Small Angle Neutron Scattering  Part 6
Yet more systems (2 phase, fractal, magnetic, oriented systems ...) and conclusions
Two phase models giving a “peak” - 1

Teubner & Strey assume a sinusoidally varying $g(r)$, damped by exponential correlation length, no prediction as to the 3-d structure!

$$g(r) = \frac{d}{2\pi r} \exp\left(\frac{-r}{\zeta}\right) \sin\left(\frac{2\pi r}{d}\right)$$

Gives $I(Q)$ as broad peak, height $I_M$ at $Q = Q_M$. Domain size $d$, correlation length $\zeta$ are easily obtained from fit parameters.

$$I(Q) = \frac{I_0}{(1 - I_0 / I_M)((Q / Q_M)^2 - 1)^2 + I_0 / I_M} = \frac{I_0}{1 + AQ^2 + BQ^4}$$

Two phase models giving a “peak” - 2
Random wave, Spinodal, Bicontinuous and other models

Sinusoidal $g(r)$ of random directions, amplitudes and phases. Developed by Cahn for spinodal decomposition, the method was extended by Berk for more random bicontinuous systems.

“special” cases such as spinodal decomposition or phase separation in polymers or metal alloys - important constraints better define the models used or give “universal scaling”.

A large number of papers also try to investigate “bicontinuous” phases in high volume fraction microemulsions. At high $Q$ the “local structure” of the component particles may become apparent.

Spinodal decomposition - with sinusoidal “concentration waves”, is often characterised by “scaling” to a “universal” SANS pattern, e.g.

Hoell, A., F. Bley, A. Wiedenmann, J.P. Simon, A. Mazuelas, P. Boesecke
Composition Fluctuations in Supercooled Liquid State of Zr$_{41}$Ti$_{14}$Cu$_{12.5}$Ni$_{10}$Be$_{22.5}$, Scripta Materialia (2001)
Example of Random Wave method, from Trevino et.al. Langmuir 10(1994)2457-2552. Sections of one, two, 5 and 200 waves with random phases and directions but same $\lambda$.

Fitted SANS data for bicontinuous microemulsions with increasing water phase, together with sections through corresponding “models”
Some further references:


S(Q) for Volume (or Mass) Fractal

Particles of radius R aggregate to form object (agglomerate) of “size” $\xi$
If number of particles within sphere radius $r$ goes as

\[
N(r) = \left(\frac{r}{R}\right)^d
\]

$d =$ “fractal dimension” of self-similar structure, then $g(r)$ can be calculated and transformed to get

\[
S(Q) = 1 + (QR)^{-d} d \Gamma(d - 1)(1 + (Q\xi)^{-2})^{(1-d)/2} \sin\{ (d - 1) \tan(Q\xi) \}
\]

Fractal dimension $1 \leq d \leq 3$
over most of $Q$ range $S(Q) \propto Q^{-1} \rightarrow Q^{-3}$

Gamma function $\Gamma(d-1)$ is related to factorial, for integer $n$, $\Gamma(n+1)=n!$
d \sim 1.8 \text{ diffusion limited aggregation (particles stick on first contact)}
\text{d} \sim 2.1 \text{ reaction limited aggregation (some relaxation after sticking).}
Q < 1/\xi \text{ scattering flattens out (} R_G \text{ for whole aggregate.)}

In some cases \xi may correspond to size of sample, in others USANS or USAXS, electron microscopy or light scattering may be needed to get to smaller Q.

Voids on larger (micron) distance scales, may transfer to “surface” fractal scattering at small Q with the curve becoming steeper!

NOTE \quad I(Q) \text{ should include } P(Q) \text{ for primary particle!}
If they are very small, then \ P(Q) \to 1.
Larger, well defined, primary particles may have \ Q^{-4} \text{ Porod at high } Q.

