Small Angle Neutron Scattering Part3
SANS from particles - more detail

Remember that for a rotationally averaged or centrosymmetric particle, I(Q) is proportional to the square of the Fourier transform of $r^2\rho(r)$.

So what happens if we change the shape of the particle ....
DILUTE PARTICLE
SHAPE

\[ R_G = 31 \text{Å} \] (i.e. are same at small Q)

Rod  \( R=10 \text{Å}, L=104.5 \text{Å} \)

Disc  \( R=43.6, L=10 \)

Gaussian coil  \( R_G = 31 \text{Å} \)

Monodisperse sphere  \( R = 40 \) has  \( R_G = 40 \times \sqrt{3/5} = 31 \text{Å} \), has resolution smearing.

Polydisperse (Schultz)  \( R_{bar} = 40 \text{Å}, \sigma/R_{bar} = 0.15 \), is steeper at small Q
DILUTE PARTICLE SHAPE log-linear plot

$P(Q)$

$Q(\text{Å}^{-1})$

$R_g = 31 \text{ Å}$

Rod

Gaussian Coil

Disc

Polydisperse sphere

Sphere

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$0.1$
Cylinder (rod or disc)

\[ I(Q) = N(\Delta \rho)^2 V^2 \int_0^{\pi/2} F^2(Q) \sin(\gamma) d\gamma \]

\[ F(Q) = \frac{\sin(\frac{1}{2} QL \cos \gamma) \ 2J_1(QR \sin \gamma)}{\frac{1}{2} QL \cos \gamma \ QR \sin \gamma} \]

Randomly oriented rods full length L, radius R, \( V = \pi R^2 L \)

\( J_1(x) \) = “first order Bessel function of the first kind”

is NOT same as \( j_1(x) \) on next slide!

As \( x \to 0, \ J_1(x)/x \to \frac{1}{2} \ & \ \sin(x)/x \to 1 \) so \( P(Q \to 0)=1 \)

Integrate numerically over \( \gamma = \text{angle between } Q \text{ and rod axis.} \)

Partially oriented rods (e.g. under shear), anisotropic SANS has to be numerically integrated over a two dimensional “orientation distribution”. [See model 18 notes in FISH manual]
Ellipsoid

ellipsoid radii $R$, $R$, and $XR$

$X>1$ prolate (~ rugby ball),

$X<1$ oblate (~ pumpkin), $X=1$ sphere.

$$V = \frac{4\pi}{3} XR^3$$

$$I(Q) = N(\Delta \rho)^2 V^2 \int_0^{\pi/2} F^2(u) \sin(\gamma) d\gamma$$

$$F(u) = \frac{j_1(u)}{u} = \frac{3(\sin(u) - u \cos(u))}{u^3}$$

$$u = QR(\sin^2 \gamma + X^2 \cos^2 \gamma)^{1/2}$$

Note $F(u)$ is same as $F(QR)$ for sphere!

Change of variable to $\mu = \cos(\gamma)$ makes computation simpler:

$$I(Q) = N(\Delta \rho)^2 V^2 \int_0^{1} F^2(u) d\mu$$

$$u = QR((1 - \mu^2) + X^2 \mu^2)^{1/2}$$

Can be hard to distinguish $X<1$ and $X>1$, and also polydisperse spheres - absolute intensities, shape at high $Q$, and $S(Q)$ may help.
NOTE many text books and lecture courses focus on deriving all the equations - we will not do that here - but focus on how to use them to generate some good science!

Always look in the texts or research papers for a better understanding.

www.isis.rl.ac connects to Large Scale Structures and LOQ page
http://www.isis.rl.ac.uk/LargeScale/LOQ/loq.htm which has links to my FISH fitting program and to other places such as

“Collective Aid for Nomadic Small Angle Scatterers” canSAS at http://whisky.ill.fr/lss/canSAS/

The NIST NCNR reactor SANS group in USA has some useful lecture notes to download and an interactive SANS simulator program at:
http://www.ncnr.nist.gov/resources/simulator.html

Manfred Kriechbaum, Austria, has a simulator and more at http://scattering.tripod.com/
Gaussian coil (ideal polymer)

For a random chain, radial distribution $\rho(r)$ falls off exponentially, polymer segments are randomly oriented, $R_G =$ radius of gyration, the rms (root mean square) radius.

$$I(Q) = I_0 \left\{ \frac{2(y - 1 + \exp(-y))}{y^2} \right\}$$

$$y = (QR_G)^2$$

$R_G =$ radius of gyration, the rms (root mean square) radius – same as in Guinier plot.

