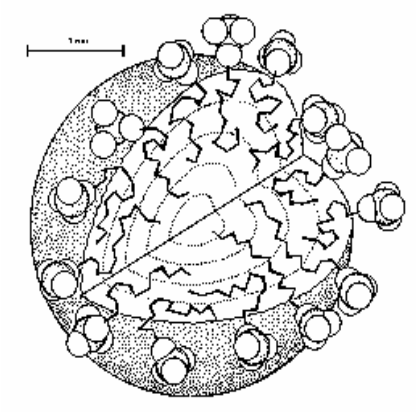
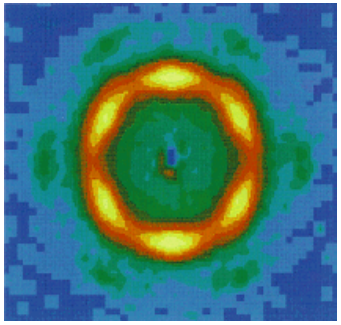
Oxford Summer School. September 2007

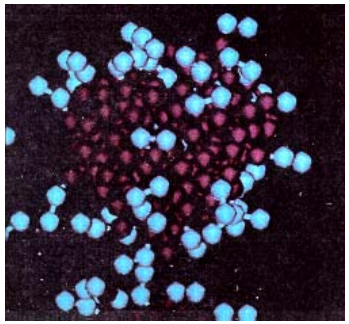
Soft Condensed Matter 2

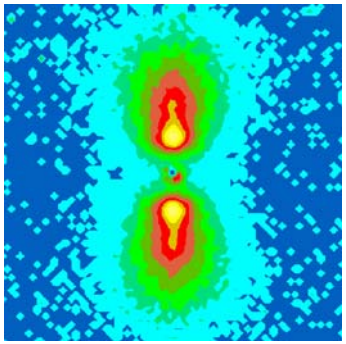
The study of surfactant self-assembly, and polymers in solution using Small Angle Neutron Scattering



Jeff Penfold
ISIS Facility, Rutherford Appleton Lab



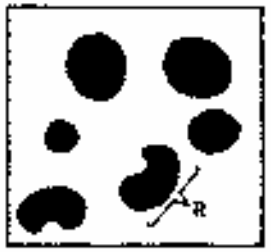


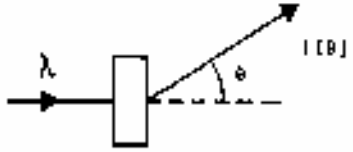


CLRC

ISIS

Small Angle Scattering





SAS is scattering in the forward direction, and is related to the scattering properties of materials at small scattering vectors, Q

Wave vector transfer Q defined as

$$Q = \frac{4\pi}{\lambda}\sin\theta/2$$

$$\frac{d\sigma}{d\Omega} = N\left\langle \left| \sum_{i(V)} \bar{b}_i \exp\left(iQ.R_i\right) \right|^2 \right\rangle_Q$$

$$Q = k_i - k_f = 2k_i \sin\theta/2$$

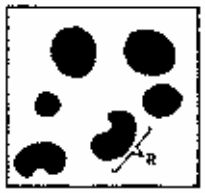
A Guinier, G Fournet, Small angle scattering of x-rays, Wiley & Sons, NY, 1955

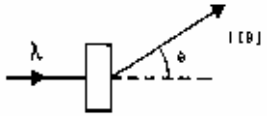
CLRC

ISIS

Contrast Variation

$\rho(r)$ **Scattering length density**





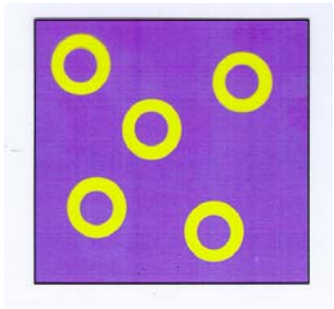
$$\rho(r)\delta v = \sum_{j(V)} b_j$$

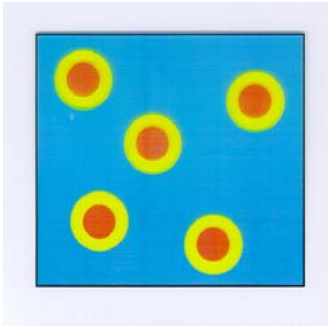
$$\frac{d\sigma}{d\Omega} = N\left\langle \left| \int_V p(r)\exp(iQ.r)dr \right|^2 \right\rangle_Q$$

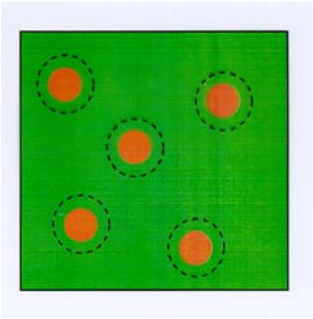
$\langle\ \rangle_Q$ all orientation with respect to Q

N is the number of scattering objects

Molecule	Bulk density ($g.cm^{-3}$)	Molecular weight ($g.mol^{-1}$)	Molar volume ($Å^3$)	Scattering length density ($10^{10}cm^{-2}$)
H_2O	1.0	18.015	29.915	-0.560
D_2O	1.112	20.0314	29.915	6.400
toluene C_7H_8	0.865	92.140	176.884	0.939
C_7D_8	0.9407	100.205	176.884	5.647
heptane C_7H_{16}	0.684	100.20	243.267	-0.547
C_7D_{16}	0.794	116.33	243.267	6.300
cyclohexane C_6H_{12}	0.779	84.161	179.403	-0.278
C_6D_{12}	0.891	96.258	179.406	6.685
silicon	2.329	28.0855	20.025	2.074
SiO_2 vitreous	2.2	60.0843	45.352	3.475
SiO_2 α quartz	2.648	"	37.679	4.183
TiO_2	4.23	79.899	31.366	2.604
Al_2O_3	3.97	101.961	42.648	5.699
poly(ethylene)- CH_2-	0.92	14.027	25.318	-0.329
poly(styrene) - C_8H_8-	1.05	104.151	164.71	1.412
d-poly(styrene) - C_8D_8-	1.131	112.216	164.71	6.468



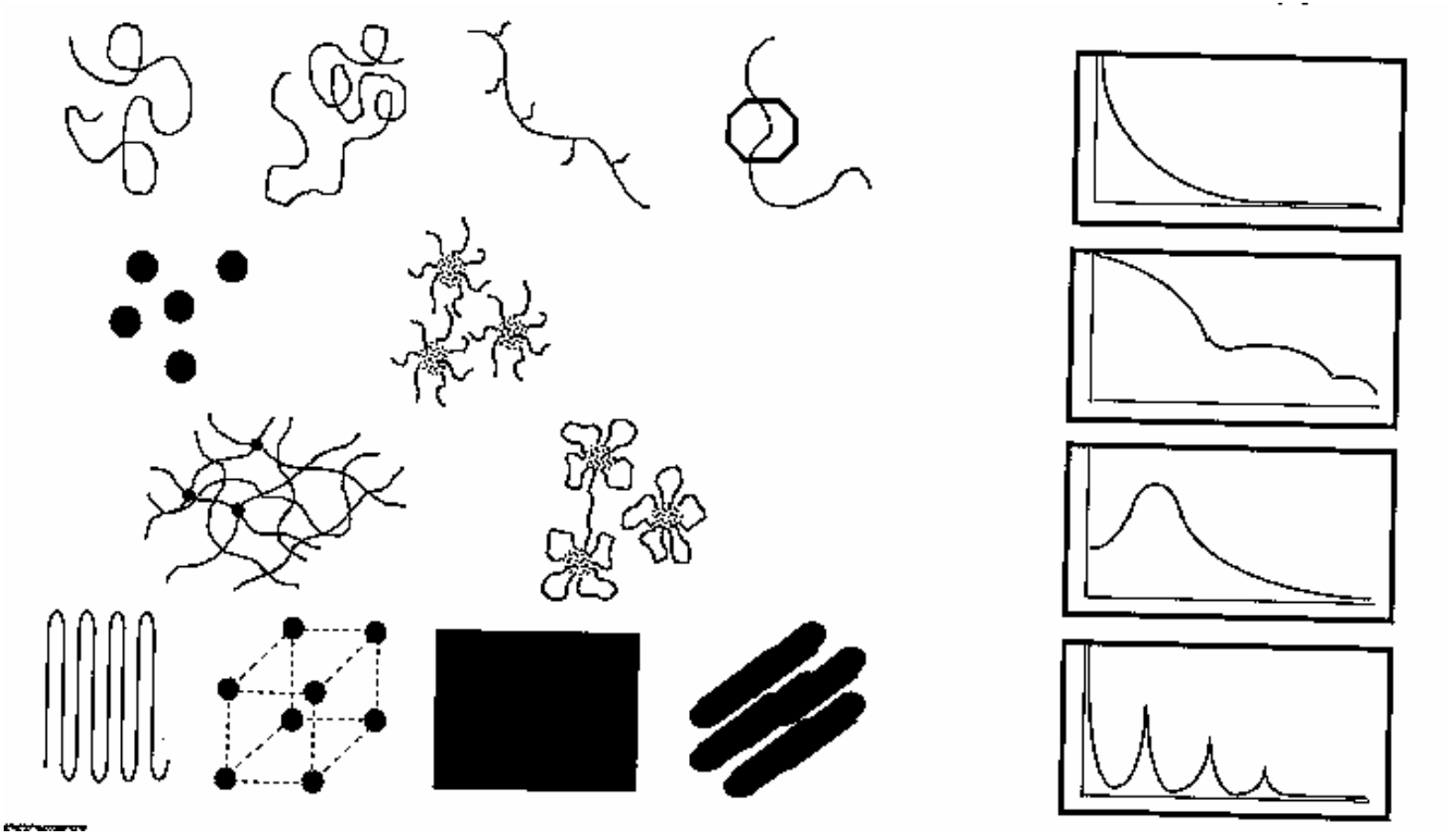




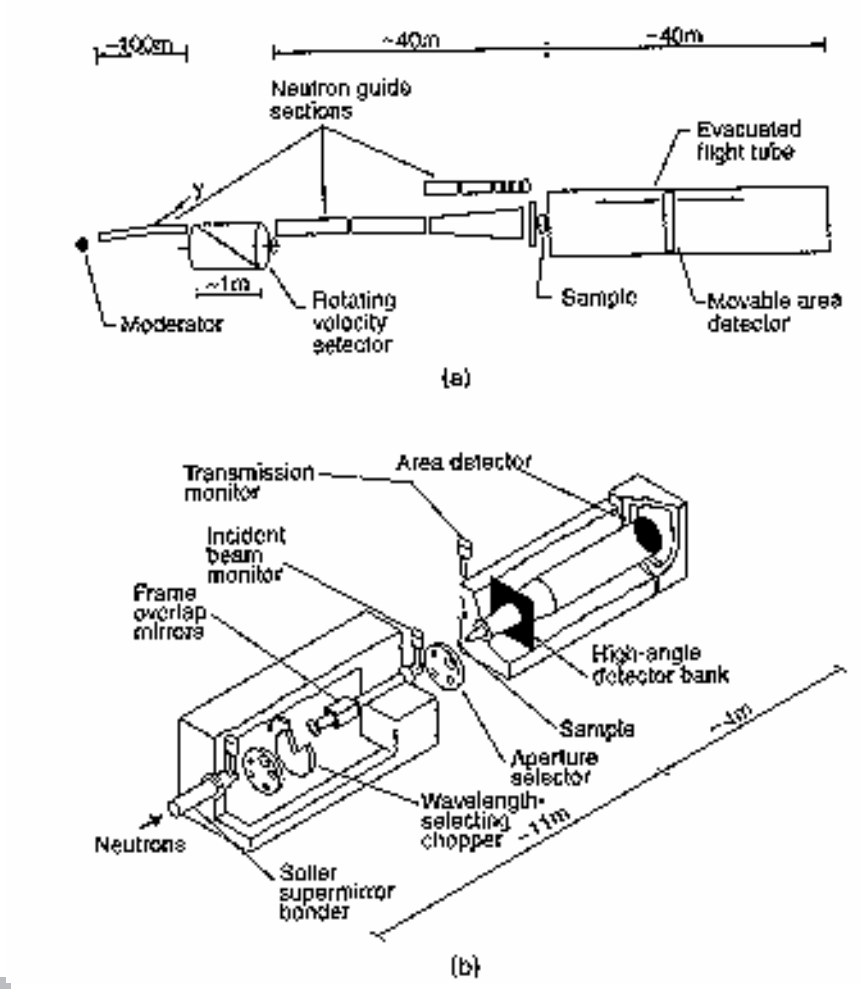
CLRC

ISIS

Some characteristic scattering patterns



Instrumentation



D11/D22 (ILL)
Monochromatic

LOQ (ISIS)
White beam TOF

Typical Q range 2 x 10^{-3} to 0.5 $Å^{-1}$, Probes dimensions ($\sim 2\pi/Q$) ~ 3000 to 10Å

W Schmatz, J J Schelten, J Appl Cryst 4 (1974) 410

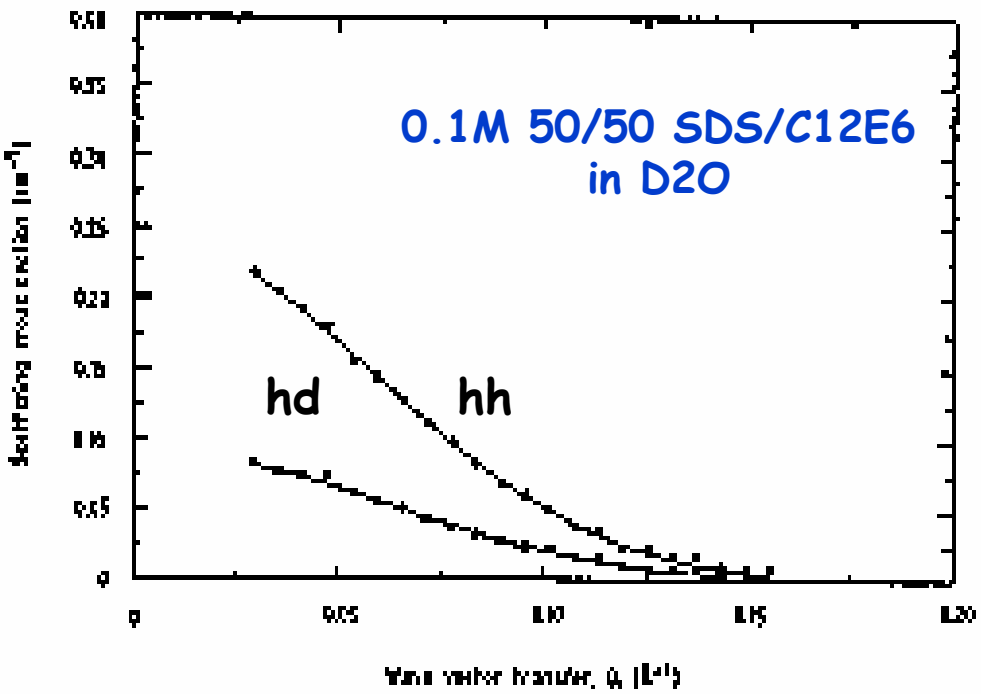
CLRC

ISIS

Dilute Solution : non-interacting particles

Scattering from isolated particles, determined by particle form factor

$$\frac{d\sigma}{d\Omega} = N\left\langle F^2(Q)\right\rangle_Q$$



$$F(Q) = \int_{Vp} (\rho(r) - \rho_s)\exp(iQ.r)dr$$

$$I(Q=0) = NV^2(\rho - \rho_s)^2$$

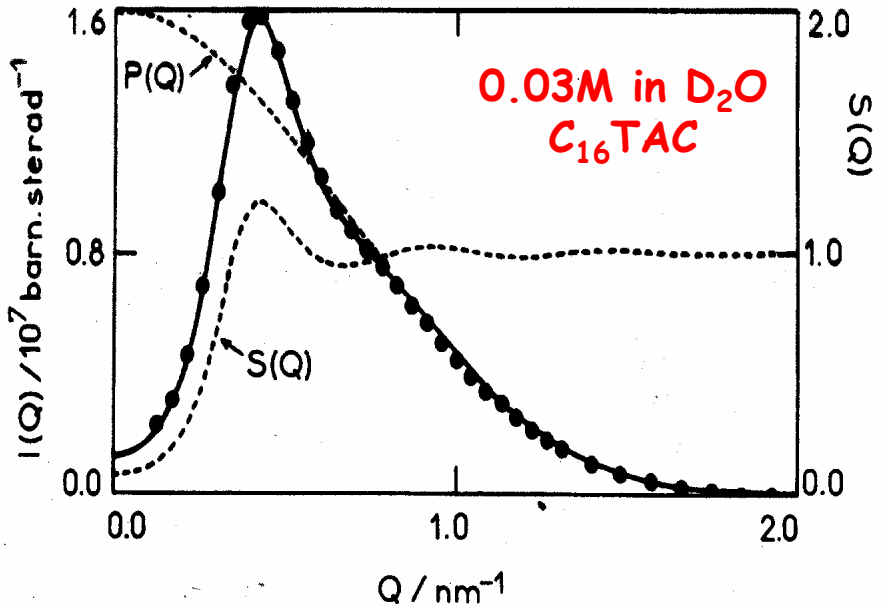
Extrapolation to Q=0 determined by scattering volume and contrast

CLRC

ISIS

Concentrated Solution : interacting particles

For globular interacting polydisperse particles, in the 'decoupling approx' (no correlation between position and orientation)



$$\frac{d\sigma}{d\Omega} = N\left[S(Q)\left\langle F(Q)\right\rangle_Q^2 + \Delta(Q)\right]$$

$$\Delta(Q) = \left\langle \left|F(Q)\right|^2 \right\rangle_Q - \left\langle F(Q)\right\rangle_Q^2$$

S(Q) is the inter-particle structure factor, $\Delta(Q)$ a coherent disorder term switched on by interactions

For monodisperse spheres

$$\frac{d\sigma}{d\Omega} = NP(Q)S(Q) \qquad P(Q) = \left|F(Q)\right|^2$$

J B Hayter, J Penfold, Colloid Polym Sci 261 (1983) 1022
M Kotlarchyck, S H Chen, J Chem Phys 79 (1983) 2461

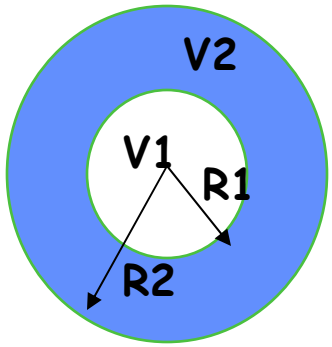
CLRC

ISIS

Form Factors: Spheres and core+shell

For monodisperse particles with centro-symmetry

$$\left\langle F^2(Q)\right\rangle_Q = \left\langle F(Q)\right\rangle_Q^2 = F_Q^2(Q)$$