\text{Q^{-n} power laws are not necessarily “fractal”}
e.g. a long thin cylinder is \sim Q^{-1} & \text{infinite thin flat sheet } \sim Q^{-2}. 
Example: Mass fractal

\( S(Q) \) \( d=2.5, \ \xi = 500 \ \text{Å}, \ R=20 \ \text{Å} \)

\( P(Q) \) \( R_{\text{bar}} = 30\text{Å}, \ \sigma/R_{\text{bar}} = 0.40 \)

\( P(Q)S(Q) \) goes as \( Q^{-2.7} \) then \( Q^{-4.1} \) (not -2.5 and -4.0, need to fit!)
P(Q) for Surface Fractal

Large object or pores of size $\xi << 1/Q$, “surface scatter”:

$$P(Q) = \pi \Delta \rho^2 S \Gamma(5 - d_s) \sin\{(d_s - 1)\frac{\pi}{2}\} Q^{-(6-d_s)}$$

$2 \leq d_s < 3$ gives over most of Q, $P(Q) \propto Q^{-4} \rightarrow Q^{-3}$

Smooth      Rough

$S =$ surface area per unit volume, at least for $d_s = 2$ when $P(Q)$ reduces to Porod’s law.

$d_s = 3$ is also a volume fractal, though possibly over a restricted range of dimensions.

NOTE graded or diffuse interfaces may give $P(Q)$ steeper than $Q^{-4}$.

Gradients as steep as $Q^{-5}$ have been seen for surface coated porous silicas etc. [example later in this talk].
Example: fumed silica aggregates

J. Hyeon-Lee, G. Beaucage, S. E. Pratsinis & S. Vemury, Langmuir 14(1998)5751-5756  SAXS & USAXS of flame generated silica aggregates. Isolated aggregates (can be diluted in solution) of large primary particles $R \sim 100$ Å, which can also be imaged by electron microscopy. Small “mass fractal” region, surface fractal at higher $Q$ for some samples.
Is this Fractal?

Electron micrograph (Degussa AG) commercial, Aerosil. Primary particles are polydisperse & tend to partially fuse with others of a similar size.

SANS on LOQ is $Q^{-4}$ as large particles, smooth and homogenous. Match point shows $\rho$ as amorphous SiO$_2$. 
Diffuse interfaces

A concentration gradient, normal to a smooth interface is not the same as a surface fractal. Another equation which appears in various contexts shows that we can get gradients steeper than Porod’s $Q^{-4}$.

One derivation starts from an infinite flat interface, convoluting this with a Gaussian “smearing”, of standard deviation $\sigma$, multiplies $I(Q)$ by an exponential:

$$I(Q) = \frac{2\pi S(\Delta \rho)^2}{Q^4} \exp(-\frac{1}{2} Q^2 \sigma^2)$$

This of course has the same form as the approximate equation for scattering from a polymer at an interface!
Example: Alumina membrane with ~ 200 Å holes,
---------- Porod ~ Q^{-4}
Clog with diffuse protein layer,
1g.dm^{-3} BSA in D_2O,
2 hours in flow cell
00000 pH 3, little adsorption
++++ pH 7, fit \sigma = 15\pm3 \text{ Å}
∇∇∇∇ pH5, fit \sigma = 43\pm3Å (gradient around Q^{-5})

\[
I(Q) = \frac{2\pi S(\Delta \rho)^2}{Q^4} \exp\left(-\frac{1}{2} Q^2 \sigma^2\right)
\]

Thin sheets

SANS of infinite flat sheet of thickness $\ell$ is in the directions normal to the sheet

$$I(Q) \propto \frac{\sin^2(Q\ell/2)}{(Q\ell/2)^2}$$

Small Q  “Sheets Guinier”, gradient of $\log_e(Q^2I(Q))$ against $Q^2$ is $-\ell^2/12$.

Randomly oriented sheets “spread out” $I(Q)$ over a sphere in $Q$ space, as $Q^{-4}$ rather than $Q^{-2}$, same as for a thin spherical shell of large radius:

$$I(Q) \propto \frac{1}{Q^2} \frac{\sin^2(Q\ell/2)}{(Q\ell/2)^2}$$

For intermediate cases a “Lorentz factor” may be useful:

$$L_N(Q) = \frac{1}{1 + \frac{1}{2} Q^2 (R\sigma)^2}$$

Single parameter ($R\sigma$) covers both “curvature” and “undulations” ( see e.g. N.T.Skipper, A.K.Soper & J.D.C.McConnell, J.Chem.Phys. 94(1991)5751-5760 )
Thin sheets – lamellar stacks

The absolute scaling requires some thought for particular cases. [See FISH manual model 28 ]

Multiplied by a one dimensional S(Q) for a “paracrystalline lattice”, a thin sheet P(Q) may be used to attempt to fit lamellar peaks etc.

