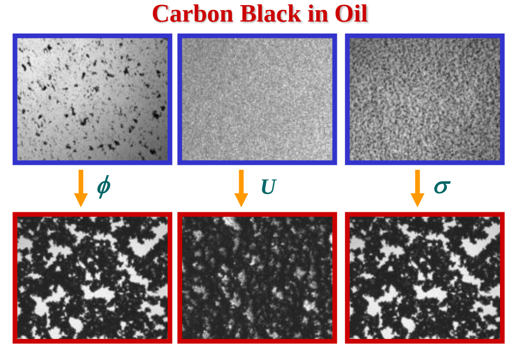
Fluid-Solid Transition

Weakly Attractive Systems

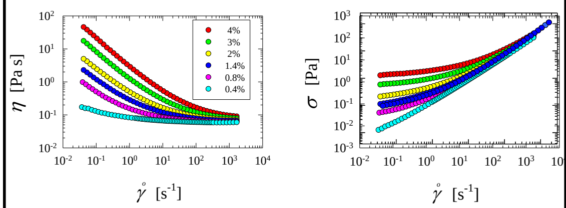


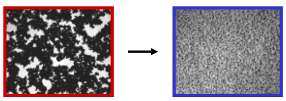
Fluid-Solid Transitions

Carbon Black in Oil



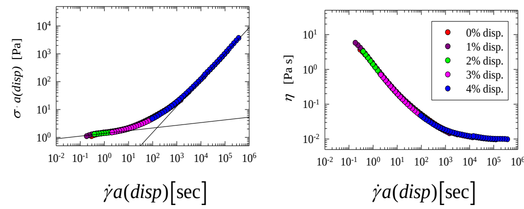
Fluidization through Shear



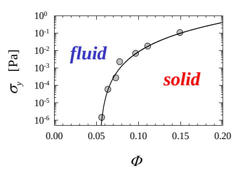


CB in S150N 25oC

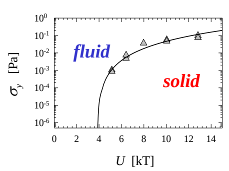
Dispersant-Shear Equivalence



Shear Induced Fluid-Solid-Transition

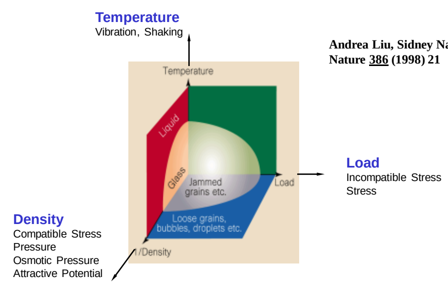


$\sigma_y = \sigma_\Phi\,(\Phi-\Phi_c)^{3.4}$



$\sigma_y = \sigma_u\,(U-U_c)^{2.4}$

Jamming Transition – Arrest of Motion



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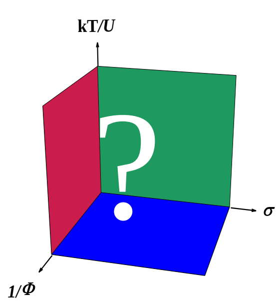
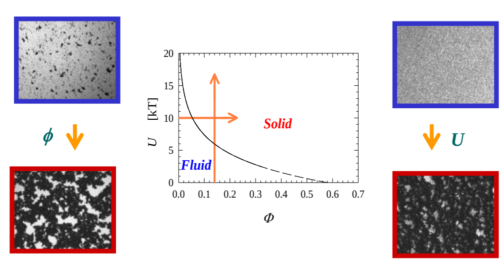
Jamming Transitions for Colloidal Systems with Attractive Interactions

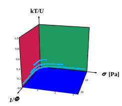


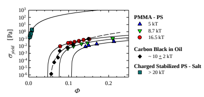
Phase Boundary in *U*-*ϕ* Plane



Yield Stress as Phase Boundary

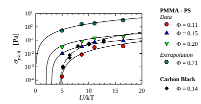
$\sigma_y = \sigma_o (\phi - \phi_c)^\mu$

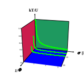




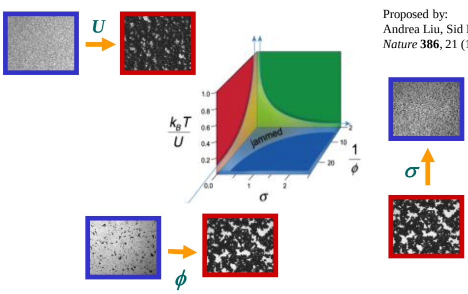
Phase Boundary in $U - \sigma$ Plane
ϕ = const.

$\sigma_y = \sigma_o (U - U_c)^\nu$





Jamming Phase Diagram for Attractive Systems



Proposed by:
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Completely new way to look at viscosity of soot in oil