For uniform spheres of radius R

$$V = 4\pi R^3/3$$

$$F_s(Q) = V(\rho - \rho_s)F_0(QR)$$

The geometrical form-factor , $F_0(QR)$, is given as,

$$F_0(QR) = 3[\sin(QR) - QR\cos(QR)]/(QR)^3 = 3j_1(QR)/(QR)$$

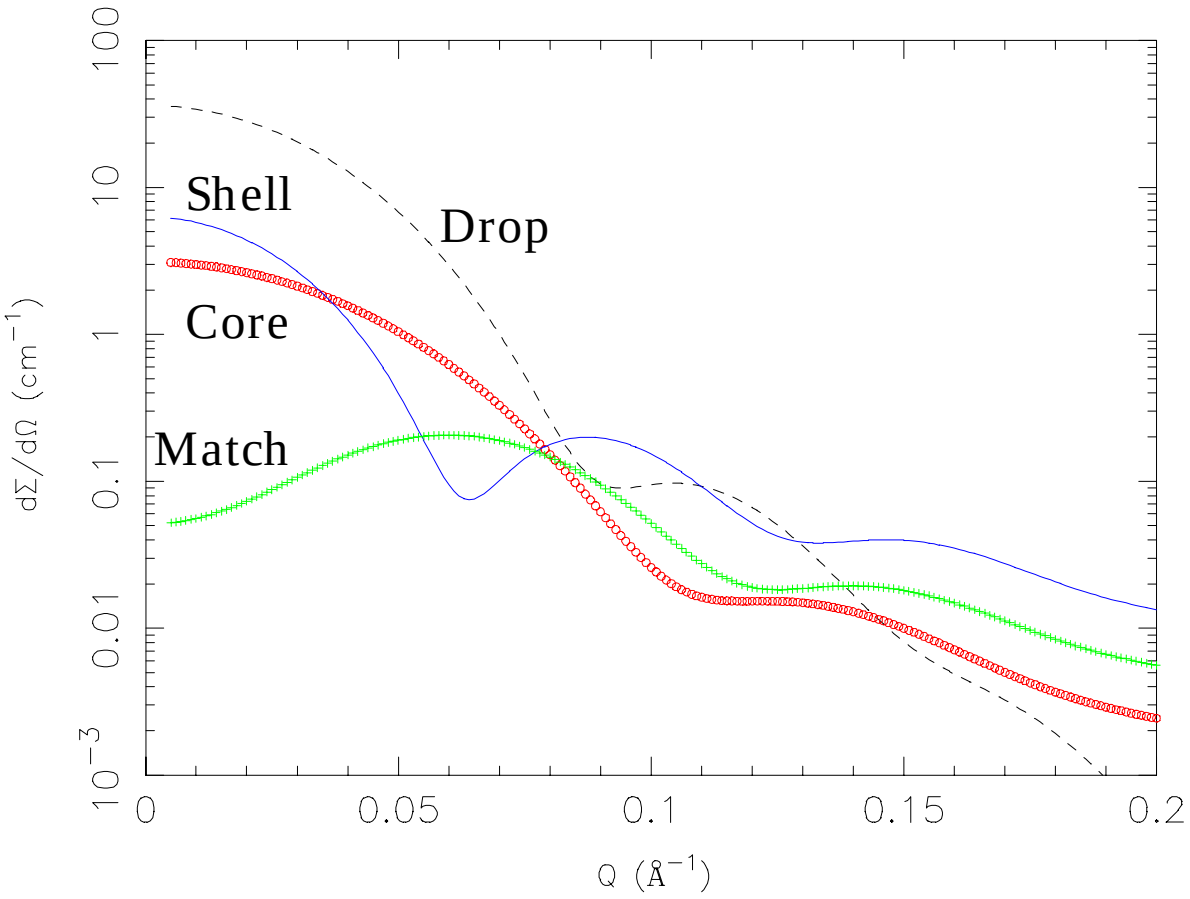
For m concentric spherical shells,

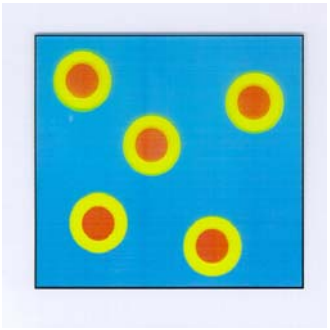
$$F_s(Q) = V_1(\rho_1 - \rho_2)F_0(QR_1) + V_2(\rho_2 - \rho_3)F_0(QR_2) + V_m(\rho_m - \rho_s)F_0(QR_m)$$

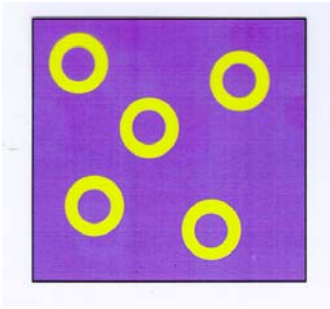
CLRC

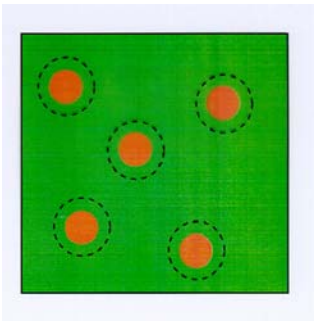
ISIS

Drop, shell, core form-factors









CLRC

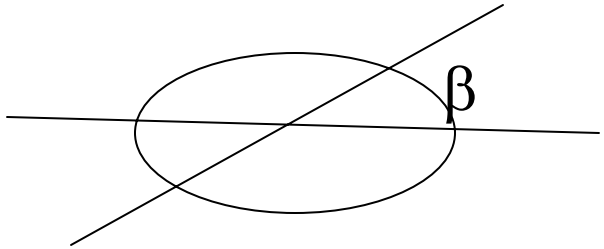
ISIS

Form Factors: Ellipses and rods

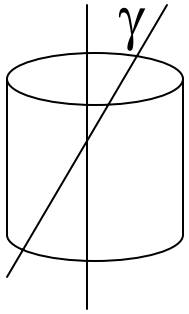
Ellipsoids

$$\left\langle F^2(Q)\right\rangle_Q = V_e^2(\rho-\rho_s)^2\int_0^1 F_0^2\left\{Qa\left[1+\left(e^2-1\right)x^2\right]^{1/2}\right\}dx$$

where x=cosβ, angle between Q and major axis of ellipsoid with axes a, a, ae



Cylinders or Rods



$$\left\langle F^2(Q)\right\rangle_Q = V^2(\rho-\rho_s)^2\int_0^{\pi/2} F^2(Q)\sin\gamma d\gamma$$

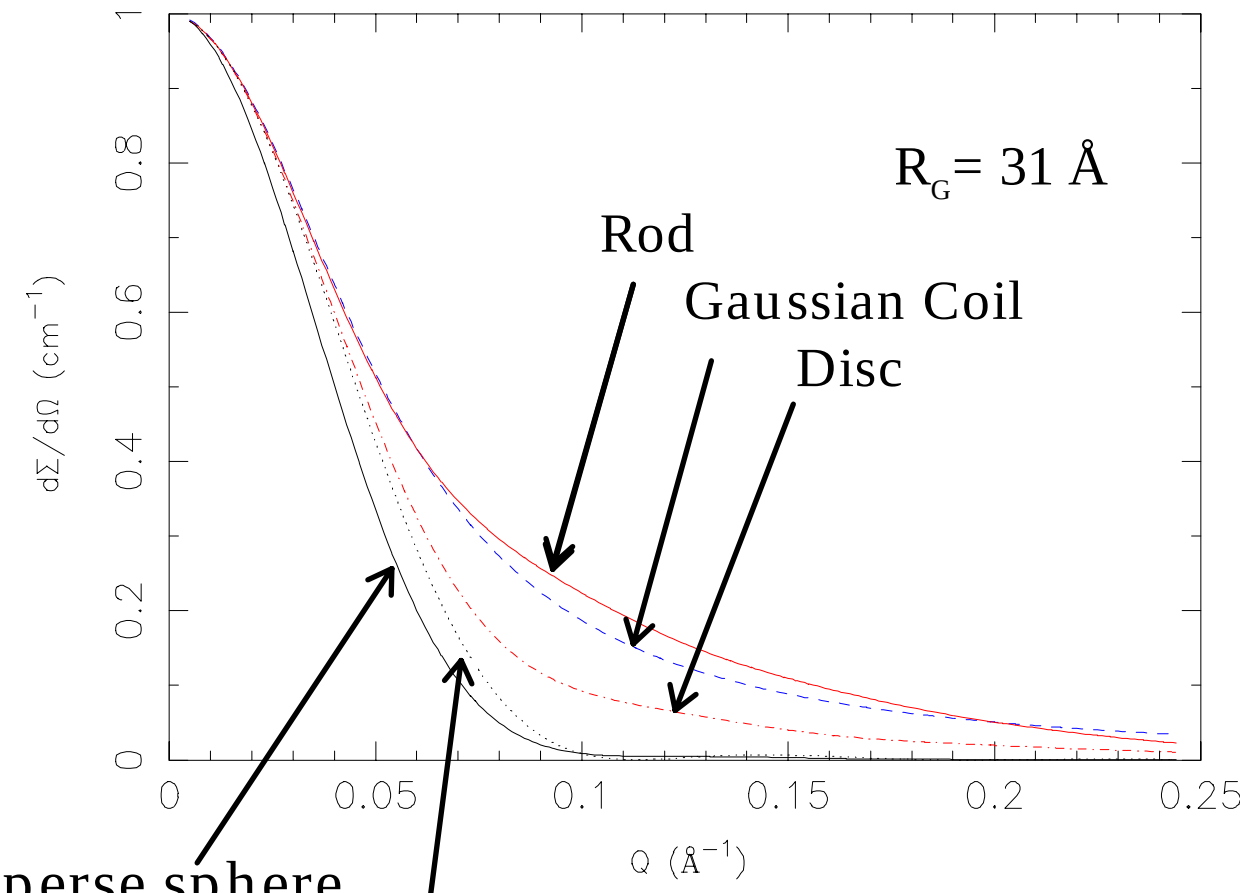
$$F(Q) = 2\,j_0(Ql\cos\gamma)\,J_1(Qa\sin\gamma)/(Qa\sin\gamma)$$

γ is angle between Q and cylinder axis, l is rod half length, a radius, $J_1(x)$ first order Bessel function of first kind, $j_0(x)=\sin x/x$

CLRC

ISIS

Particle Form-factors

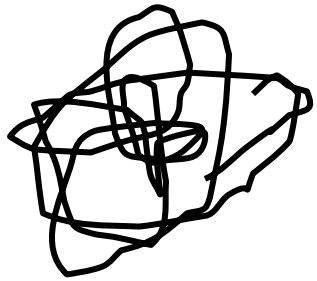


CLRC

ISIS

Other Form-Factors

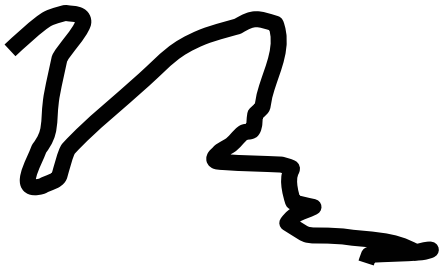
Gaussian Coil



$$\frac{d\sigma}{d\Omega} = NV^2(\Delta\rho)^2\left[\frac{2\left(\exp\left(-y^2\right)+y^2-1\right)}{y^4}\right]$$

y=QRg

Kratky-Porod Worm-like Chains



$$\frac{d\sigma}{d\Omega} \approx \pi NV^2(\Delta\rho)^2\frac{1}{QL}\exp\left(-\frac{Q^2R_g^2}{2}\right)$$

CLRC

ISIS

Approximate Relationships, Limiting Laws

I(Q=0)

$$\frac{d\sigma}{d\Omega}(Q=0) \approx NV^2(\Delta\rho)^2$$

Invariant

$$\int_0^\infty Q^2 \frac{d\sigma}{d\Omega} dQ = 2\pi^2\phi(1-\phi)\Delta\rho^2$$

Volume fraction, ϕ=NV, $\Delta\rho=(\rho-\rho_s)$

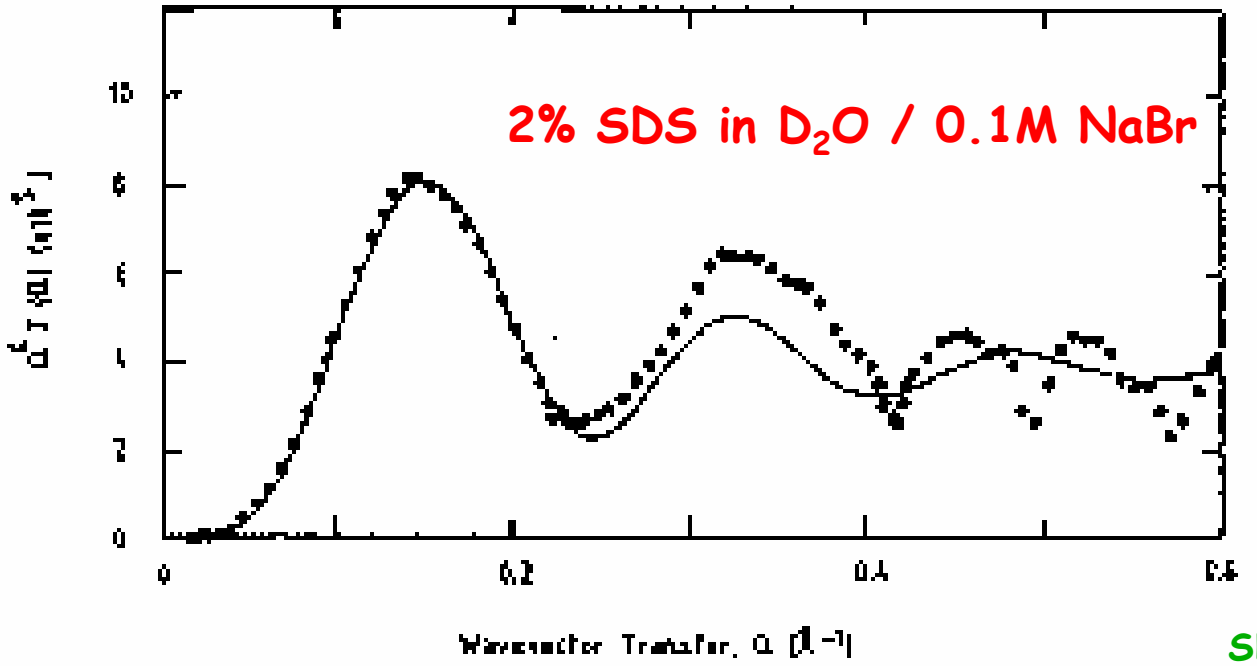
Provide information about total scattering volume and contrast
Important information and constraints for subsequent modelling

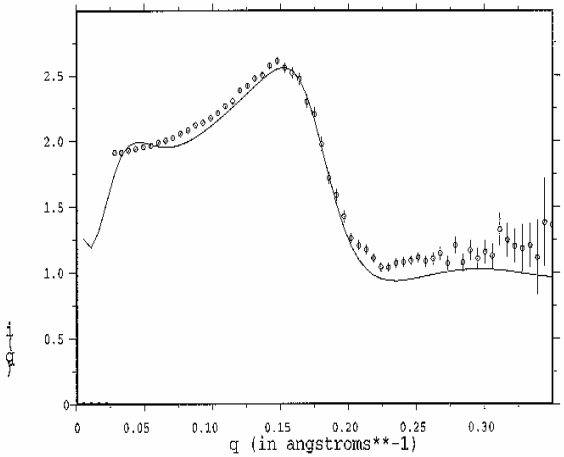
ISIS

POROD's Law : limit at high Q

For particles with well-defined interface scattering at high Q decays as Q^{-4}.

Extrapolation to high Q provides estimate of surface area





1.43e-2M 70/30
SDS / C12E6 / 0.01M NaCl

$$\frac{d\sigma}{d\Omega}(Q \to \infty) \approx 2\pi \frac{(\Delta\rho)^2}{Q^4} S$$

S is the surface area per unit volume of sample

CLRC

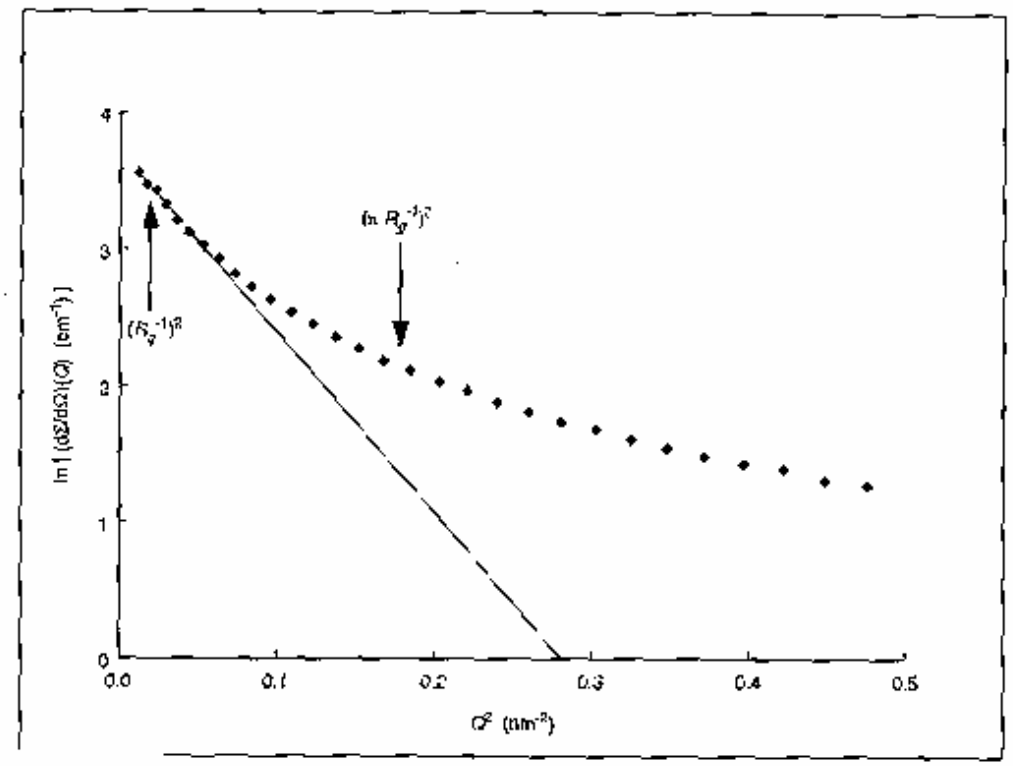
ISIS

Guinier's Law

At low Q, scattering cross-section can be approximated by Guinier expansion,

Series expansion of P(Q),

$$P(Q) \approx 1 - \frac{(QR)^2}{10} +$$



$$\frac{d\sigma}{d\Omega} \approx NV^2(\Delta p)^2 \exp\left(\frac{R_g^2 Q^2}{3}\right) \qquad R_s^2 = \frac{5}{3}R_g^2$$