This is useful where there is a FINITE NUMBER of layers, where there is often strong scatter at small Q from the total thickness of the stack (compare the Fourier transform method or Caille peak fit for an infinite stack or neutron reflection from multi-layers).

P(Q) for infinite sheets is easily modified for shell/core/shell with various shell types, as it is a one-dimensional transform.

Sheets randomly oriented about vertical axis, have I(Q) spread out over surface of cylinder - axially symmetric “fibre diffraction” pattern, much Xray literature.
Example: 3% DPPC lipid in D2O, multi-lamellar stack, fit by randomly oriented paracrystal model.

\[ Q_{PEAK} = \frac{2\pi}{D} \]

Fit has 18 layers of (L = 4.64nm lipid + 1.32nm water)  \( D = 5.96 \text{ nm} \)

\( \sigma_D/D = 7\% \), \( \sigma_L/L = 10\% \) (fixed)
SANS from Magnetic systems

• Unpolarised neutrons and particles with Fe.

• Revealing magnetic component - temperature variation?

• Polarised neutrons - spin-flip SANS

• Clever stuff - flux line lattice
Unpolarised neutrons and particles with Fe, Co etc

Atoms with a magnetic dipole have a magnetic neutron scattering length, which is often significant. Randomly oriented dipoles in zero field, simply add the Normal and Magnetic terms:

\[
I(Q) = I_N(Q) + I_M(Q) = N[|F_N(Q)|^2 + \frac{2}{3}|F_M(Q)|^2]S(Q)
\]

For a point dipole of S Bohr magnetons, magnetic scattering length (amplitude) \( p = 0.27 \times 10^{-12} \text{ cm} \)

e.g. Fe has \( b = 0.96 \times 10^{-12} \text{ cm} \), for Fe, Fe2+, Fe3+ \( S = 2, 4, 5 \) and \( p = 0.6, 1.08 \ & 1.35 \times 10^{-12} \text{ cm} \), so \( I_M(Q) \) may be significant.

If the “magnetic” particle is not the same size or shape as the “structural” particle the SANS becomes interesting!

[check the 2/3, is it 1/2 ?]
Magnetic critical scattering

The magnetic SANS may be revealed by temperature change especially at a magnetic phase boundary. If the sample is a powder, has voids, or composition fluctuation the normal nuclear SANS may dominate, but even so the magnetic SANS may appear in a different Q range.

(A.Hannon & S.Hibble)
Polarised neutrons and particles with Fe, Co etc

With polarised neutrons, magnetic atoms and a magnetic field the magnetic scattering length depends on the angle between the neutron spin and the magnetic field $H$ and the neutron spin may flip (sf) or not (snf).

With no polarisation analysis of the scattered beam, and the neutron spins parallel (-) or anti-parallel (+) to $H$ we get:

\[ I^+(Q, \alpha) = \langle |F^{++}|^2 \rangle + \langle |F^{+-}|^2 \rangle = F_N^2 + \{F_M^2 - 2PF_NF_M\} \sin^2 \alpha \]

\[ I^-(Q, \alpha) = \langle |F^{--}|^2 \rangle + \langle |F^{-+}|^2 \rangle = F_N^2 + \{F_M^2 + 2P\varepsilon F_NF_M\} \sin^2 \alpha \]

$\alpha = \text{angle between } H \text{ and } Q$

Polarisation $P$ with spin flipper of efficiency $\varepsilon$

\[ P = \frac{(n^+ - n^-)}{(n^+ + n^-)} \]

Sum gives same signal as in non-polarised beam, with a magnetic field:

\[ \frac{1}{2} (I^+ + I^-) = F_N^2 + F_M \sin^2 \alpha \]

Difference gives anisotropic magnetic-nuclear cross term:

\[ I^- - I^+ = 2P(1 + \varepsilon)F_N F_M \sin^2 \alpha \]

Simultaneous fits give nuclear & magnetic structures.

Co ferrofluid, H horizontal

1/2(I^+ + I^-)  (I^- - I^+)

A.Wiedenmann, Physica
B297(2001)226-233
Co ferrofluid in d-h toluene


Open symbols $I^-$
closed $I^+$

**a)**

Scattering cross-section [cm$^{-1}$]

- Red line: 0% D
- Blue line: 14% D
- Black line: 43% D
- Green line: 100% D

Momentum transfer [nm$^{-1}$]

**b)**

Graph showing the ratio $I(Q)/I(0)$.