For dilute polymer, as usual

$$I_0 = NV^2(\Delta \rho)^2$$
Absolute intensity of non-dilute samples & polymers

For dilute and concentrated (solid or melt) polymers and other particles:

\[ I_0 = \phi (1-\phi)V(\Delta\rho)^2 = \frac{c}{d}(1-\frac{c}{d})\frac{M}{dN_A}(\Delta\rho)^2 \]

\( \Phi = \) volume fraction
\( V = \) particle volume
\( \Delta\rho = \) scattering length density difference
\( c = \) concentration (g.cm\(^{-3}\)),
\( M = \) molecular weight (g.mol\(^{-1}\)),
\( N_A = \) Avogadro’s number,
\( d = \) bulk density (g.cm\(^{-3}\)).

**NOTE** at 50%vol, \( \phi(1-\phi) \) halves the usual intensity.

Polymer equations - often “disguised” with

(polymerisation index) \( \times \) (monomer molecular weight, segment length etc.)

For micelles M gives the aggregation number.
Gaussian coil - more

- Gaussian coil equations apply in solution and in bulk solid or melt of mixed D- and H- chains.

- In the bulk (solid or melt) there is a remarkable “cancellation” of intermolecular cross-terms so $S(Q) = 1$ and we see ONLY “single chain scatter” even at $\phi = 0.5$. The structure of a D-polymer chain around an H-chain is the same as the structure of the H-chain around the D-chain. SANS on a mixture of H- and D-polymers is a unique way to see the conformation of an individual chain.

Spaghetti – real polymers have a much shorter “persistence length”

“Deuterium Labelled” spaghetti, neutrons can see the shape and size of individual chains.
Gaussian coil – yet more

- simple modified equation for polydisperse Gaussian coils.

- Expect \( R_G^2 = \frac{n^2}{6} \) for \( n \) segments of length \( \ell \) in the chain.

- In solution Gaussian coil equation may only be approximately correct, modifications for solvent interaction (good, poor, theta etc.) are possible.


- BEWARE some times D- and H- polymers may phase separate.

- Worm models e.g. Kholodenko (in FISH) can switch smoothly between long rigid rod and Gaussian coil.

[ More on polymers later]
Contrast variation - introduction

For core plus shell spherical particle

e.g. Spherical Shell $R_1 = 40 \text{ Å}$ \((R_2-R_1) = 15 \text{ Å} \) (with 15% polydispersity)

\[
I(Q) = N\left\{ (\rho_1 - \rho_2) V_1 F(Q, R_1) + (\rho_2 - \rho_3) V_2 F(Q, R_2) \right\}^2
\]

\[
F(Q,r) = \frac{3(sin(Qr) - Qr \cos(Qr))}{(Qr)^3}
\]

At “contrast match” $\rho_1 = \rho_3$, then we see “hollow shell” with oscillation in $I(Q)$ which is very sensitive to the details of the structure.

\[
I(Q) = N(\rho_1 - \rho_2)^2 \left\{ V_1 F(Q, R_1) - V_2 F(Q, R_2) \right\}^2
\]
CONTRAST VARIATION - CORE/SHELL PARTICLES

e.g. Core $\rho_1 = 6 \times 10^{10}$ cm$^{-2}$, mean $R_1 = 40$ Å, $\phi = 1\%$, $\sigma/R_{\text{bar}} = 15\%$
$R_2 - R_1 = 15$ Å shell $\rho_2 = 3 \times 10^{10}$ cm$^{-2}$.

“drop” contrast sees whole particle
( here some effect of the shell )

“core” - solvent
“matches” shell

“Shell” - solvent
“matches” core

“interference” – rarely seen, but be aware! Solvent between “core” & “shell” matches the average sld of the whole particle.
Small Q, long dist. SANS ~ zero,
High Q, short distances some scatter!
NOTE  I(Q) from “shell contrast” scales non-linearly with particle size - trial calculations are useful to plan experiments.

typical background levels?
POLYDISPERSITY

Sum SANS over size distribution - Gaussian, log-normal, uniform, etc. “Schultz distribution” is similar to log-normal but I(Q) is analytic. Generally SANS is only sensitive to mean $R_{\text{bar}}$ and “polysdispersity” $\sigma(R)/R_{\text{bar}}$ where $\sigma(R)$ is the standard deviation.