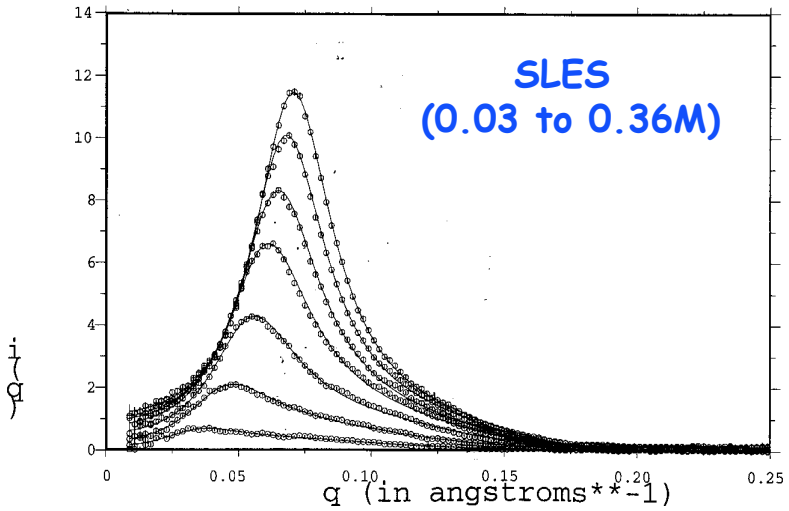
Valid for $QR_g < 1$

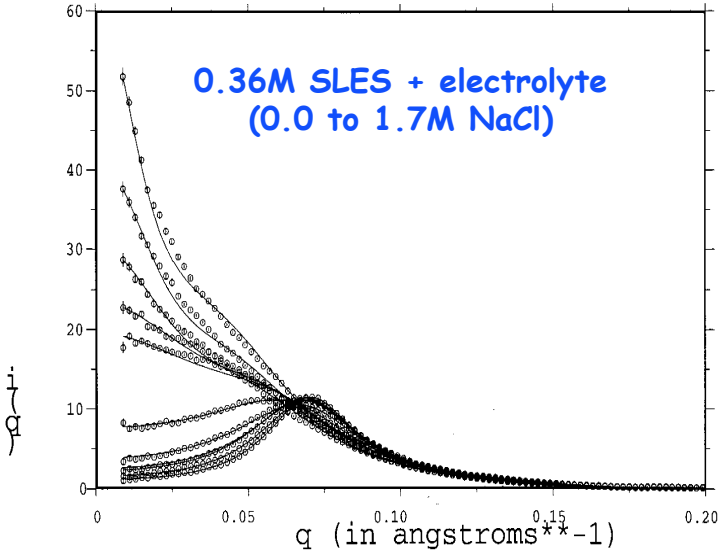
Plot of Log(scattering intensity) v Q^2 is linear with slope related to Rg and intercept $NV^2(\Delta\rho)^2$

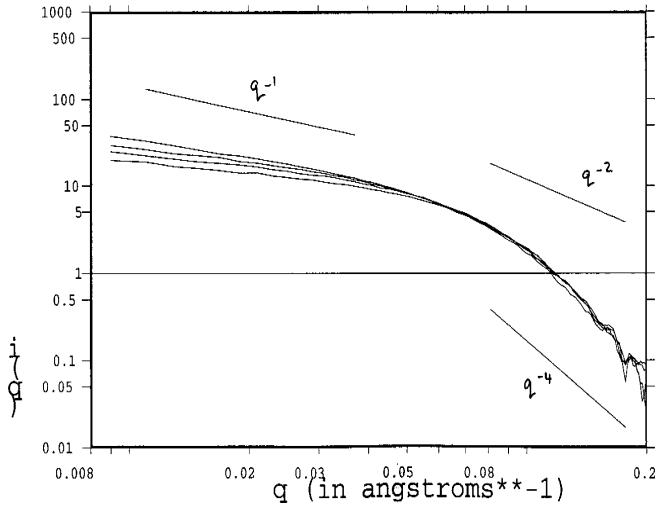
CLRC

ISIS

For rod-like or elongated structures







At low to intermediate Q, Q^{-1} dependence

$$Q\frac{d\sigma}{d\Omega} = \pi N V^2 (\Delta\rho)^2 \exp -(QR_c)^2/2$$

At intermediate Q, or QRc < 1, a plot of logQdσ/dΩ v Q^2 will be linear, Q^{-2} Guinier regime

At high Q, Q^{-4} dependence, the scattering contains only information about the local rod cross-section

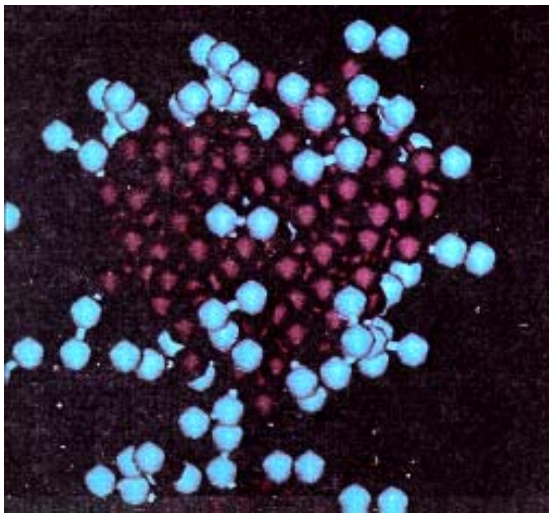
$$\frac{d\sigma}{d\Omega} \approx \frac{4\pi}{Q}\left(\frac{J_1(QR_c)}{QR_c}\right)^2$$

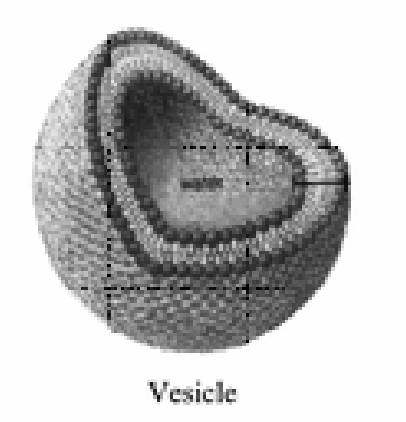
CLRC

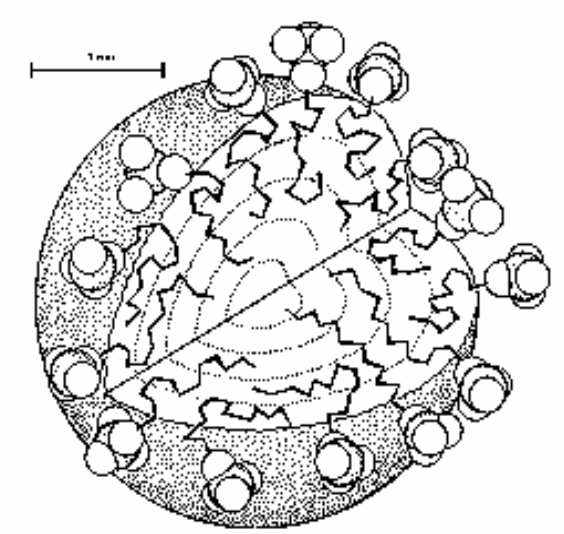
ISIS

Self-Assembly

Surfactant micelles and meso-phases







J Penfold, Encyl of Surface and Colloid Science (2002) Marcel Dekker, NY

CLRC

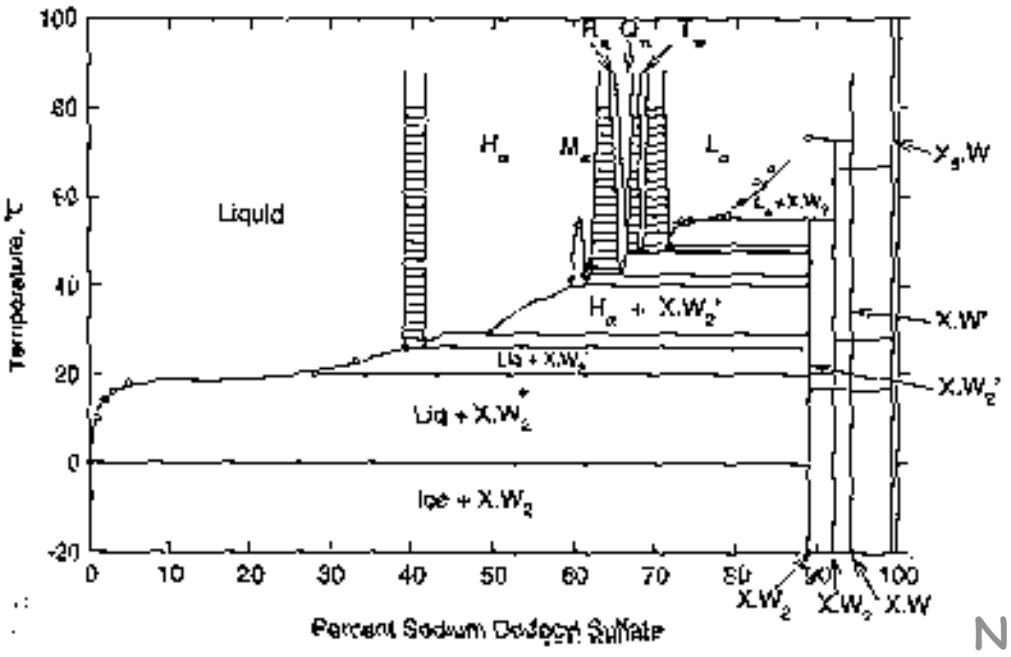
ISIS

Surfactants
(solution behaviour)

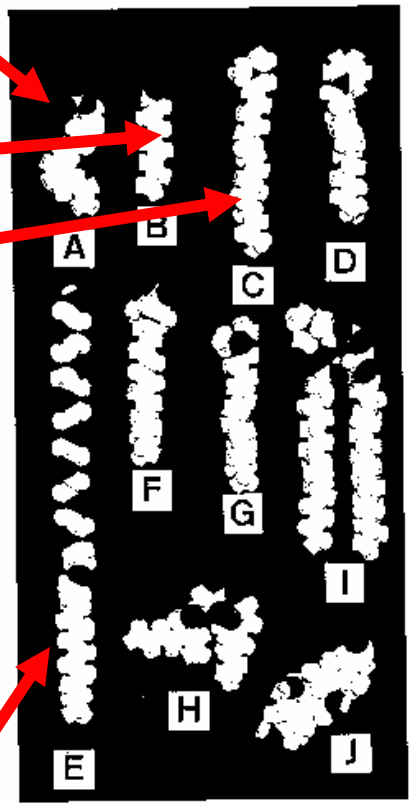
Sodium dodecyl sulphate, SDS
$CH_3(CH_2)_{11}OSO_3^-Na^+$

Sodium Octanoate, NaO
$CH_3(CH_2)_7CO_2^-K^+$

n-hexadecyltrimethyl ammonium bromide
$C_{16}TAB$, $CH_3(CH_2)_{15}N^+(CH^3)^3Br^-$



Phase diagram for SDS

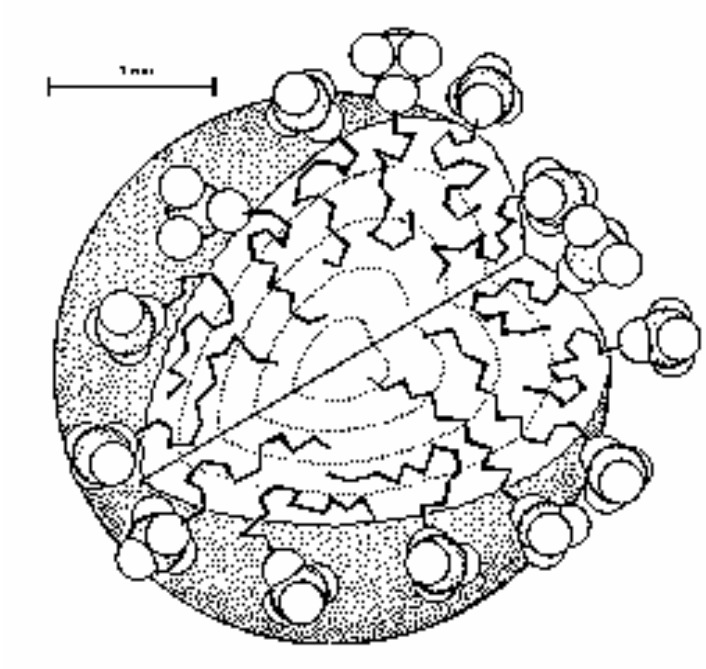


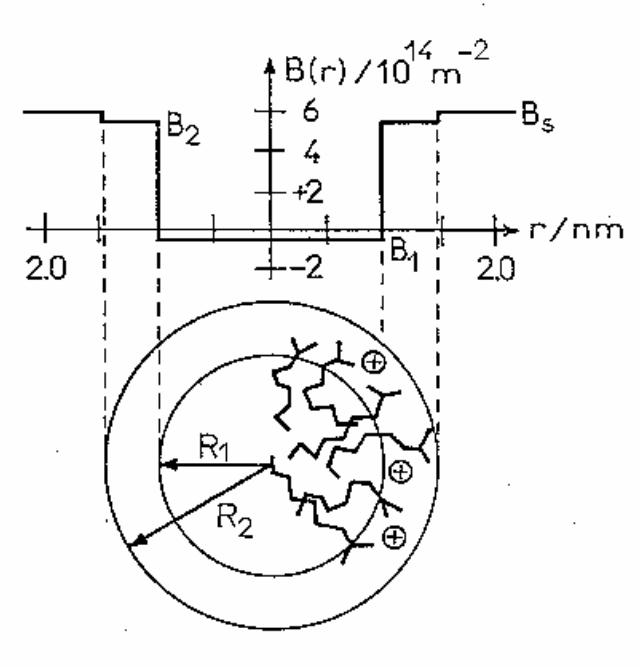
N-dodecyloctaetyleneglycol monoether
$CH_3(CH_2)_{11}(OCH_2CH_2)_8OH$

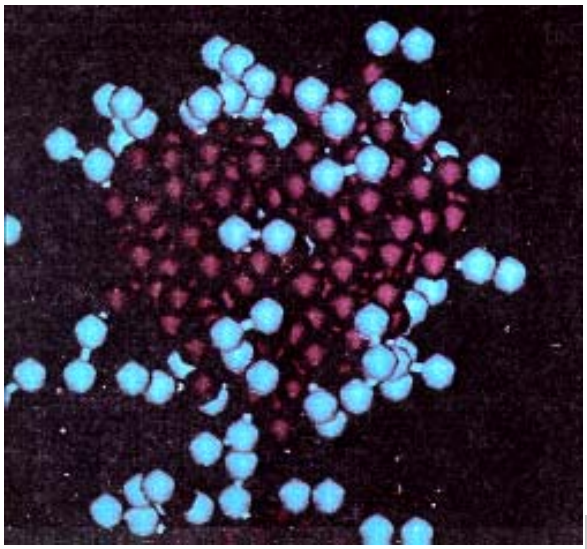
CLRC

ISIS

Micelle Structure







Gruen, Prog Coll Polym Sci (1985) 70 6

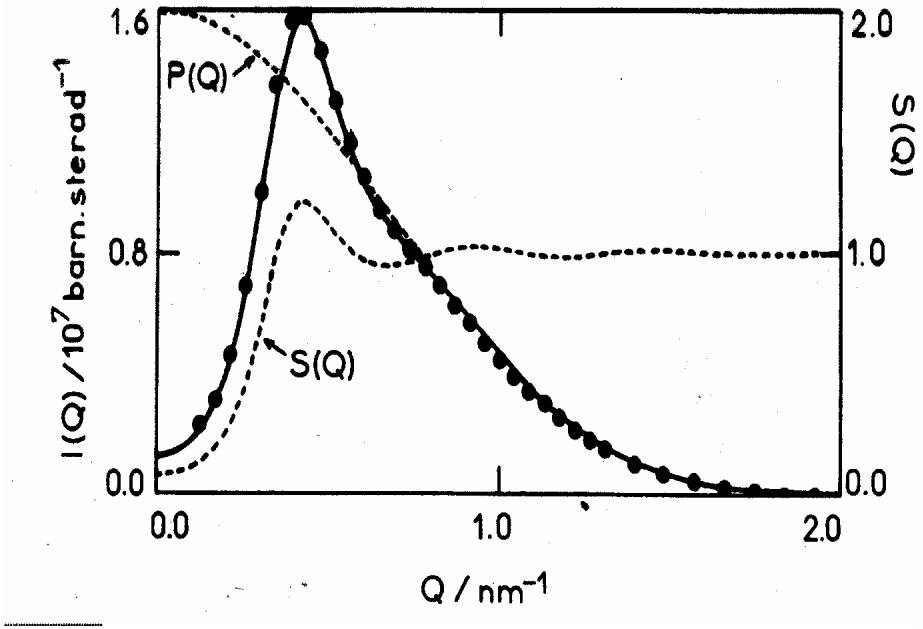
B Smit et al, Nature 348 (1990) 624,
J Phys Chem 95 (1991) 6361