**c)**

Volume distribution

- Magnetic core
- Core + shell

**d)**

L(x): Langevin function for $<R1>=3.7$ nm.

**e)**

$B_{\text{eff}}(H)/B_{\text{eff}}(1.1T)$

Magnetic field [T]

$\eta$ [10$^{-10}$ cm$^{-2}$]

Radius [nm]

Polarised neutrons need a “guide field” to maintain polarisation. Best suited to monochromatic beam, e.g at HMI Berlin, Delft etc.

SANSPOL at BENSC, HMI Berlin
Polarised neutrons and Hydrogen

H atoms can be spin polarised in a magnetic field at very low temperature.

H.B.Stuhrmann & others attempt to use this to provide additional contrast information for biomolecules etc.

Flux line lattice in superconductors


hexagonal flux lines in pure Nb

heavy fermion superconductor UPt$_3$

TmNi$_2$B$_2$C
“Oriented systems”

We have already seen anisotropic scatter from “fibres” and some concentrated micellar samples.

There are many other types of “oriented” system.

Including orientation can make SANS patterns easier to understand!

(Thanks to Jeff Penfold for many of the images in this section)
Ordered Systems: Lyotropic micellar and liquid crystalline phases

Progression of micellar shapes based on simple geometric constraints as molecular geometry changes with concentration, temperature, salt, pH, counterion binding etc.

“Packing parameter” from Volume $V$ and Length $L$ of hydrophobic tail, and Area $A$ of head group gives approximate transitions:

- $V/AL < 1/3$: Spherical
- $1/3 < V/AL < 1/2$: Rods
- $1/2 < V/AL < 1$: Bilayers
- $V/AL > 1$: Inverted
Liquid Crystals

Calmatic

Wide range of structures form spontaneously, or under shear, magnetic field etc.
Liquid crystalline structures have characteristic diffraction patterns which may appear in small angle or at the lower end of "wide angle" diffraction ranges.
Block-copolymers and complex surfactant systems, often with 3 or 4 phases, may show even more complex structures at higher concentrations. These may “invert” around 50% volume fraction. Again there are characteristic diffraction patterns - but they may be hard to conclusively interpret!
Example: Conformation of side chain polymeric liquid crystals in the smectic C phase

Side chain liquid crystal polymer
poly-[w-(4’-methoxybiphenyl-4-yloxy)butyl methacrylate]

Two orders of Bragg reflection from smectic ordering, from layers oriented normal to field
Mesogens tilted with respect to field

Anisotropic scattering from backbone
Backbone adopts oblate conformation

Aligned in 9.4T magnetic field, whilst cooling from 170 to 30°C
SANS using mixtures of unlabelled molecules and molecules with perdeuterated backbones

Ordered Systems – shear alignment

Long rod micelles/polymers, and many lamellar systems can be at least partly aligned in a shear flow.

These include aqueous solutions and polymer melts (in which crystallisation may be induced).

At ISIS we have use of cells (some belong to individual research groups) for Couette flow (low temperature glass, high temp. aluminium), Poiseuille(linear) flow, Extensional flow and a disc and plate device with simultaneous rheology.
Unilever / RAL Couette Shear flow cell

Constant and Oscillatory flow. Shear gradient $G$ is speed/gap distance $\sim$ 1 to 25000 sec$^{-1}$, (gap is 0.5mm, radius 25mm)

Constructed in quartz, outer cylinder rotates. Rotating seal reduces solvent loss and foaming

(Hayter, Penfold J Phys Chem 1984 88 4589; Cummins, Staples, Penfold, Millen, Meas Sci Techn 1990 1 179)
Flow pattern

**Poiseuille Flow**

**Couette Flow**

\[ V(r) \]

\[ G = \frac{dV}{dy} \]

Significant alignment when shear gradient \( G \gg Dr \) the rotational diffusion due to Brownian motion.

(Particles \( \gg \sim 1000 \, \text{Å} \) long)


H G Jerrard, Chem Rev 51 (1852) 345

'Local Ordering' in rod-like systems

For interacting systems, such as charged micellar rods, shear also affects $S(Q)$ as neighbouring rods start to align.