Schultz distribution:

$$N(r) = \left[ \frac{(Z + 1)}{R_{\text{bar}}} \right]^{Z+1} \frac{r^Z}{\Gamma(Z+1)} \exp \left\{ \frac{-(Z+1)r}{R_{\text{bar}}} \right\}$$

$$\frac{\sigma}{R_{\text{bar}}} = \frac{1}{(Z + 1)^{1/2}}$$

$$Z = \left( \frac{R_{\text{bar}}}{\sigma} \right)^2 - 1$$

NOTE: at large $\sigma$ the Schultz is very skewed and has significant numbers of small particles. Gamma function $\Gamma(n) = (n-1)!$ Care is needed in numerical calcs as $Z$ may be large.
Core, Shell, Drop contrasts – real microemulsion example with polydispersity.

Water/DDAB/oil microemulsions
DDAB has two C$_{12}$ chains.

SHELL CONTRAST

polydispersity $\sigma/R_{\text{bar}} = 0.30$, 0.25, 0.10 and 0.05 (sharpest)
(Q resolution smearing included here)

Vary scattering length density of the shell, corresponding to mixing solvent into shell.

$\rho_{\text{shell}} = -0.40$, +0.5, +1.0 and +2.0 (lowest) x $10^{10}$cm$^{-2}$

$\sigma/R_{\text{bar}} = 0.20$
SIMULTANEOUS FIT
To Core, Shell and Drop contrasts.

INDIVIDUAL FITS
Typical Polydispersity

RESULTS
Water/DDAB/cyclohexane microemulsion

\[
\begin{array}{cccccc}
\text{R}_{\text{bar}} \text{ core} & \sigma/\text{R}_{\text{bar}} & (\text{h}+\text{t}) & \rho_{\text{film}} & \text{R}_{\text{drop}} \\
(\text{Å}) & (\text{Å}) & (10^{10}\text{cm}^{-2}) & (\text{Å}) & \\
\text{CORE individual} & 21.2 & 0.20 & - & - & - \\
\text{SHELL} & 20.1 & 0.25 & 11.6 & +0.4 & 31.7 \\
\text{DROP} & - & 0.23 & - & - & 28.2 \\
\text{SIMULTANEOUS} & 19.7 & 0.25 & 11.0 & -0.4 & 30.7 \\
\end{array}
\]

\(\rho_{\text{film}}\) for DDAB shows NO solvent mixing into C12 - C12 tails

Note DROP minus CORE sizes suggests \((\text{h}+\text{t}) = 28.2 - 21.2 = 8 \text{ Å}, which is too small!
Here contrast variation gives a better structure and provides clues about composition. Asymmetric C12-C18 surfactant does have \(\sim 8\%\) solvent in surfactant film.
How much can SANS tell about interfacial structure?

For a sphere

\[ F(Q,r) = \frac{3(\sin(Qr) - Qr \cos(Qr))}{(Qr)^3} \]

Complex spherical interfaces can be modelled as a series of small steps:

\[ I(Q) = N\left[ (\rho_1 - \rho_2)V_1 F(Q, R_1) + (\rho_2 - \rho_3)V_2 F(Q, R_2) + \ldots \right]^2 \]

e.g. trial fits to polydisperse hollow shell, given \( R_1 \)
How much can SANS tell about interfacial structure?

SANS provides information about density or composition profiles, especially if we can contrast match the core or substrate.

This is very useful for thicker layers of polymers, as we will see later.

Diffuse spherical shells

Apart from a vertical step in $\rho(r)$, there are some other equations, e.g. in previous example if $\rho(r)$ increases linearly from zero to $\Delta \rho$ between radii $a$ and $b$,

$$F(Q) = \frac{4\pi \Delta \rho}{Q^4(b-a)} \left\{ 2(\cos(Qa) - \cos(Qb)) + Qa\sin(Qa) - Qb\sin(Qb) \right\}$$

Core, Shell, Drop contrasts – “drug delivery” microemulsion

EC/DDAO/water - oil in water microemulsion 1.4% vol, $R_{DROP} \sim 32 \, \text{Å}$, $R_{CORE} \sim 17 \, \text{Å}$

Fits $\sim 29\%$ vol ester oil in tails, Dashed lines - no oil in tails, SSE is x5 worse

NOTE - cannot ignore $S(Q)$ even for $C_{12}H_{25}NO(CH_{3})_2$ [More later]

Interfacial structure - example

A bio-compatible block copolymer micelle in water. Had to synthesise d-poly lactic acid core.