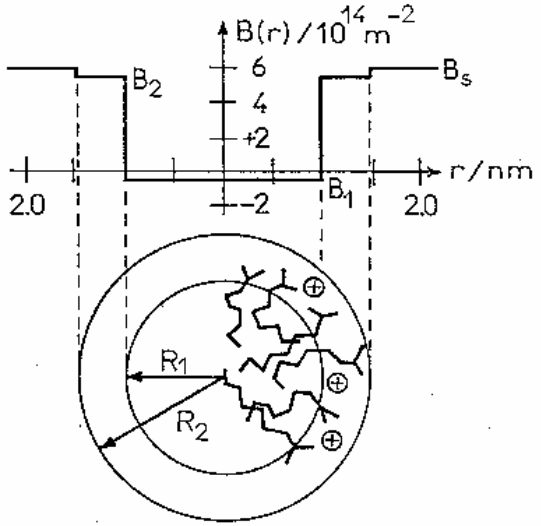
CLRC

ISIS

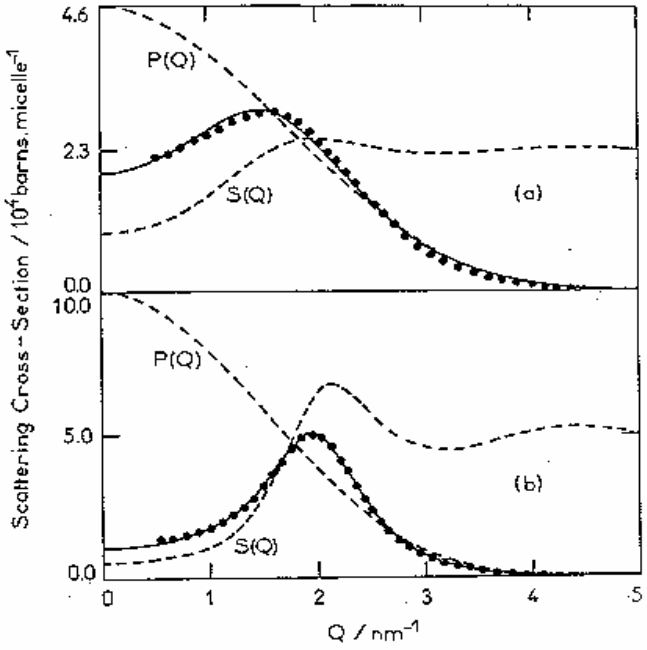
Micelle Structure

0.03M $C_{16}TAC$ in D_2O





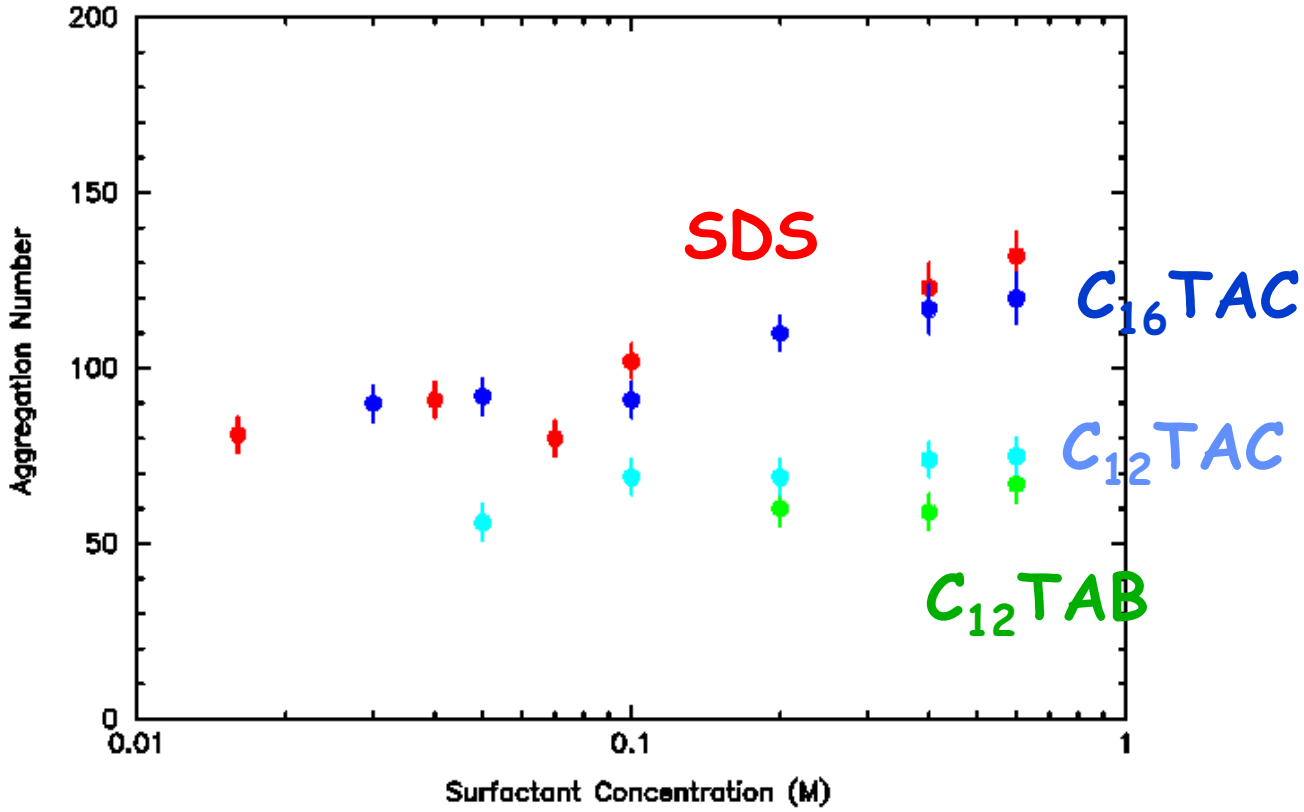
0.6 and 1.2M Na Octanoate in D_2O



CLRC

ISIS

Some model parameters for some simple micelles



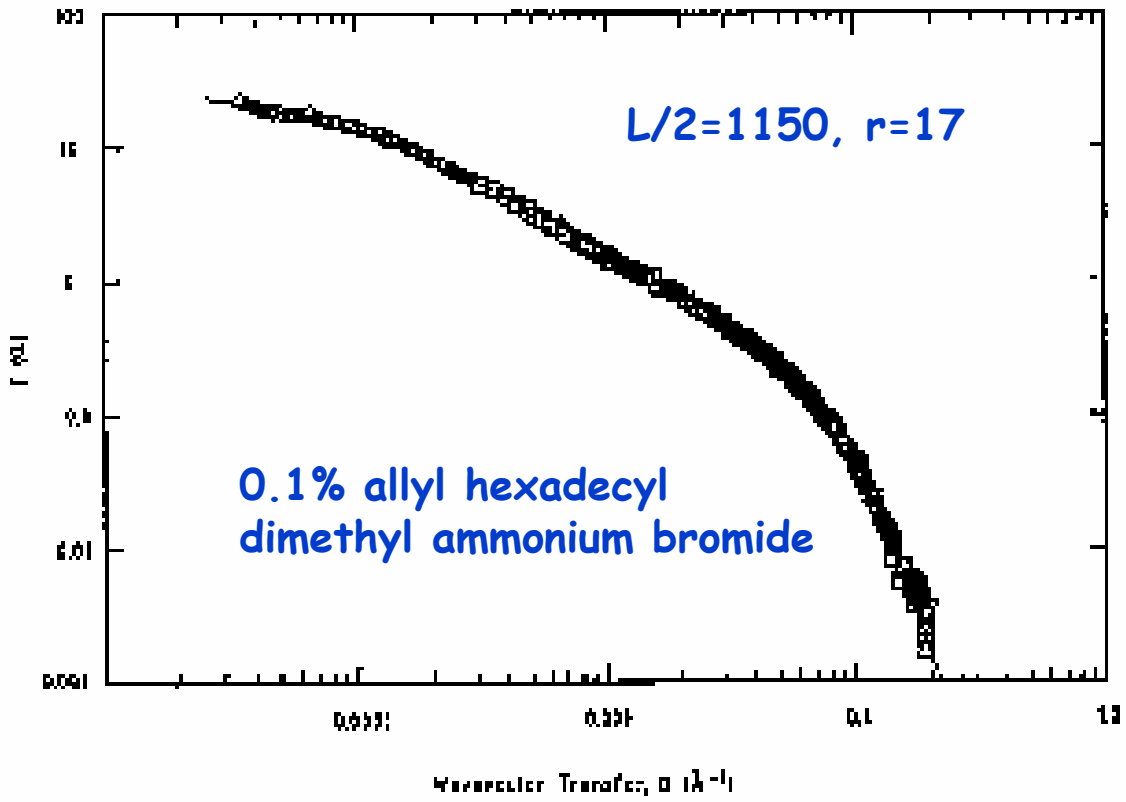
Effect of concentration

$C_{12}TAB$ (C) : small spherical micelles
SDS, $C_{16}TAC$: elliptical, ee 1.23 to 2.47

CLRC

ISIS

Micelle Growth : elongated structures



Surfactant conc, electrolyte induces micellar growth to rod-like structures

Counterions, such as salicylate, induce extreme growth and highly elongated structures

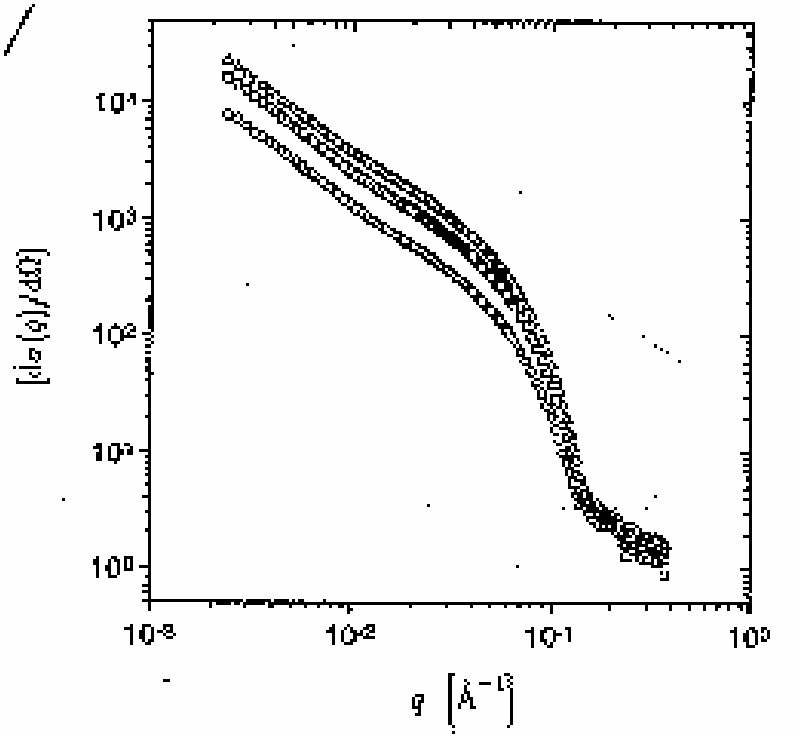
Measured over 3 decades of Q, and 4 decades of intensity
Consistent with randomly oriented rigid cylinders with exponential distribution of lengths

Lin et al, Phys Rev E 53 (1996) 4302

CLRC

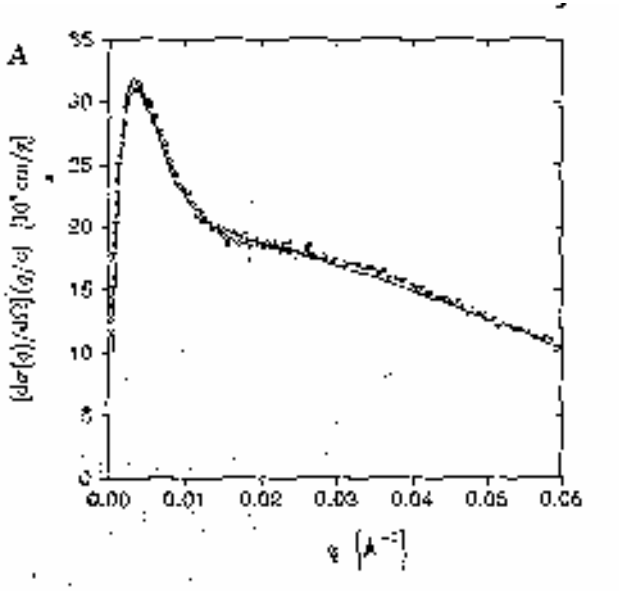
ISIS

Micelle Growth : elongated structures



Persistence length,
lp=1.9/Q*

C16E6 in D2O,
0.6, 1.2, 1.8 g/L



Holtzer plot (QI(Q) v Q)
emphasises Q^{-1} to Q^{-2}
transition to provide estimate of
Persistence length

C16E6 shows substantial conc induced growth of,
interpreted as polymer-like micelles or worm-like chains

Schurtenberger et al, Langmuir 12 (1996) 2894; 14 (1998) 6013

CLRC

ISIS

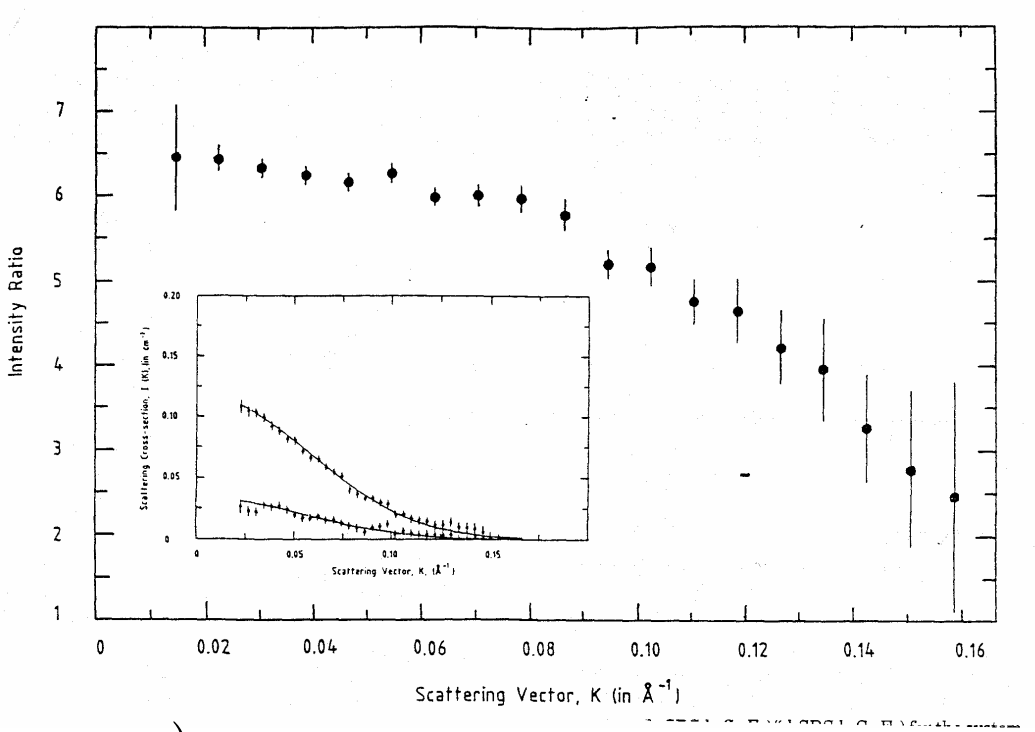
Composition of mixed surfactant micelles

If P(Q), S(Q) ~ 1.0 then

$$I(Q) \approx \sum_i N_i V_i^2 \left(\rho_{ip} - \rho_s\right)^2$$

From measurements, for example, **h-SDS/ h-C12E6** and **h-SDS / d-C12E6** in **D2O**

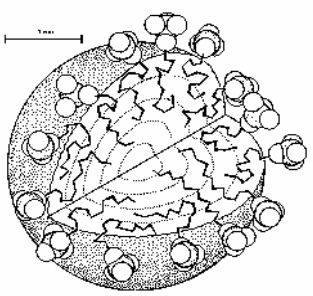
$$R = \frac{I(Q)_{hh}}{I(Q)_{hd}} \left(Q \rightarrow 0\right)$$



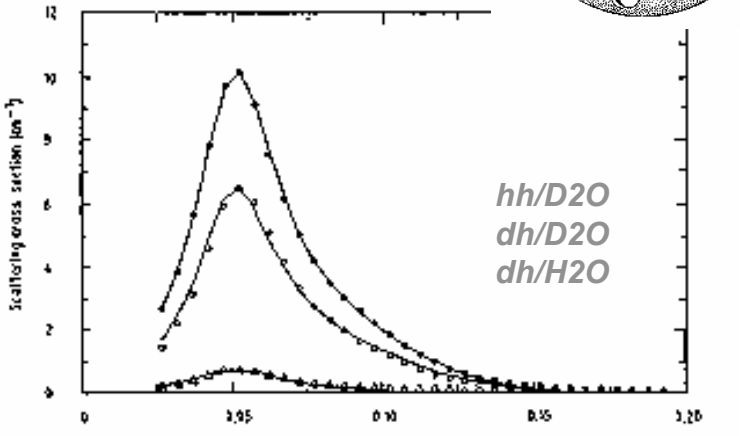
$$V_f = \frac{\left(\sqrt{R} - 1\right)\left(\rho_{hSDS} - \rho_{D2O}\right)}{\left(\rho_{hC12eE6} - \rho_{hSDS}\right) - \sqrt{R}\left(\rho_{dC12E6} - \rho_{hSDS}\right)}$$

Penfold et al, Langmuir 11 (1995) 2496

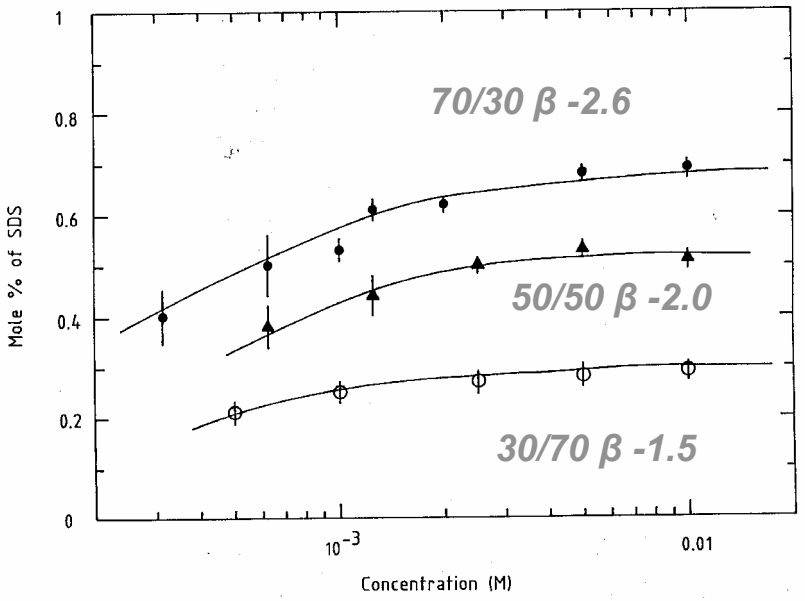
Mixed Surfactant micelles

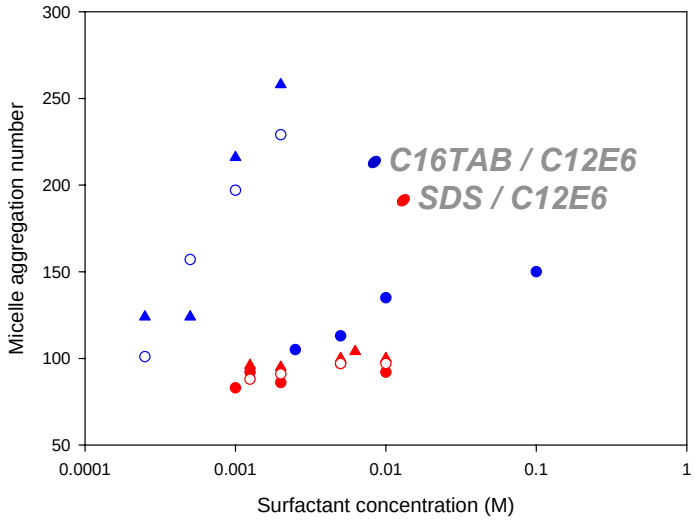


0.1 M C16TAB / C12E6
0.1M NaCl

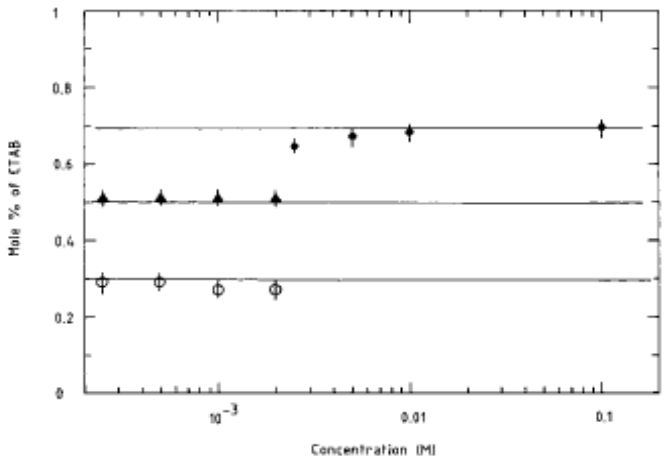


SDS / C12E6 / 0.1M NaCl





C16TAB / C12E6 0.1M NaCl

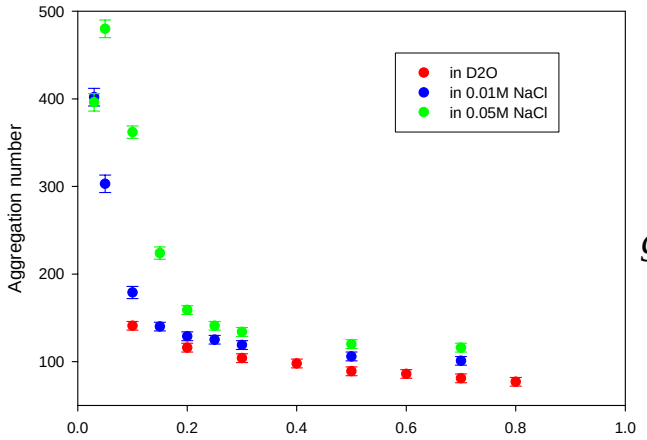


CLRC

ISIS

Mixed Surfactant micelles

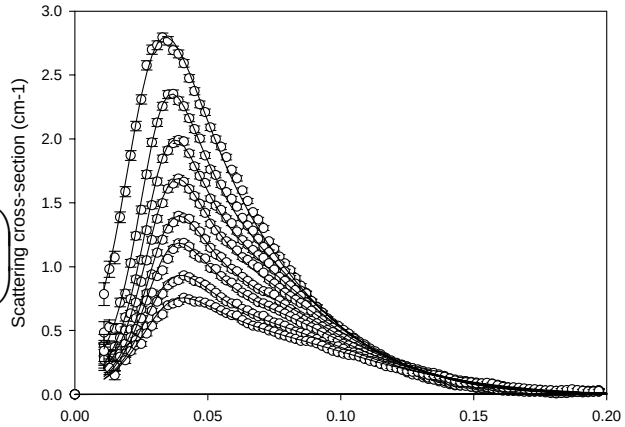
Simple free energy terms explains main trends
Growth of C12E6 rich micelles attributed to dehydration