The $P(Q)S(Q)$ peak than scales as $[\text{concentration}]^{1/2}$ for a two dimensional system instead of $[\text{concentration}]^{1/3}$ for a 3 dimensional array.

---

3% C16E6 / 0.3% C16TAB

---

B Wayerich, B D’Aguanno, E Canessa, R Klein, Faraday Disc 90 (1990) 245
Shear orientation of lamellar phases

At least 3 ways to orient!

(a) Lamellar sheets aligned parallel to flow - vorticity plane
   (director in direction of shear gradient)

(b) Aligned parallel to flow - shear gradient plane
   (director parallel to vorticity)

(c) Aligned parallel to Vorticity - shear gradient plane
   (director in flow direction)
Example: SANS, SAXS & DSC of sheared surfactant phases

I Tucker, L. Soubiran et al. (Unilever), J Penfold (ISIS)

ID13, ESRF, 20μm beam scanned across gap at 100μm intervals in tangential geometry, $G = 0.4 \text{ s}^{-1}$

$G=0.4\text{s}^{-1}$

Radial scan at different gap positions

Pattern near centre of gap
Pattern near outer edge

45% 2HT, distribution of orientations and co-existence of states across the gap. Lamellae ordered predominantly in flow-vorticity plane close to outer surface
2HT, di-octadecyl dimethyl ammonium chloride, shear thickens as aligned lamellae become multi-lamellar vesicles.

DSC shows $L_\alpha/L_\beta$ transition around 55°C, but SANS shows the ordered phase appears at 46°C.

Hot mixed products were traditionally sheared on cooling from 65 - 70°C, but time and energy are saved by delaying shear until low temperatures. (Within 3 months of the SANS changes were implemented to 15 ton production plant.)
Lyotropic Lamellar phases – infinite stack of wavy sheets

Caille says shape of Powder averaged "Bragg" peak at $Q_0 = 2\pi/d$ is:

$$I(Q) \approx |Q - Q_0|^{(\eta^{-1})}$$

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

$\eta$ is the Caille constant
$d$ the interlamellar spacing
$\kappa$ the bending modulus
$B$ the compressibility
$m$ the diffraction order

For perfectly oriented sample need:

$$I(Q) \approx |Q - Q_0|^{(\eta^{-2})}$$

A Caille, C R Heb, CR Acad Sci B 274(1972) 1733
Lyotropic Lamellar phases

Powder average from resolution broadened finitely large domains:

\[
I(Q) \approx Q^{-2} P(Q) S(Q)
\]

\[
P(Q) = \frac{2\Delta \rho^2}{Q^2} (1 - \cos(Q\delta)) e^{-Q^2\sigma^2/2}
\]

\[
S(Q) = 1 + 2\sum_{1}^{N-1} (1 - n/N) \cos(nQd) e^{Q^2/2} \langle (u_n - u_0)^2 \rangle
\]

\(N\) is the number of correlated layers in stack

\(\langle (u_n - u_0)^2 \rangle\) is the correlation function describing inter-layer fluctuations

B S Yang, J Lab, P Richetti, C M Marques,
Some further SANS examples
Stop flow solution mixing - kinetics - SANS on D22 at ILL, Grenoble

B.Robinson, D.Steytler (UEA), J.Eastoe (Bristol), I.Grillo (ILL), R.Heenan (ISIS)

D22 at the ILL in Grenoble has as the best neutron flux of any SANS instrument.

Can measure even quiet small cross sections (with not so good Q resolution) in 10 – 30 sec, $\lambda = 6$ Å, 4m sample-detector (1m square, with beam on one edge to expand Q range).

7-SLABS

\[ \text{CH} \quad \text{SO}_3\text{-Na}^- \]

Stop-Flow cell

- aperture
- B4C
- detector tube
- silicium window
- waste
- 1mm quartz cell
- delay line
- end of the guide
Stop-flow measurements on 7-SLABS systems – a surfactant on the edge of stability?

sodium 7-tridecylibenzenesulfonate (7-SLABS), cmc 2 mM without salt

Spontaneous vesicle formation in ~ minutes, when [7-SLABS] = 5 -10 mM and [NaCl] >~7mM

Lab. based stop-flow spectroscopy, light scatter etc. investigated kinetics of vesicle formation & breakdown as function of [SLABS], [NaCl] and Temp for 6-SLABS & 7-SLABS, see:


10mM 7-SLABS in D2O  D22 Stop -flow

5mM 7-SLABS + 10mM NaCl

20mM [NaCl] in D2O
7-SLABS micelle to vesicle on adding salt

5mM 7-SLABS + 10mM NaCl, D22 6Å, 4m, Stop-Flow 2 to 198 sec in 2 sec slices, repeated 4 or 5 times

times: 0 - 2 sec (circle), 20 (+), 30(*), 70 (X), 198 (square) sec.