Core/shell/shell model answers:
“Is the PEG shell a mushroom (with a maxima in the density) or a pancake?”
dPLA(3000)-PEG(5000) block copolymer micelle

Simultaneous fit $R_C \sim 60\text{Å}, \delta \sim 100\text{Å}$


Close to “interference” contrast - difficult to fit!
Interacting particles - in more detail

\[ I(Q) = P(Q) \times S(Q) = \text{Form Factor} \times \text{Structure Factor} + \text{BKG} \]

where \( S(Q) \) can be calculated for hard spheres, charged spheres etc. As volume fraction increases \( I(Q) \) is pushed down at small \( Q \) until it becomes a “Bragg” peak at \( d = \frac{2\pi}{Q} \)

e.g. 26% vol hard sphere \( S(Q) \) of \( R = (40 \, \text{Å core} + \text{matched} 15 \, \text{Å shell}) \) with polydispersity \( \sigma/R_{\text{bar}} = 0.15 \) \( (\Delta \rho = 6 \times 10^{10} \text{cm}^{-2}) \)
SDS surfactant micelles (ISIS training course data)

0.5% & 2% SDS in D2O, with 2% SDS + 0.2% w/w NaCl in D2O

Charged particles have a VERY strong S(Q), even at low volume fraction

S(Q = 0) ~ 1/compressibility

no salt, charged system is less compressible

S(Q) may be “damped” by adding salt, BUT this often causes the micelle structure to change (usually larger, more rod like, as also happens with increasing concentration)
S(Q) for particles in solution - Introduction

Measure $S(Q)$, assuming $P(Q)$ constant using a series of concentrations, “divide by most dilute $P(Q)$”.

But $P(Q)$ for micelles often changes! Better to fit SANS data (over a wide $Q$ range), which shows where $S(Q) \rightarrow 1$ and $P(Q)$ can be trusted.

Monodisperse Hard Sphere $S(Q)$ - analytic equation, depends on Diameter $\sigma$ and Volume fraction $\eta$. “Works” for (slightly) anisotropic particles. [more examples later]

Modifications to hard sphere can add attractive or repulsive square well potential (e.g. Sharma & Sharma square well).

Full maths for polydisperse hard spheres solved by van Beurten & Vrij.

Hayter & Penfold, charged spheres, needs diam $\sigma$, volume $\eta$, the charge on the particle (surface potential) and $\kappa = 1/r_D$, the “inverse Debye length”.
Aside - Debye Length – for charged particle interactions

Debye length is such that the effective strength of the charge falls off by 1/e. For simple solutions Debye length may be calculated:

\[ r_D^2 = \frac{\varepsilon_0 K_r RT}{2 \rho N_A e^2 I} \]

 Ionic strength \[ I = \frac{1}{2} \sum (m_+ z_+^2 + m_- z_-^2) \]

e.g. 1:1 electrolyte, at 0.1 molal in water at 25°C (e.g. approx 0.1M NaCl)

\[ r_D^2 = \frac{(8.85 \times 10^{-12} \text{C}^2 \text{N}^{-1} \text{m}^{-2})78(8.31 \text{JK}^{-1} \text{mol}^{-1})(298\text{K})(10^{20} \text{Å}^2 \text{m}^{-2})}{2(1000\text{kg.m}^{-3})(6.02 \times 10^{23} \text{mol}^{-1})^2 (1.6 \times 10^{-19}\text{C})^2 (0.1\text{mol.kg}^{-1})} \]

\[ r_D = 9.6\text{Å}, \quad 1/r_D = 0.10 \text{ Å}^{-1} \]
S(Q) for particles in solution - Introduction

Most of the useful S(Q) equations assume the “Decoupling Approximation” positions of particles are not dependent on their size or orientation, i.e. no cooperative effects or preferred orientations for anisotropic particles.