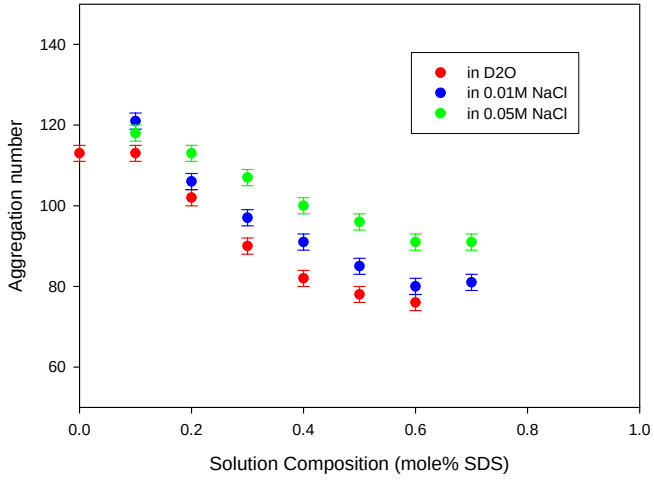


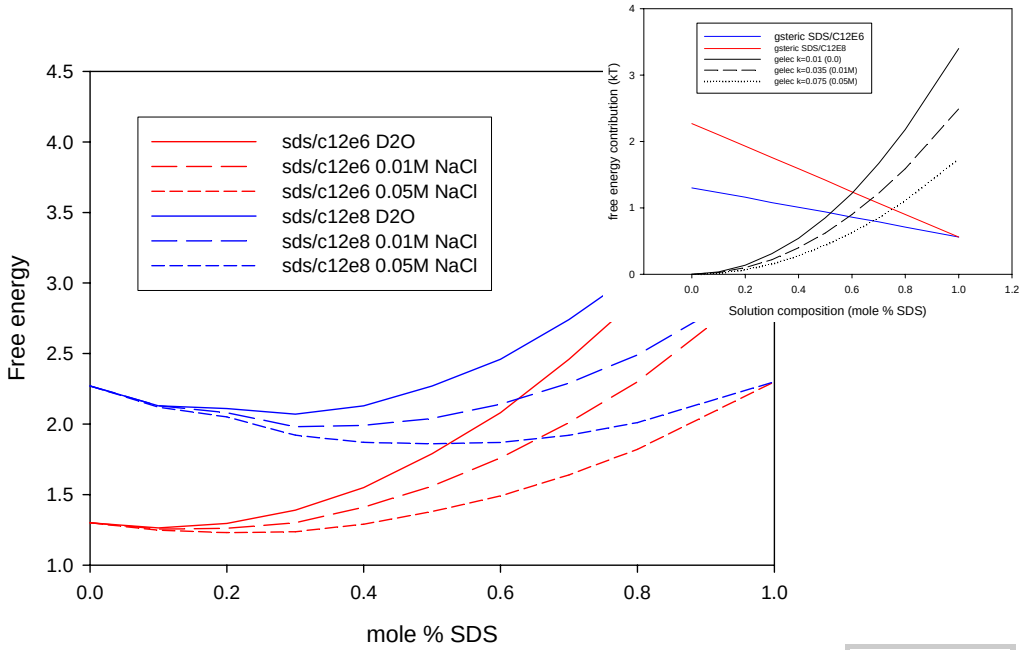
$$\upsilon = \left(\frac{4\pi l_c^3}{3V_o}\right)\left(\frac{a_e l_c - 2}{V_o}\right)^{-1}$$

$$g_{ster}^{mix} = -kT\left[\alpha \ln\left(1-\frac{a_{ha}}{a}\right)+(1-\alpha)\ln\left(1-\frac{a_{hb}}{a}\right)\right]$$

$$g_{elec}^{a} = \frac{2\pi e^2 d}{\varepsilon a_e}\left(1/1+\kappa_o l_c\right)$$







Alkyl chain contribution
~ -17 to18 kT

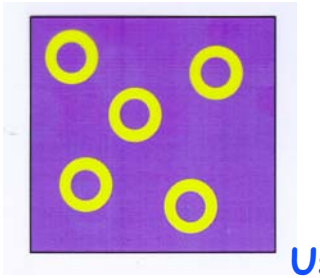
Penfold et al, J Phys Chem B 109 (2005) 10760

More significant variation in headgroup contribution for C12E6 than for C12E8

CLRC

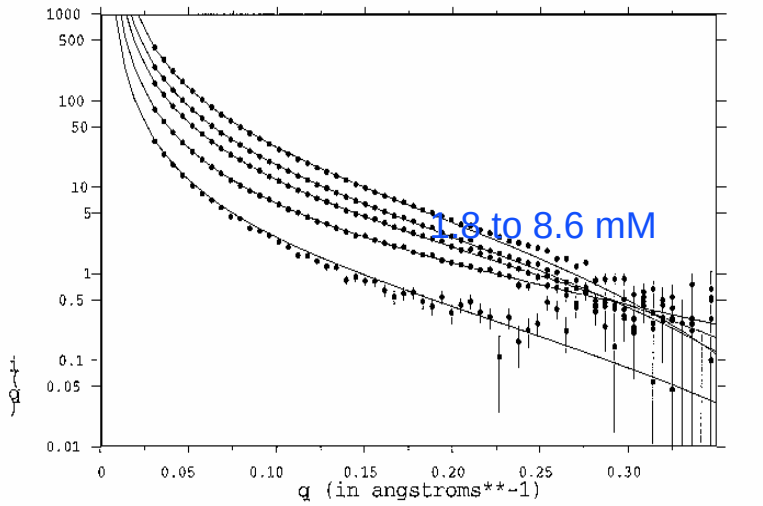
ISIS

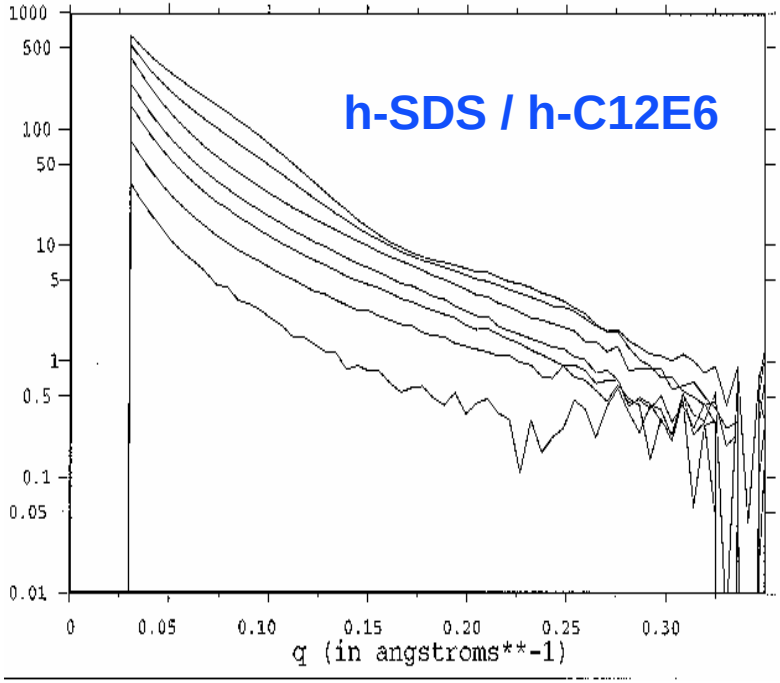
Adsorption of mixed surfactants (SDS / C12E6) at the oil-water interface



Prepare hexadecane in water emulsions(σ~0.2 microns) by ultrasound

Use h/d hexadecane to index match to D2O Can dilute and add surfactant





See Scattering from adsorbed layer only + free micelles

Adsorbed layer thickness varies from 8 to 15 Å

Adsorbed amount from 2.05 to 6.68 x 10-10 mol cm-2

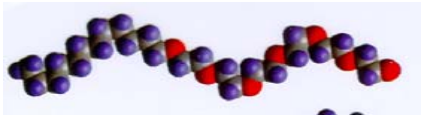
Adsorbed amounts and composition from

$$\Gamma = \frac{d\left(\rho_s - \rho_2\right)}{N_a V\left(\rho_s - \rho_a\right)}$$

Penfold et al, J Phys Chem B 104 (2000) 606

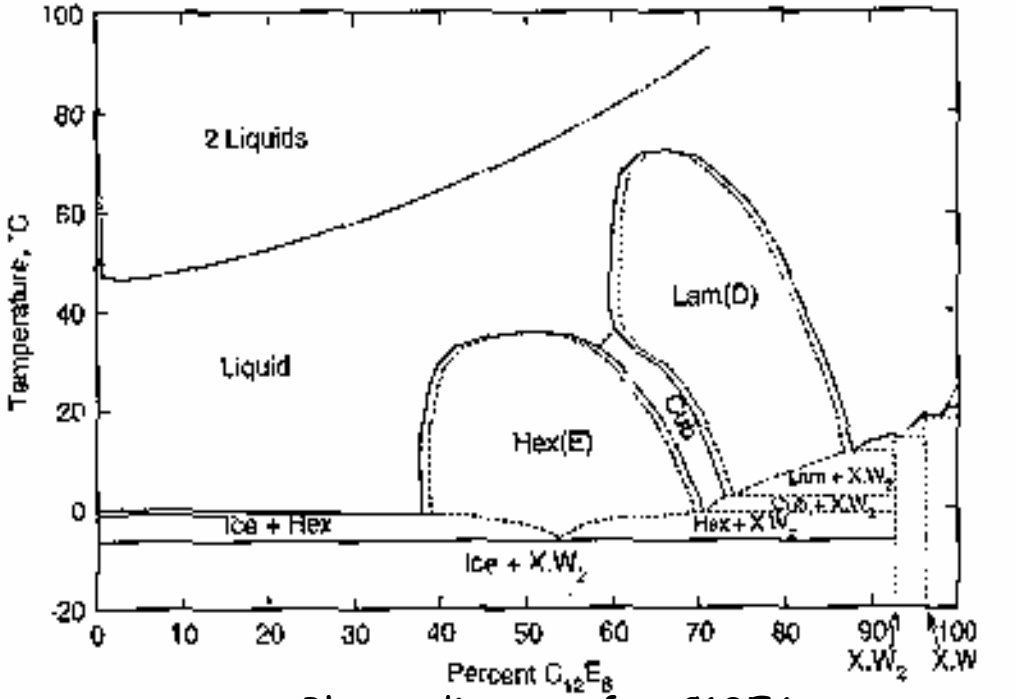
CLRC

ISIS

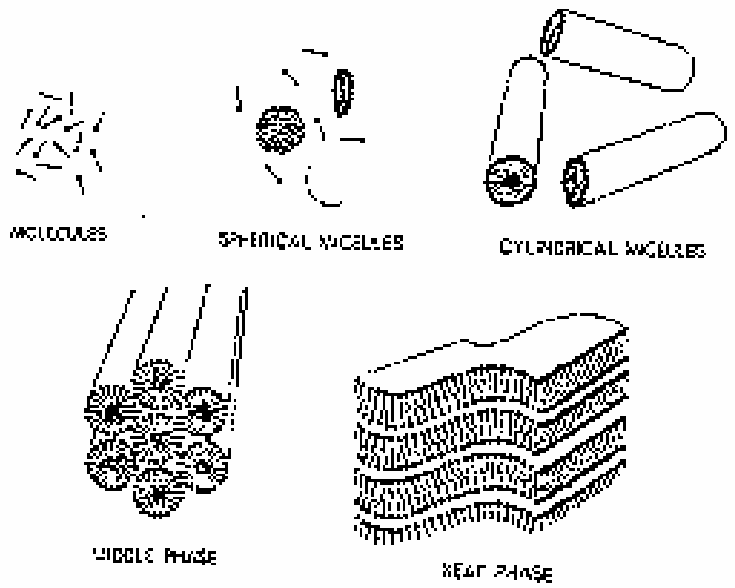


Conc / ordered Systems

Lyotropic micellar and liquid crystalline phases



Phase diagram for C12E6



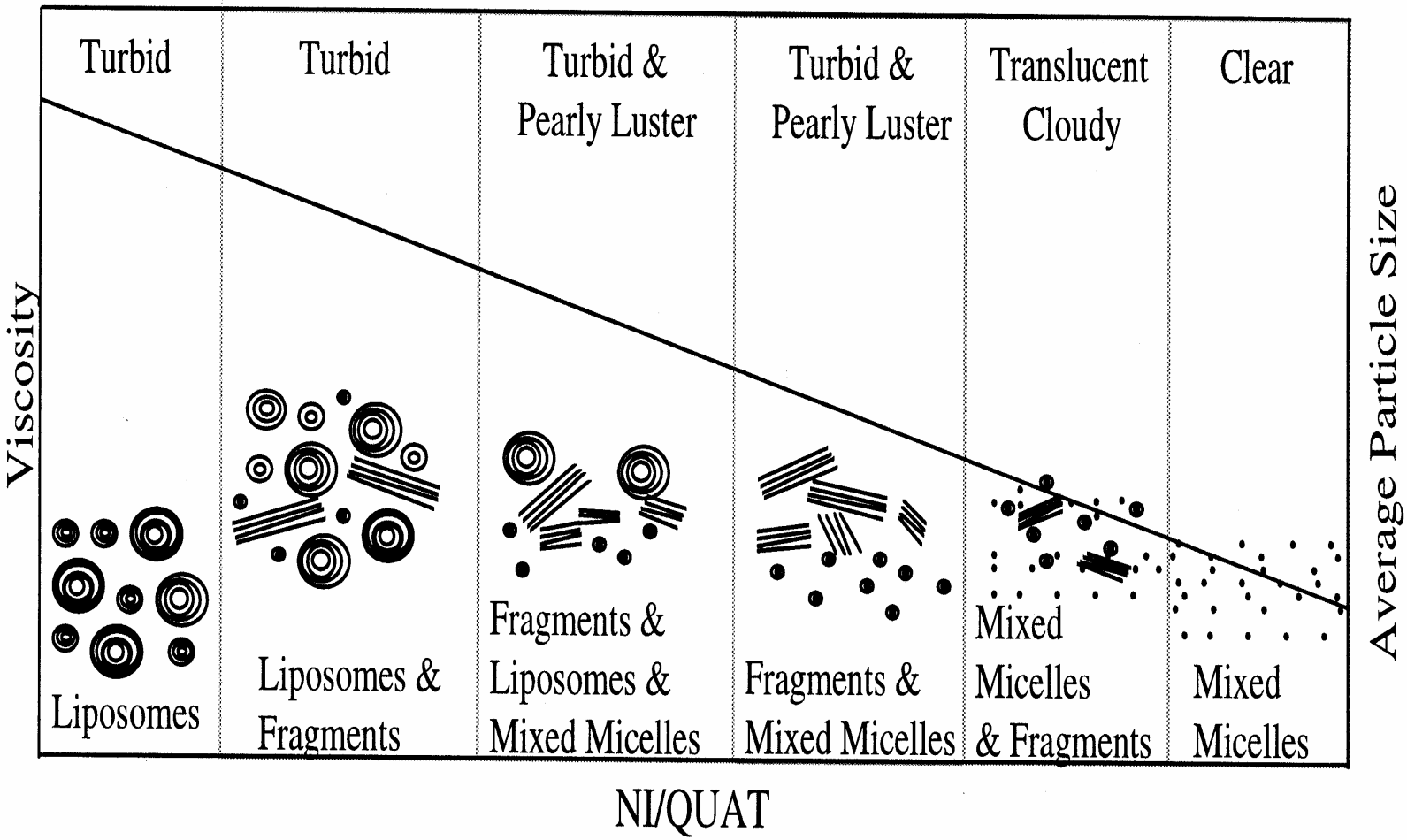
Progression of micellar shapes based on simple geometric constraints

V/Al <1/3	Spherical
1/3<V/Al<1/2	Rods
1/2<V/Al<1	Bilayers
V/Al >1	Inverted

Increasing order with increasing surfactant concentration
Additional phases (not shown) include cubic, bicontinuous, mlv

CLRC

ISIS



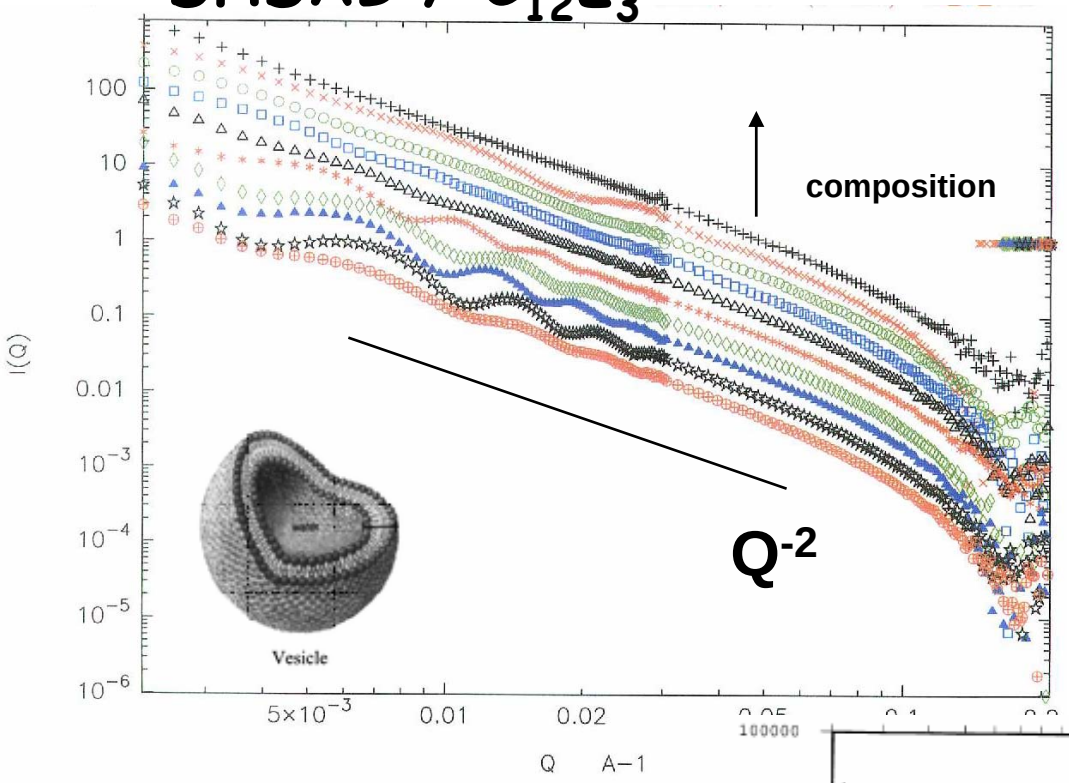
Complex evolution of solution microstructure, from cationic to nonionic rich. Related to relative preferred curvature of the different surfactant components.