Lines are fits $A \times (\text{micelle} \times S(Q)) + B \times \text{disk}(R \text{ adjust up, } L = 19 \text{ Å})$

$R_{\text{disk}}$ varies erratically (noise at small Q) but increases $\sim 240$ to $350$ Å, no obvious small rod or disk intermediates?
7-SLABS micelle to vesicle (R ~500 Å) on adding salt

How fast does micelle respond to cmc change? diluting
(8 mM micelle + 2 mM monomer) with salt solution, could give
(5 mM micelle + 0 mM monomer) for rapid cmc change & no vesicles
or (4 mM micelle + 1 mM monomer) for simple dilution - looks better!

Issues to resolve with absolute intensities (is static 3 mM micelle + 2 mM monomer?) &
of vesicles (final vesicle ~ 15% more in stop flow).

Do we have micelles → vesicle or micelle → monomer → vesicle
or perhaps both? - still no clear answer!
Low concentrations of SDS disrupt vesicles, at a rate varying greatly with SDS concentration.

Use contrast variation to attempt to see “intermediates” and verify micelle composition ???

7-SLABS/h-SDS/D$_2$O, 7-SLABS/d-SDS/D$_2$O, 7-SLABS/d-SDS/H$_2$O, see:

<table>
<thead>
<tr>
<th>Both</th>
<th>7-SLABS</th>
<th>SDS</th>
</tr>
</thead>
</table>

4mM 7-SLABS 10mM NaCl vesicles
(R ~ 500 Å, shell ~ 32 Å)

2mM 7-SLABS, 3mM SDS, 10mM NaCl mixed micelles (ellipsoid Rcore ~16 Å, X ~1.4)
(7-SLABS + salt) vesicle + SDS gives mixed micelles?

\[
\begin{align*}
\text{CH} & - \text{SO}_3^- - \text{Na}^+ \\
\end{align*}
\]
(7-SLABS + salt) vesicle + SDS gives mixed micelles

1 : 1.5 “just right” reaction

( two runs in Oct03 go faster than in Dec02 – ”typical for kinetics experiments” ??? )

2mM 7-SLABS, 3mM SDS, 10mM NaCl
(7-SLABS + salt) vesicle + SDS gives micelles

1 : 1.5 contrast variation

Two almost identical runs with d-sds, see only SLABS part of “mixed micelle”
(Alas with 7-SLABS, d-SDS, in H₂O the signals were too weak for meaningful results.)

2mM 7-SLABS, 3mm d-SDS, 10mM NaCl

See only 7-SLABS here – initial vesicle signal similar to previous, final micelle signal 3 - 4 times less.
Must have mixed micelles, not sure yet of composition
(7-SLABS + salt) vesicle + SDS gives micelles

1 : 2 initially rapid reaction

Here is the clearest evidence for “intermediates” \( R_{\text{DISK}} \) decreases from \(~75\) to \(~35\) Å, though residuals suggest a polydisperse disk radius at shorter times.

2 sec channels x 6 iterations
(7-SLABS + salt) vesicle + SDS gives micelles

1 : 2 initially rapid reaction – first three time slices
2 sec channels x 6 iterations

- **Best fit** $R_{\text{DISK}} = 75 \text{ Å}, 0 - 2 \text{ sec}$
- $R_{\text{DISK}} = 64 \text{ Å}, 2 - 4 \text{ sec}$
- $R_{\text{DISK}} = 48 \text{ Å}, 4 - 6 \text{ sec}$

Disk part of 2-4 sec
CONCLUSIONS

SANS is very useful - try it some time!

- Structures ~10 to > 3000 Å

- Contrast variation and magnetic scattering with neutrons are very clever.

- Unlike X-rays, no damage to samples.

I hope that you found these lectures worth while!

My thanks to you for listening and to the many colleagues whose images and data I have shown.