(e.g. Studies of mixtures of large and small particles using contrast variation, show small ones tend to spend more time in the spaces between the large one, so S(Q) would need special treatment! )

There are no routine S(Q) calculations for anisotropic particles such as ellipsoids, rods or discs, due to the problem of orientational distributions.
S(Q) for particles in solution - more detail

**S(Q) can be corrected for P(Q).**

Detailed study of the interparticle summations shows

\[ I(Q) = S(Q)\langle F(Q)\rangle^2 + \langle F(Q)^2 \rangle - \langle F(Q) \rangle^2 \]

Where \(< >\) denotes an average over shape and size.

For monodisperse spherically symmetric particles, the last two terms are the same & cancel.

In software it is convenient to write this as:

\[ I(Q) = P(Q)S'(Q) \]

\[ S'(Q) = 1 + \beta(Q)\{ S(Q) - 1 \} \]

\[ \beta(Q) = \frac{\langle F(Q)^2 \rangle}{\langle F(Q) \rangle^2} = \frac{\langle F(Q) \rangle^2}{P(Q)} \]

\( \beta(Q) \) varies from 0 to 1, it can help to distinguish polydisperse spheres from anisotropic particles such as ellipsoids.


Need to understand yet more about $S(Q)$ in order to see the limitations of the different models and to recognise some jargon!

Schematic of 2 dimensional radial distribution of atoms, averaging many times gives a smooth $\rho(r)$.

In 3 dimensions pair correlation function $g(r) = 4\pi r^2 \rho(r)$ tends to 1.0 Theory like atomic liquid BUT for colloids the particle diameter $\sigma$ becomes significant.

Diffraction pattern:

$$S(Q) = 1 + n_0 \int 4\pi r^2 (g(r) - 1) \frac{\sin(Qr)}{Qr} dr$$
Maths to predict $g(r)$ can easily deal with nearest neighbour interactions, but we also need all the indirect correlations. This becomes very messy with different species such as micelles and counter ions, so more approximations are needed.

Ornstein-Zernicke approximation relates total correlation $h(r) = g(r) - 1$ to the direct correlation $c(r)$

$$h(r) = c(r) + n_0\int c(r')h(|r - r'|)dr'$$

To solve this for 2 unknown functions needs “closure relations” such as Hypernetted Chain (HNC), Percus-Yevick (PY) or Mean Spherical Approximation (MSA).


**General results:** (1) systems with a pair potential $u(r)$

$$c(r) \rightarrow -\frac{u(r)}{k_B T} \quad \text{as} \quad r \rightarrow \infty$$

i.e. interactions can be related to structure.

(2) As $Q \rightarrow 0$  \quad  $S(0) = n_0 k_B T X$  \quad where $X$ = isothermal compressibility

So, for example, $S(Q)$ for Percus-Yevick Hard spheres needs

$$c(r) = 0 \quad r > \sigma \quad \text{and} \quad g(r) = 1 + h(r) = 0 \quad r < \sigma$$

(no correlation between particles and particles cannot overlap)

The resulting analytic $S(Q\sigma)$ is “scalable” - particles of different diameters have same $g(r)$ at same volume fractions.
S(Q\sigma) for P-Y Hard spheres at \eta = 30, 40, 50\% volume fraction

\eta = n_0 \frac{4\pi}{3} R^3 = n_0 \frac{\pi}{6} \sigma^3

N.B. close packed spheres is

\eta = \frac{\pi}{3\sqrt{2}} = 74\%

Hayter - Penfold S(Q) for charged spheres uses MSA

\[ g(r) = 1 + h(r) = 0 \quad r < \sigma \]

OCM, “One Component Macroion” approx “analytic” result (needs solve a cubic equation) for a Hard Core plus Yukawa (screened Coulomb) potential:

\[ u(r) \propto \Psi^2 \frac{\exp\{-\kappa(r - \sigma)\}}{r} \]

Falls off very fast so is hard to plot! (better DLVO potential has small attractive region next to hard core, particles are rarely that close.)

Surface potential \( \Psi \) is related to charge \( Z \), \( \kappa = 1/r_D \)

\[ c(r) = \frac{-u(r)}{k_B T} \quad \text{all} \quad r > \sigma \]

S(Q) & g(r) for Z=20 & Z=0 (hard sphere ---- ) at 30% vol
LIMITATIONS

OCM - particles large, counterions very small, uniformly spread, “continuum”. Large counterions need HNC etc. - numerical calc.