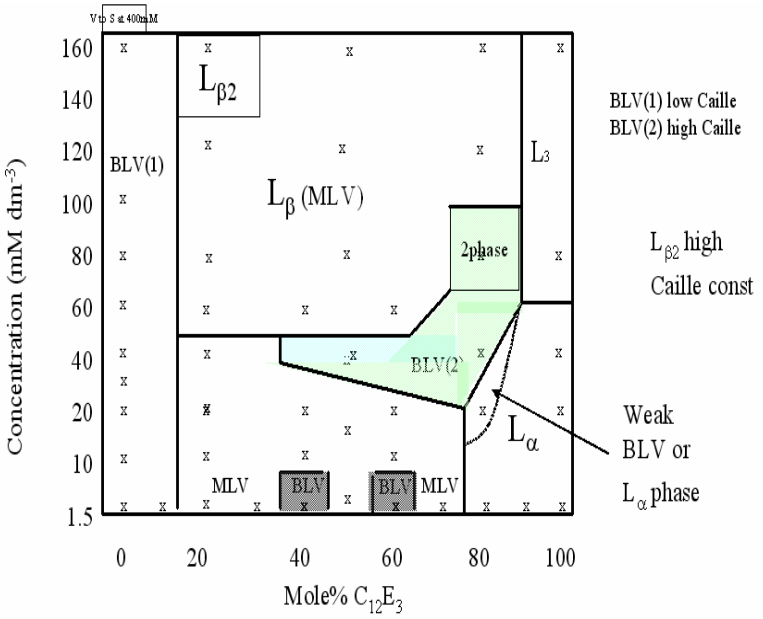
Now seen in a variety of different systems, which include lipid / nonionic mixtures and other ionic / nonionic surfactant mixtures

CLRC

ISIS

DHDAB / $C_{12}E_3$

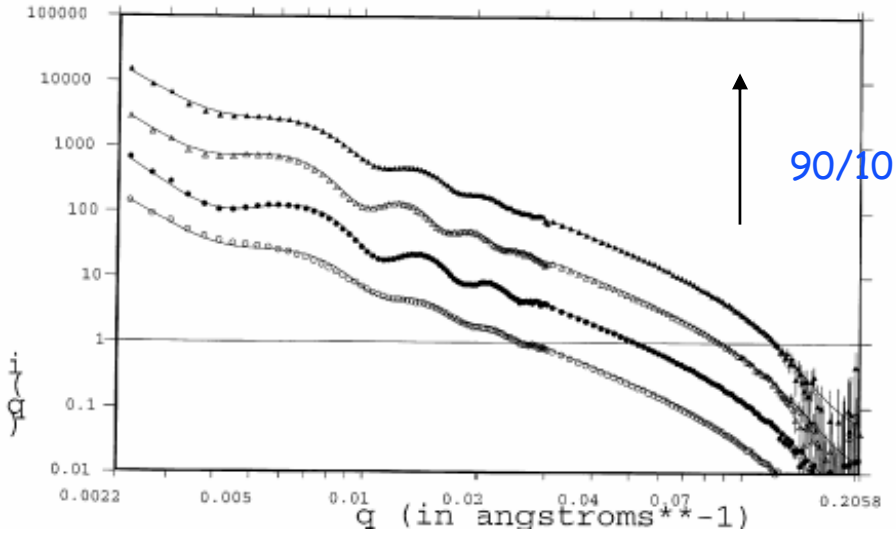




1.5 mM DHDAB / C12E3
Bi-lamellar vesicles

$$\eta = \frac{Q_0^2 k_B T}{8\pi\sqrt{\kappa B / d}}$$

d ~ 850 to 1150
δ ~ 28 to 32
η ~ 0.02 to 0.05

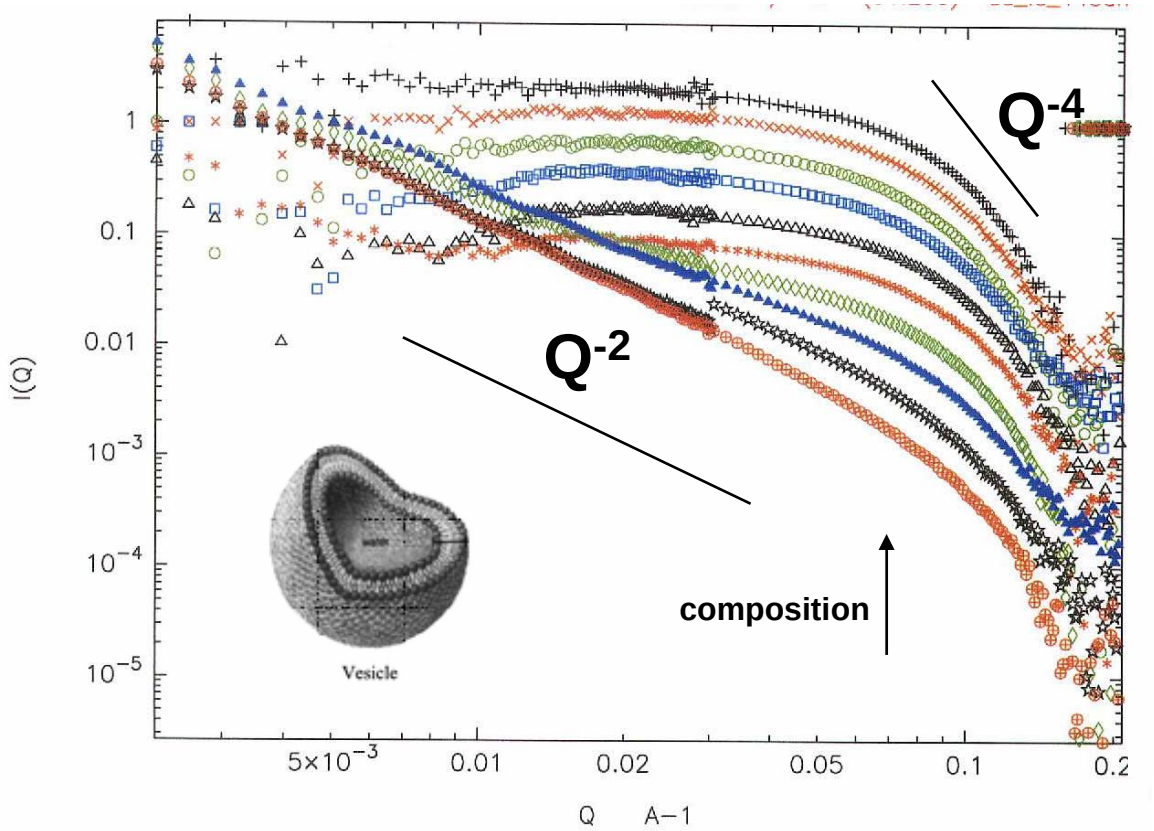


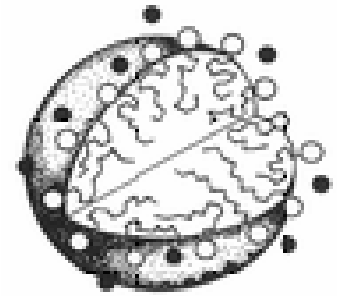
90/10 to 60/40

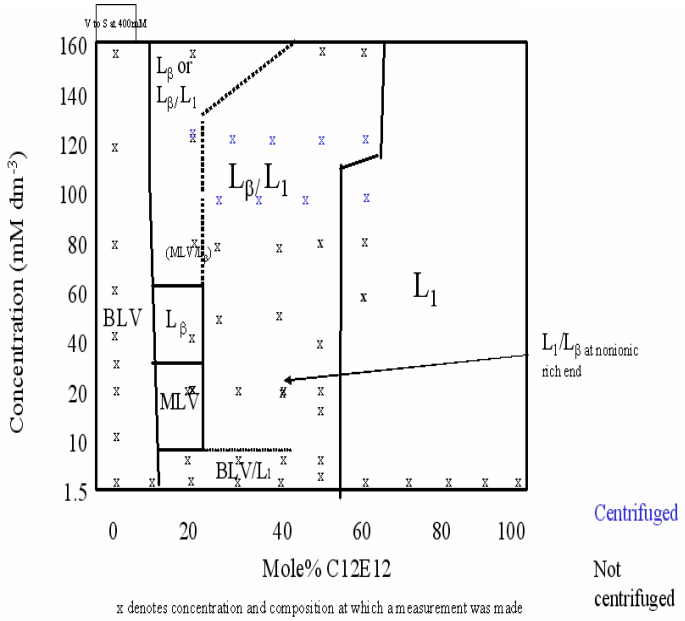
CLRC

ISIS

DHDAB / $C_{12}E_{12}$







For nonionic rich, globular micelles which grow with increasing cationic content, extensive micellar region

At low concentrations, transition to vesicles
At higher concentrations, transition to Lβ, and coexistence region

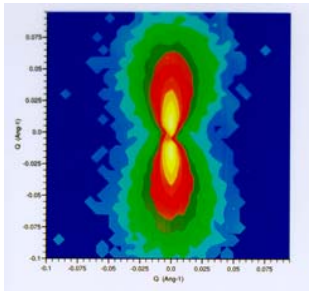
Penfold et al, Langmuir 20 (2004) 1269

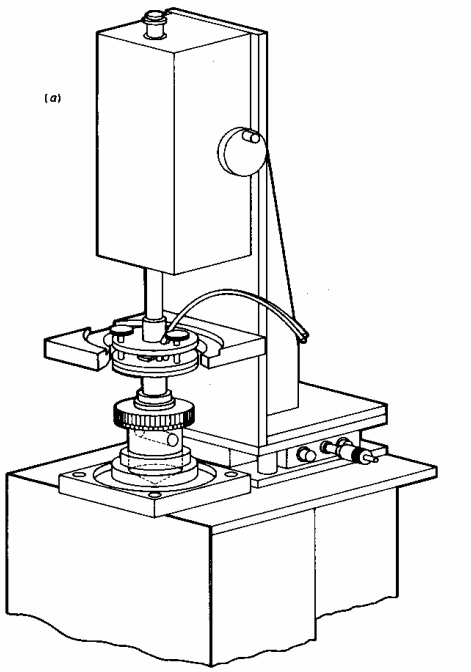
CLRC

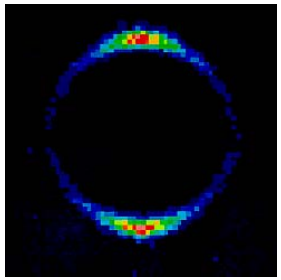
ISIS

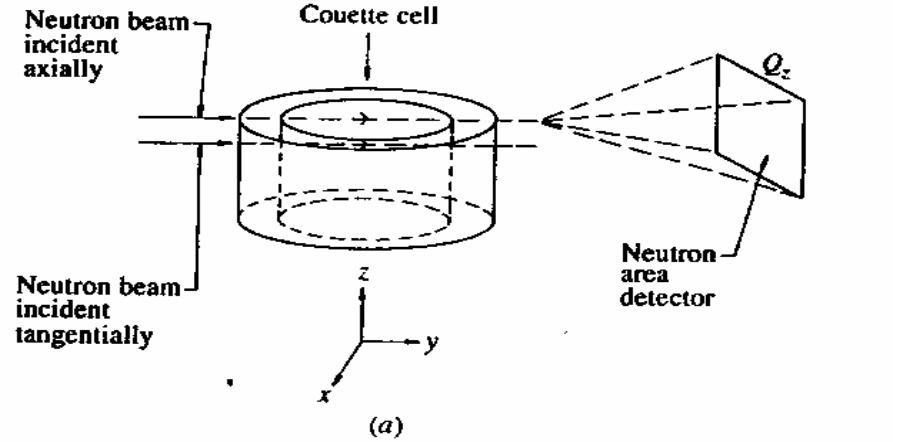
Shear flow alignment / orientation

Couette Flow Cell









d<<r shear gradient constant across gap

For ISIS Couette cell 0.5mm G=5.28N

Outer cylinder rotates

G/Dr : Elongated particles, tend to align in flow direction, Brownian motion randomises alignment, Dr

Significant alignment when G>>Dr

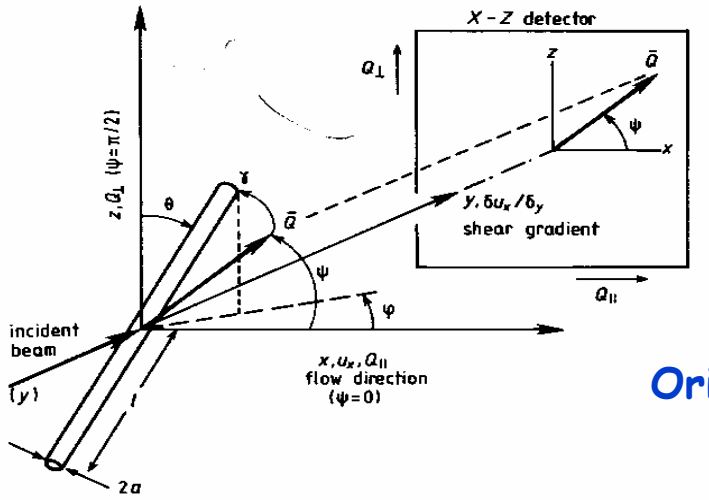
J B Hayter, J Penfold, J Phys Chem 88 (1984) 4589
H G Jerrard, Chem Rev 51 (1852) 345
H Thurn, J Kalus, H Hoffmann, J Chem Phys 80 (1984) 3440

CLRC

ISIS

For orientation in Couette flow,

$$I(Q) = I(Q,\Psi) = A\int_0^{2\pi} d\phi \int_0^{\pi} P(\theta,\phi;\Gamma)\left[F^2\left(Q,\gamma^+\right) + F^2\left(Q,\gamma^-\right)\right]\sin\theta d\theta$$



$$\cos\gamma^{\pm} = \sin\theta\cos\phi\cos\psi \pm \cos\theta\sin\psi$$

$Q_\perp$ refers to $\Psi = 0$

Q_{ll} refers to $\Psi = \pi/2$

Orientation distribution comes from solution to the diffusion equation

$$2\phi_0 = \arctan\left(8/\Gamma\right)$$

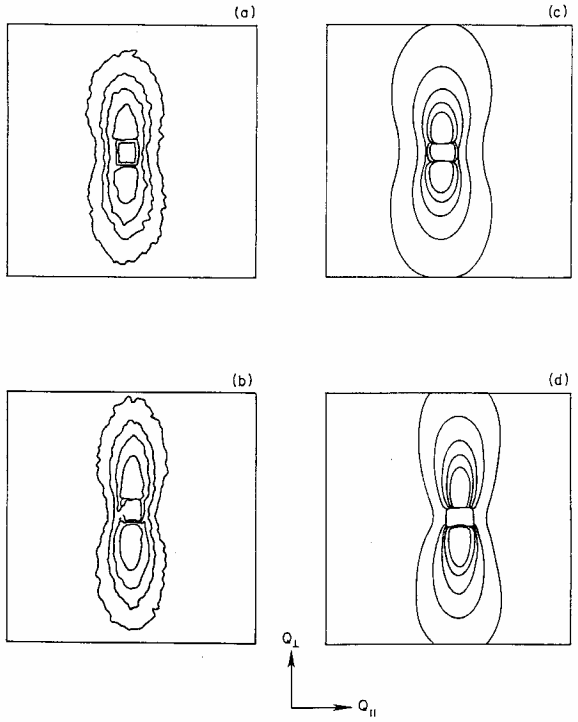
$$P(\theta,\phi;\Gamma) = \frac{\left(1-\cos^2\phi_0\right)\left(1+\sin^2\theta\cos 2\phi_0\right)^{3/2}}{4\pi\left(1-\sin^2\theta\cos 2\phi_0\cos 2\left(\phi-\phi_0\right)\right)^2}$$

J B Hayter and J Penfold, J Phys Chem, 88 (1984) 4589

CLRC

ISIS

Elongated Micelles (rod-like)

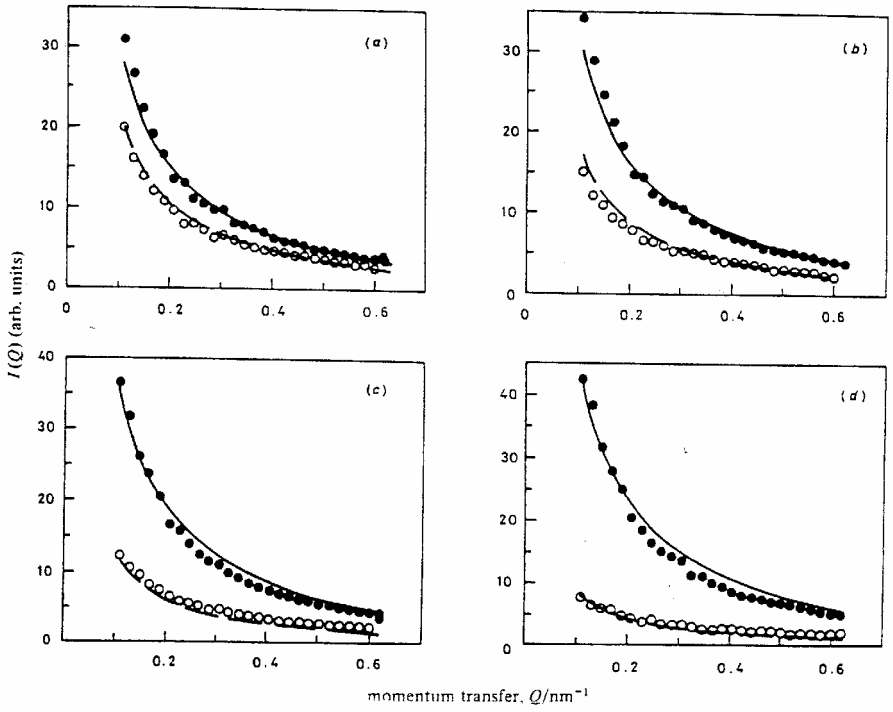


0.03M C16TAB / 0.4M KBr at
(a) G=5000s-1 and (b) G=7500 s-1

Calculation for 2l=2700, 2a=47

0.04M DDACl / 4M NaCl (a) G=2000 s-1 (b) 3000 (c) 5000 and (d) 7000

Calculation for 2l=2500, 2a=44



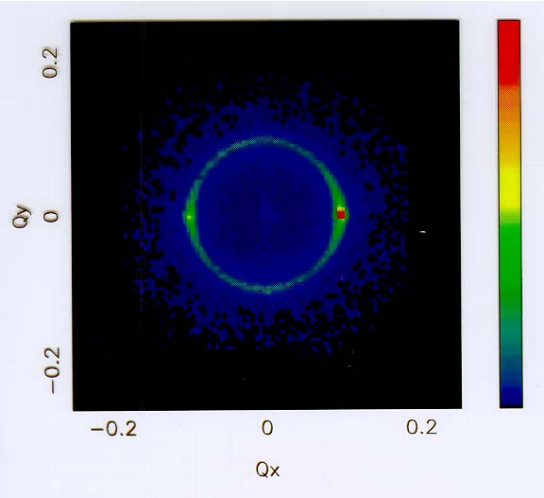
PG Cummins, E Staples, J Penfold, J B Hayter, J Chem Soc Farad Trans 83 (1987) 2773, Langmuir 5 (1989) 1195, Chem Phys Lett 138 (1987) 436

CLRC

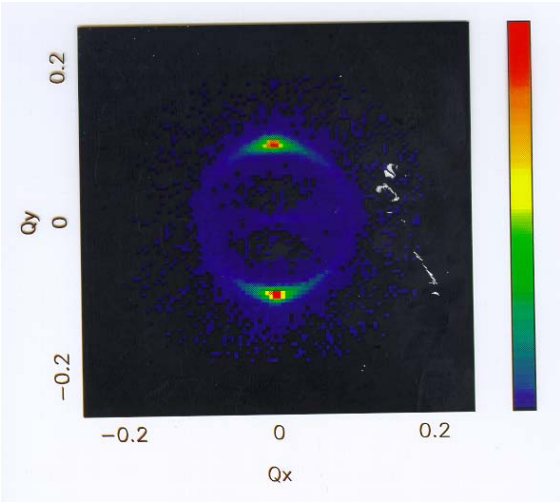
ISIS

Orientational order in concentrated lamellar phases

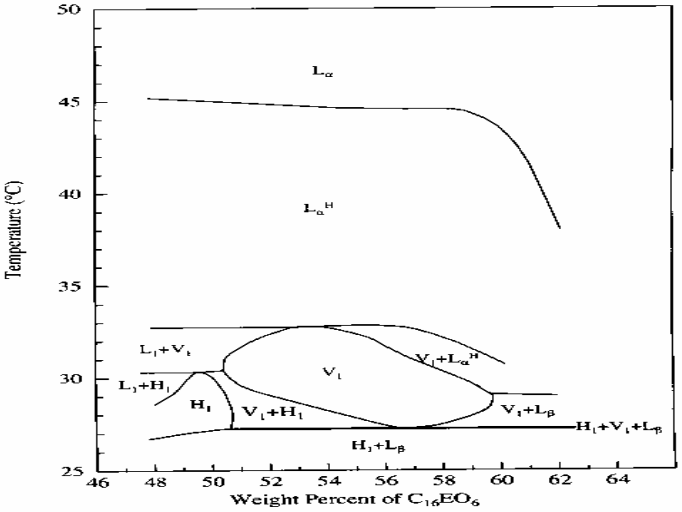
51 wt % C16E6

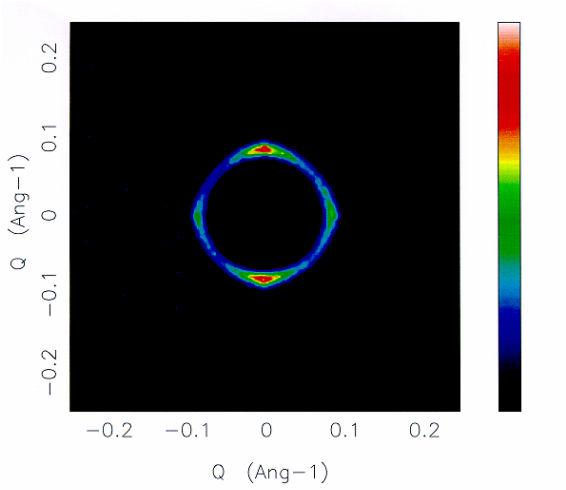


Cell side, low shear



Cell centre, G=5000s-1





Aligned parallel to flow-vorticity plane at low shear, and parallel to flow-shear gradient plane at high shear

At intermediate shear see more complex distribution

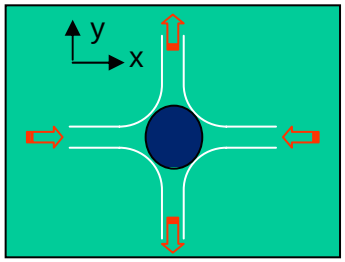
(Penfold, Staples, Khan Lohdi, Tiddy, Tucker, J Phys Chem 1997 101 66)

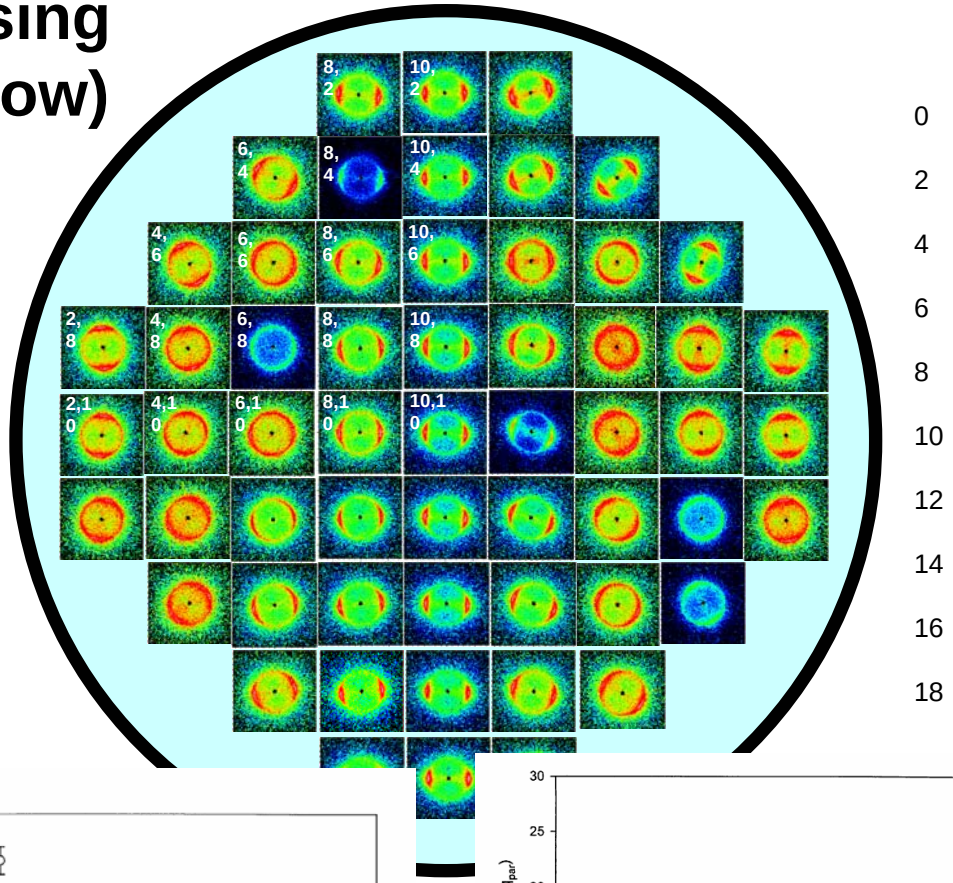
CLRC

ISIS

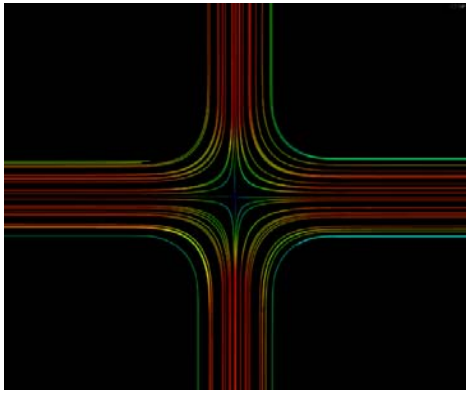
Mapping flow fields using SANS (elongational flow)

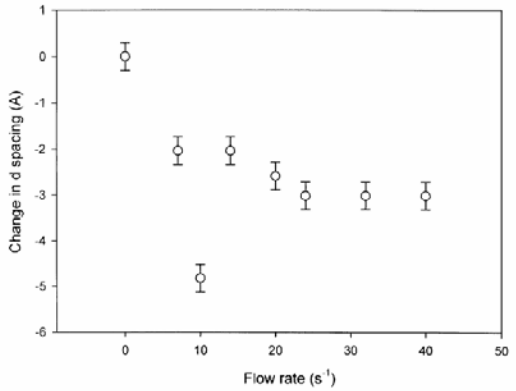
50.6 wt% $C_{16}E_6$ / D_2O at 55ºC
Lamellar phase dispersion

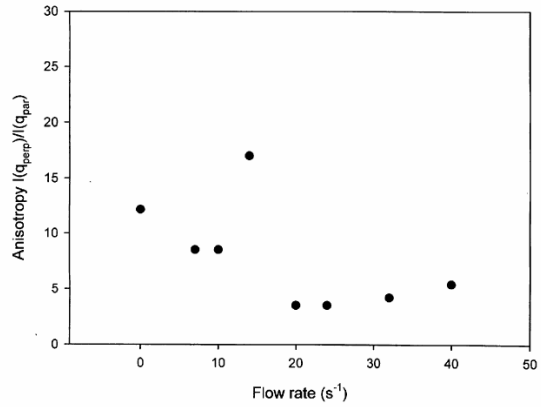




Distribution of orientational order reflects flow pattern







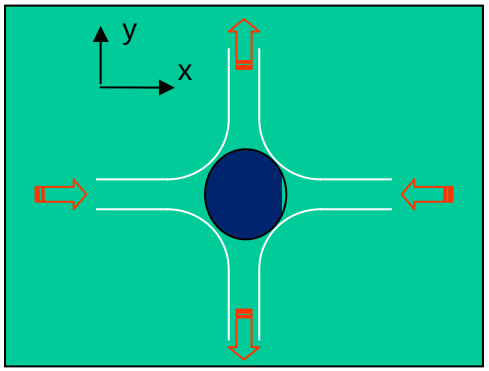
In anisotropy and d spacing variation with flow rate, see stretching of lamellae sheets and reduction in domain size

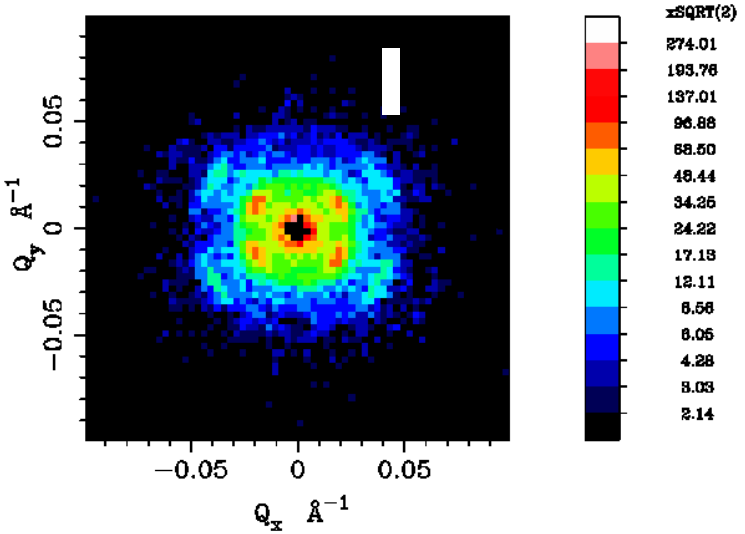
J Penfold et al, J Phys Chem B 110 (2006) 1073

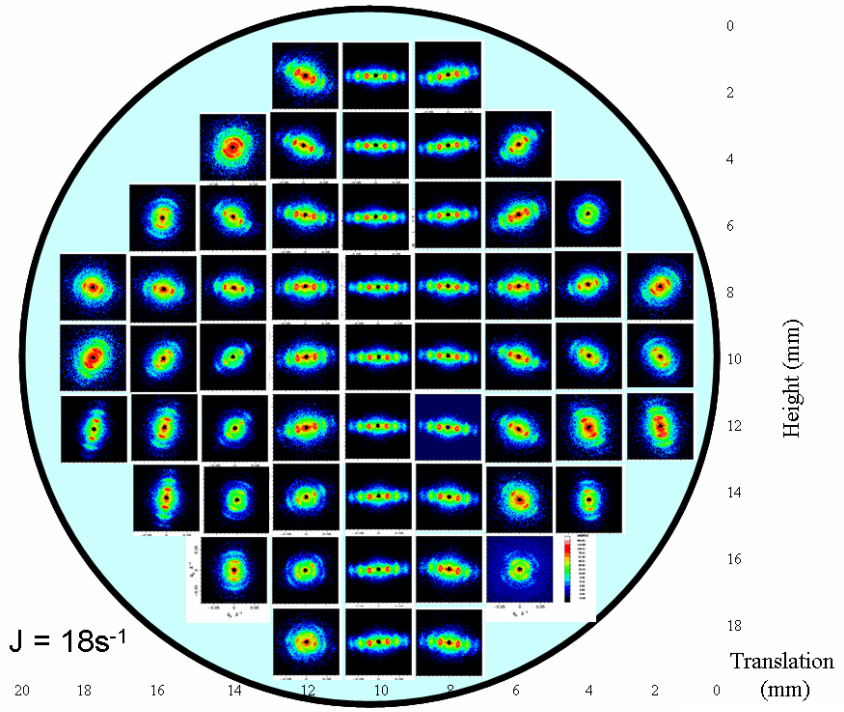
CLRC

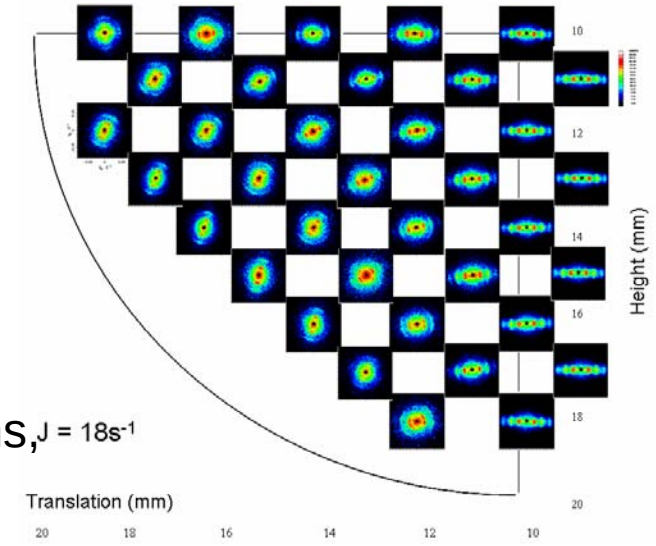
ISIS

Flow induced effects in mixed surfactant mesophases









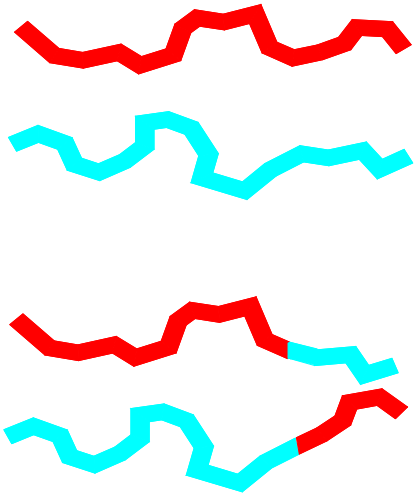
De-mixing in principle flow directions, form of 'banding'

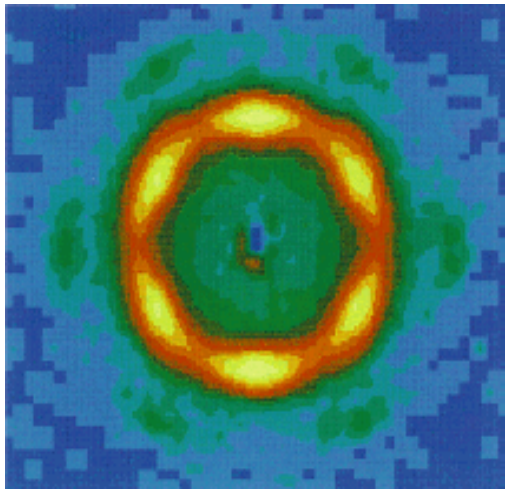
J Penfold, I Tucker, J Phys Chem B (2007) web alert

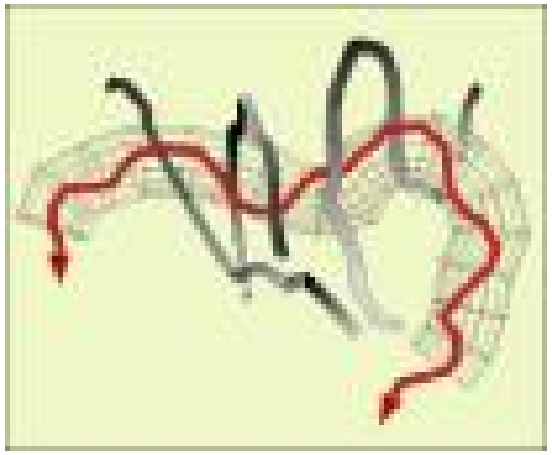
CLRC

ISIS

Polymers and polymeric materials







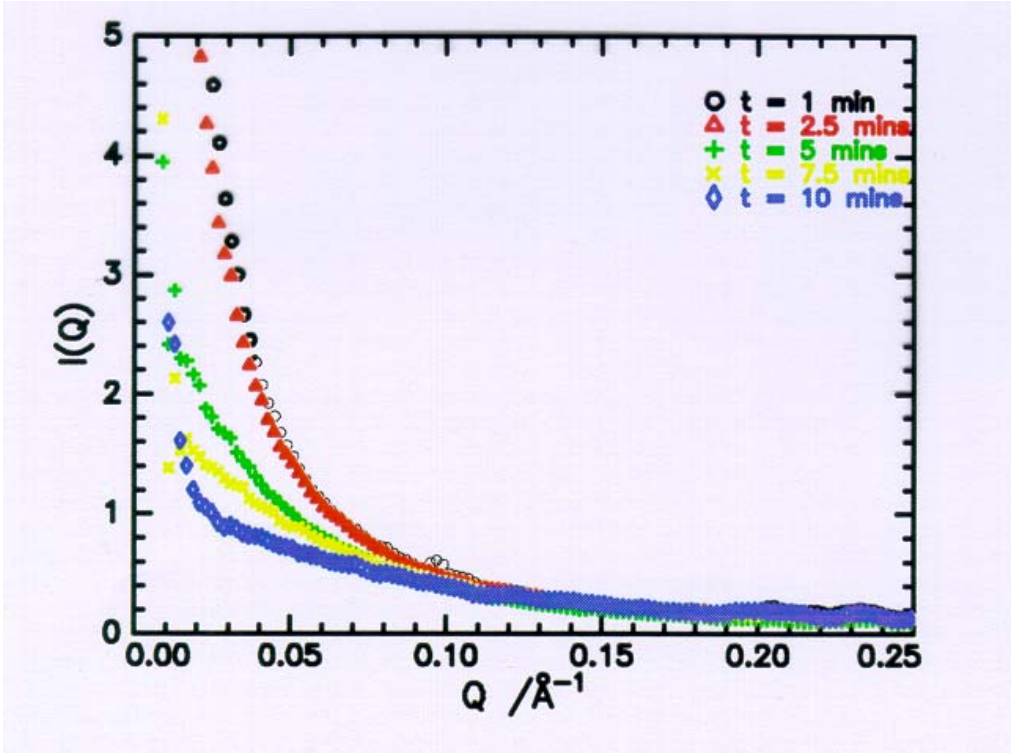
CLRC

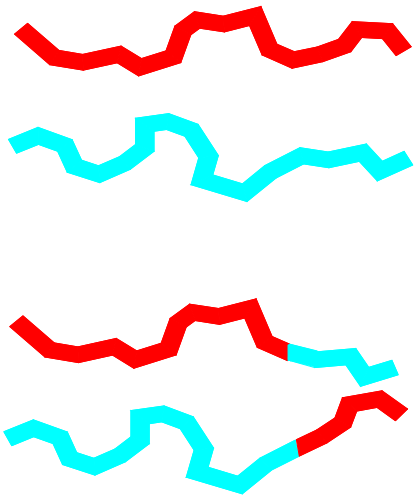
ISIS

Kinetics of co-polymer trans-esterification

(Backsona, Richards, King, Polymer 40 (1999) 4205)

Polyesters, such as PET (polyethylene terphalate) extensively used in packaging
PEN (poly-ethylene napthalene 2 6 dicarboxylate) has superior physical properties but due to high processing costs wish to use as blend





At elevated temperatures interchange reactions (scission and recombination), TRANS-ESTERFICATION, occurs