The charge in the MSA $S(Q)$ can be corrected for “penetrating background” - the counterions “inside” the particles.


MSA at low concentrations becomes unphysical

$$n_0 \to 0 \text{ then } h(r) = c(r) \text{ and } g(r) = 1 - u(r)/k_B T \text{ may be } < 0$$

Fortunately $S(Q)$ is still “rescalable” - calculation is done at higher volume and the result rescaled - “RMSA”.

J.B.Hayter & J.P.Hansen, Mol Phys 46(1982)651

OTHER MODELS

A large literature of variations to these theories & heated debates!
ATTRACTION INTERACTIONS

Ornstein-Zernicke, Critical Scattering - size fluctuations approaching a phase separation at $T_C$ - a more phenomenological approach gives a Lorentzian type term.

$$S(Q) = S_{HS}(Q) + \frac{\kappa}{(1 + Q^2 \zeta^2)} \approx 1 + \frac{\kappa}{(1 + Q^2 \zeta^2)}$$

$$\zeta = \zeta_0 e^{-\nu} \quad \chi = \frac{(T_C - T)}{T_C}$$

Baxter’s “sticky hard sphere” adds an attractive square well potential to the hard sphere, (see Sharma & Sharma paper for useful equations).


or e.g. M.H.G.Duits et.al. Langmuir 7(1991)62-68.


Yukawa MSA- H-P $S(Q)$ does work as attractive, use negative charge in their code.
DDAO Micelles - size, shape & interactions

$N,N$-dimethyldodecylamine-$N$-oxide (DDAO) or lauryldimethylamineoxide (LDAO) or $C_{12}AO$ is $C_{12}H_{25}NO(CH_3)_2$

Data and fits at 29, 7, 1.8 & 0.9 % vol. “non-ionic” needs “charged sphere” $S(Q)$!

Core radius ~ 16.5 Å, head group shell ~ 2 Å (or 3.8 Å if add 4 water per head), axial ratio $X$ ~ 1.7, aggregation number ~ 103, “charge” per head ~ 0.7

Polymer/surfactant interactions

Mixed surfactant layer on water surface

Water soluble polymer

Mixed micelle

Air

Water

Neutron contrast variation is the key!
Look at the surface with neutron reflection, the bulk solution with SANS
SDS, surfactant micelles + gelatin, polymer gel: only d-SDS visible, gelatin matched to 40% D₂O

SDS+gelatin+salt
At long distances S(Q) now more like gel?

SDS+gelatin
Little change?

SDS+salt

SDS

I(Q) cm⁻¹

Q (Å⁻¹)

SDS, surfactant micelles + gelatin, polymer gel: d-SDS matched to D$_2$O, only gelatin visible

Conclude: gelatin interacts - partly wraps micelle, long range structure dominated by charged micelle $S(Q)$ until add salt when gelatin network dominates.
SANS on a dynamic system

Quench d-decane/C\(_{12}\)E\(_5\)/water microemulsion. D\(_2\)O/H\(_2\)O matched to enhance scatter from large phase separating oil droplets.

\(R_g\) of large droplets follows power law of Ostwald ripening

SANS on a “real” complex system

Microporous silica catalyst support + surfactant + water + toluene (+ catalyst)
[ Edman Tsang *et al.*, Reading, work we gave up on!]

**Contrast matching** the silica with d/h toluene allows us to see the added surfactant plus water.

- Matched + surfactant + water
  - $Q^{-2.5}$ “fractal”
- Matched + surfactant
  - Some small droplets?
- Dry silica + d/h toluene = “matched”

![Graph](image)
SANS from Particles

diffraction from structures of ~1 to ~100nm

- **Dilute particles** - polymers, colloids, proteins etc. - size and shape.
- **Concentrated particles** - interparticle spacings & interaction potential (hard, charged repulsive, soft attractive)
- **Contrast variation** - selective deuteration or swapping H₂O for D₂O is a powerful method to highlight parts of a structure - “shell” thickness, composition, density profile, structural relationships in mixed system.
- **SANS** works best on well characterised model systems but “real” materials are sometimes possible!

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NEXT:

SANS from Polymers, Biological systems and then some other neutron techniques.