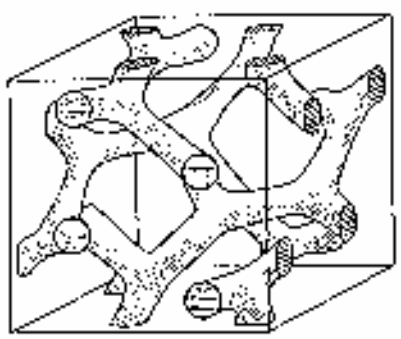
Follow reaction kinetics in-situ using SANS

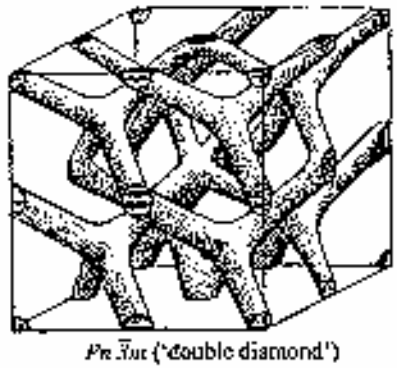
Results in formation of co-polymers in blends and changes in MW distribution in homo-polymers

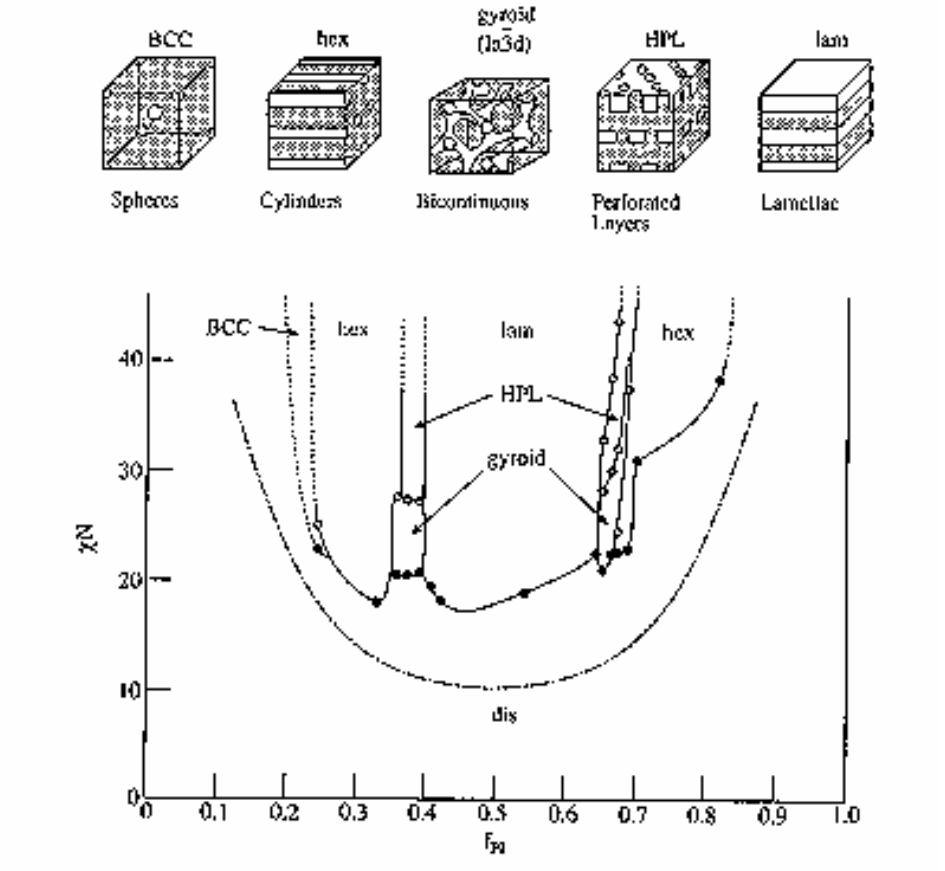
CLRC

ISIS

Block co-polymer ordered phases







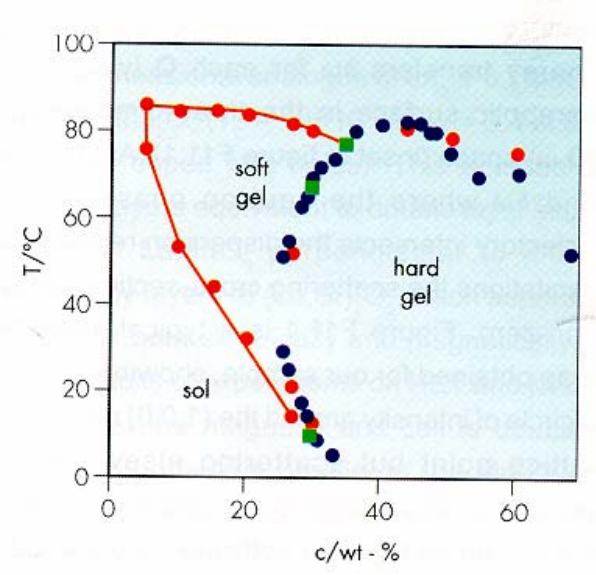
Poly-styrene - poly-isoprene block co-polymers

CLRC

ISIS

Microstructure of aqueous gels (block copolymers)

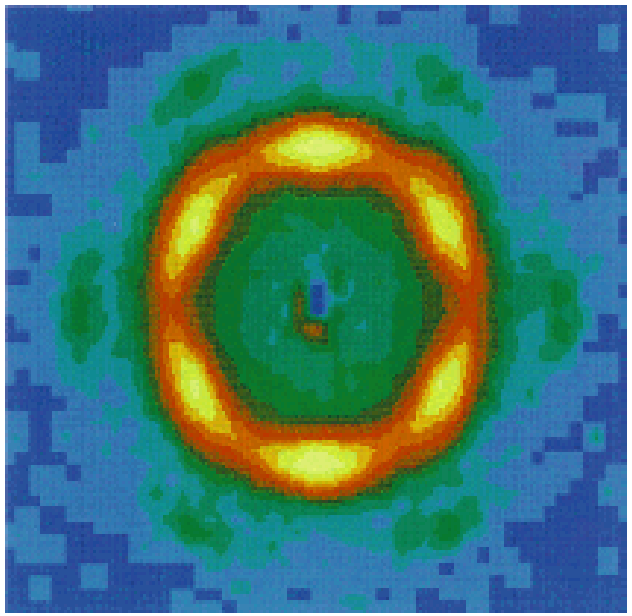
Phase diagram of aqueous solutions of E41B8 (oxyethylene-oxybutylene block copolymer) forms micellar gel with cubic packing
Hard gel is bcc or fcc, depending on preparation conditions, soft gel is a defective cubic phase



Phase diagram of aqueous solution of E41B8

Oriented fcc gel, induced by shear flow

Shear →



SANS from fcc gel of 25% E41B8 in 0.1M K2SO4 (oriented under shear)

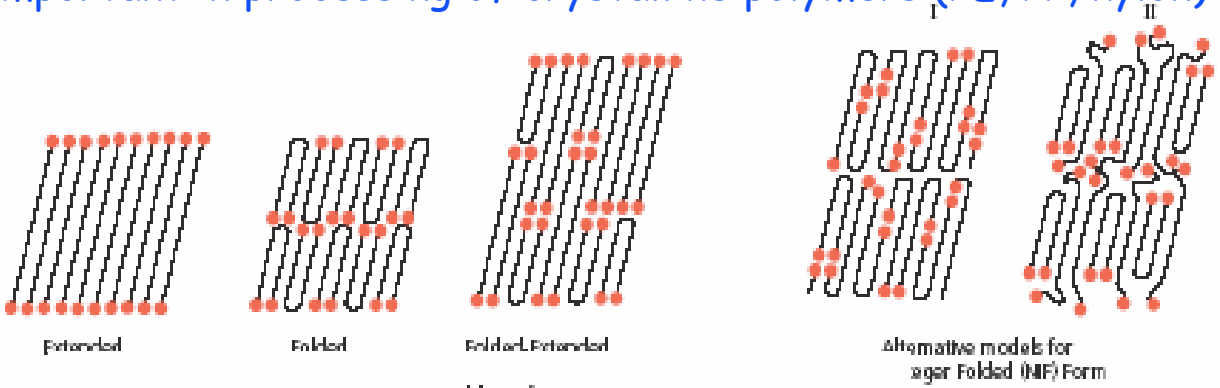
C Booth, G E Lu, S M Mai, B U Komaneschek, S M King, I A Hamley, J A Pople, A J Ryan, J P A Fairclough, N J Terrill

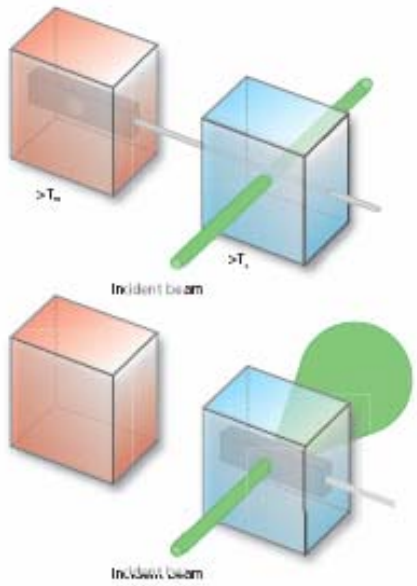
CLRC

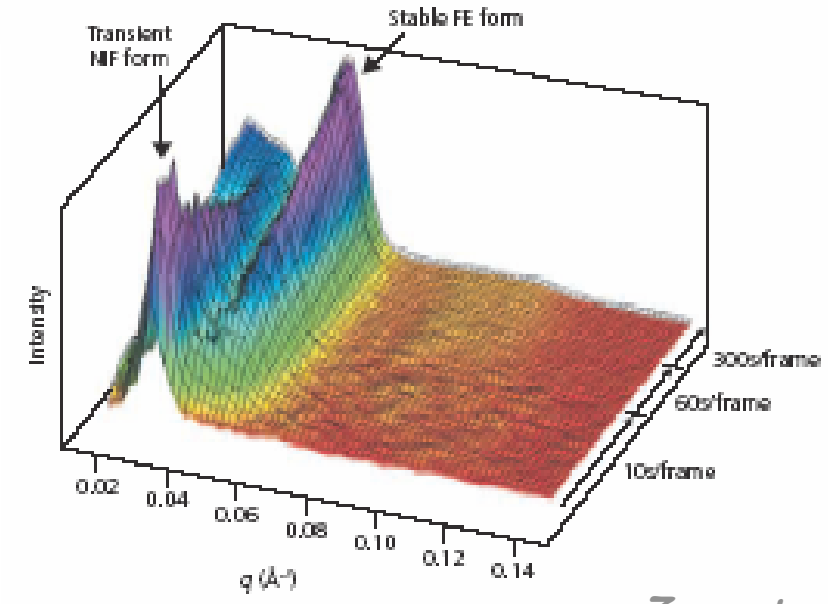
ISIS

Real time SANS study of transient phases in polymer crystallisation (Ungar, Spells)

Polymers often crystallise through transient phases,
Important in processing of crystalline polymers (PE, PP, nylon)







SANS data show that initial transient structure is in form of NIF which subsequently transforms to FE.

Final structures can be E, F, or FE

Zeng et al, Phys Rev Lett 30 (2003) 155508

CLRC

ISIS

Structural rearrrangements in polymer / surfactant mixtures (Cosgrove et al)

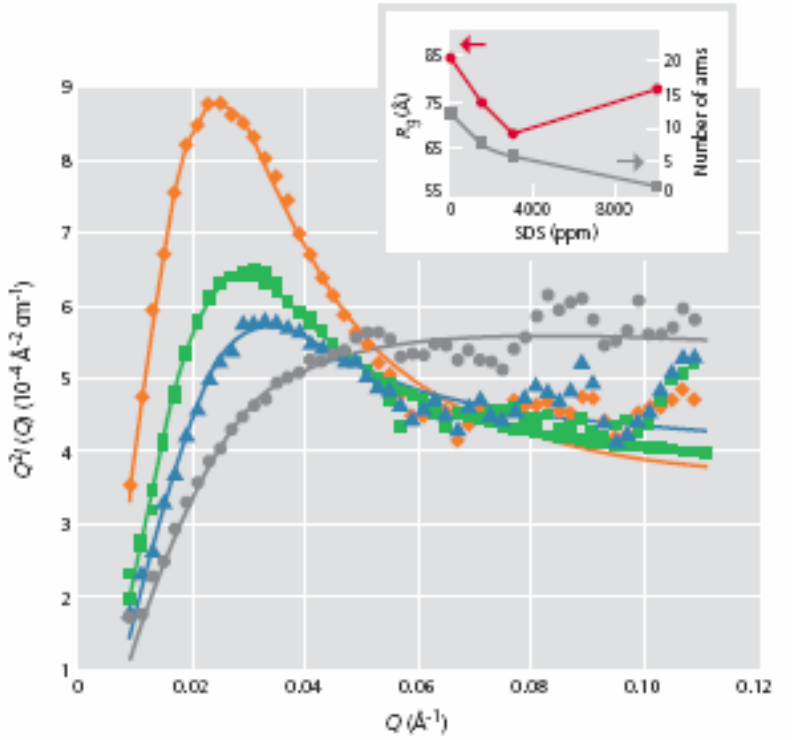
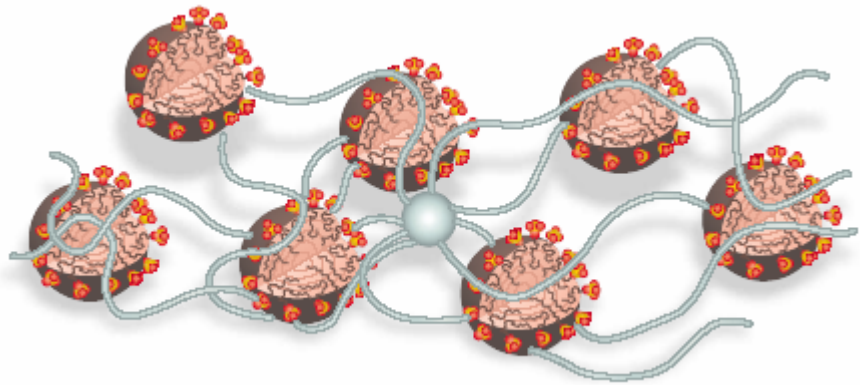


Fig. 1: SANS data shown as $Q^2I(Q)$ against Q, for 15-arm PEO star (130000 g mol^{-1}) in D_2O, adding D-SDS. ◆, without SDS; ■, 1500 ppm SDS; ▲, 3000 ppm SDS; ●, 10000 ppm SDS. Solid lines are fits to the Benoit star form factor, with the corresponding radius of gyration and the number of arms shown in the inset.

Weakly interacting polymer chains / surfactants form 'pearl necklace' structures



Rather different behaviour seen when polymer is in form of star rather than linear chain

Binding of micelles to arms of star forces conformational transformation into two bundles of stretched arms

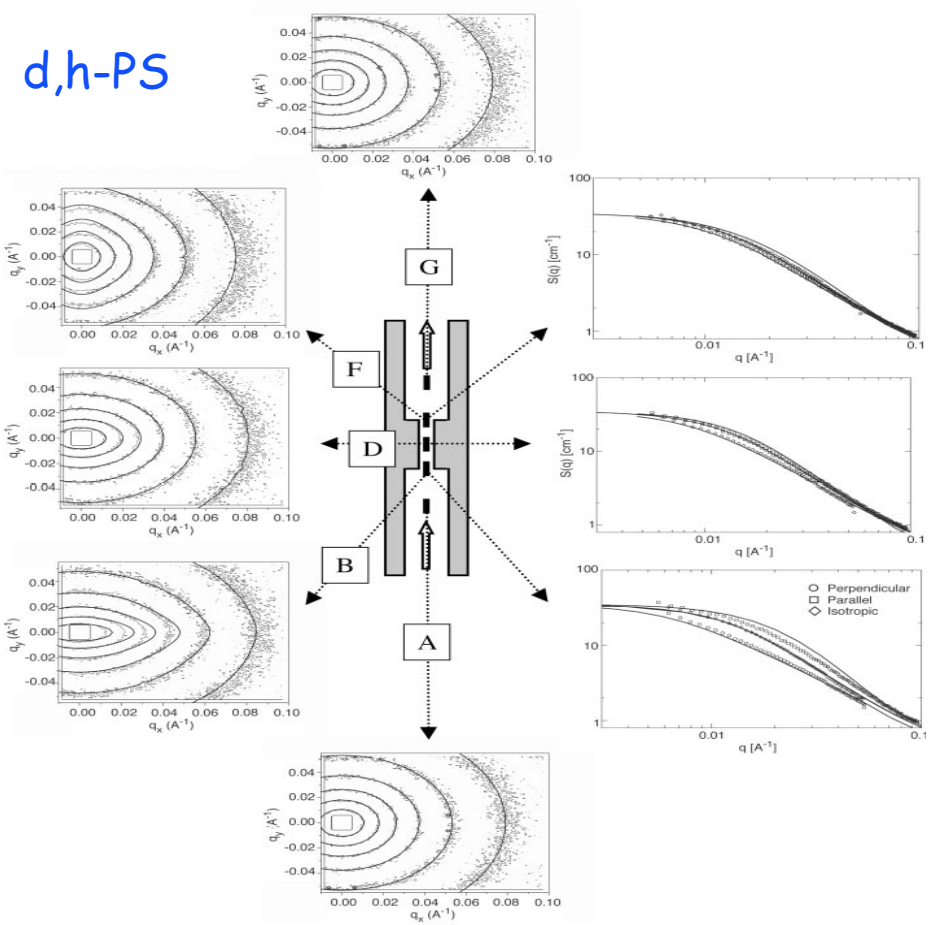
(Cosgrove et al, Langmuir 18 (2002) 855)

CLRC

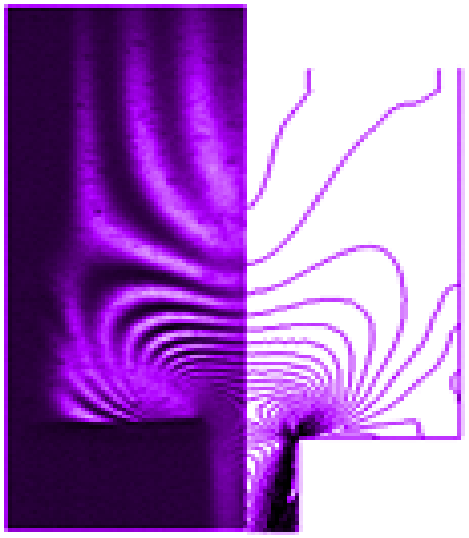
ISIS

Mapping polymer flow by SANS (McLeish et al)

d,h-PS



Entangled polymer melt flow through extended contraction visualised by SANS



Comparison of birefringence (stress difference pattern), and theory

SANS and stress patterns calculated from 'tube' model
Reptation + contour length fluctuations (tube breathing modes)
+ (in stronger flows) convective constraint release (disappearance / reapperance of entanglements due to flow)

Bent et al, Science 301 (2003) 1691, Graham et al Macromol 39 (2006) 2700

CLRC

ISIS

Summary

Described basics of technique

Illustrated the scope of the technique with examples from Soft Matter, over a broad range that included,

Surfactant aggregates, emulsions, super-critical fluids, liquid crystalline phases, micro-gels, and polymers

Presented work from a number of collaborations and other groups, which include,

Richardson (Bristol), Ryan (Sheffield), Thomas (Oxford), Richards (Durham), Cosgrove (Bristol), Ungar (Sheffield), McLeish (Leeds), and Unilever

ISIS