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Introduction to SANS I: Contrast variation, deuteration and complementarity with SAXS

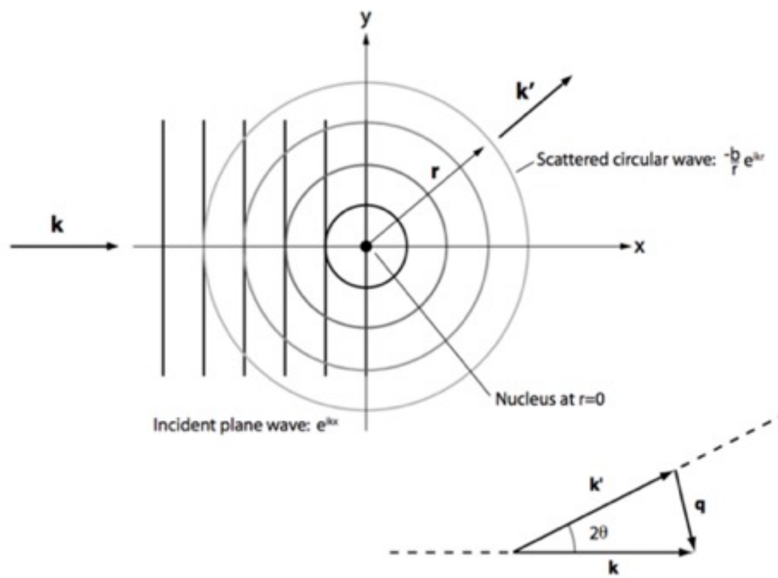
Adrian Sanchez-Fernandez

- Scattering length, length density and excess.
- Contrast variation.
- Deuteration.
- Some contrast variation methods.
- Complementarity with SAXS.

Scattering length and length density

- Neutrons are **scattered by nuclei (and unpaired electrons) –** the **neutron scattering length** (*b* or b_i) describes the interaction of the neutron with the nucleus.

$$\psi_s = -\frac{b}{r}e^{ikr}$$



Scattering length and length density

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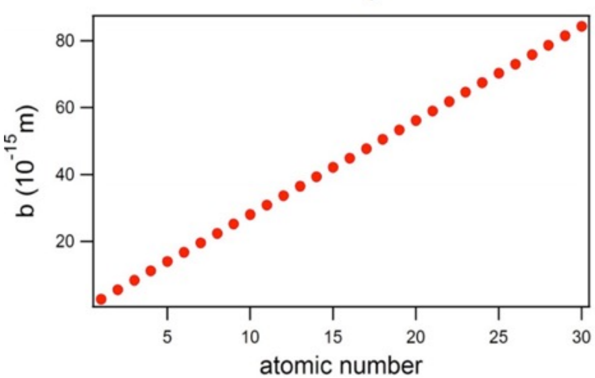
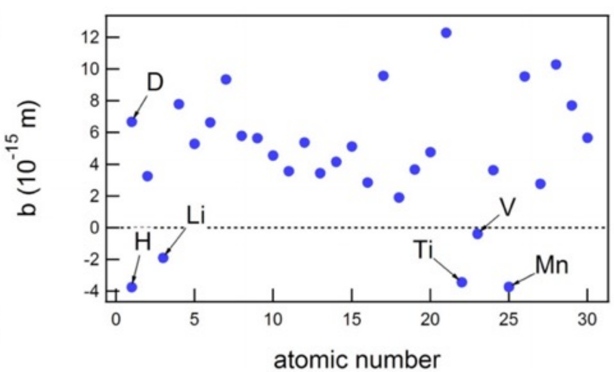
$$\psi_s = -\frac{b}{r}e^{ikr}$$

- Neutron scattering length **randomly varies** across the periodic table.
- Neutron b_i is **isotope dependent**.

X-rays



neutrons



Isotope	b / fm	Z r_e* / fm
^{1}H	-3.741	2.8179
^{2}H	6.671	2.8179
^{3}H	4.792	2.8179

*r_e=2.8179 fm

Scattering length and length density

- b_i quantifies the **interaction of radiation** with an atom.
  - X-rays – electron clouds.
  - Neutrons – nuclei.

$$\frac{d\sigma}{d\Omega} = \frac{1}{N}\left|\sum_{j}^{N} b_j e^{qri} dr\right|^2$$

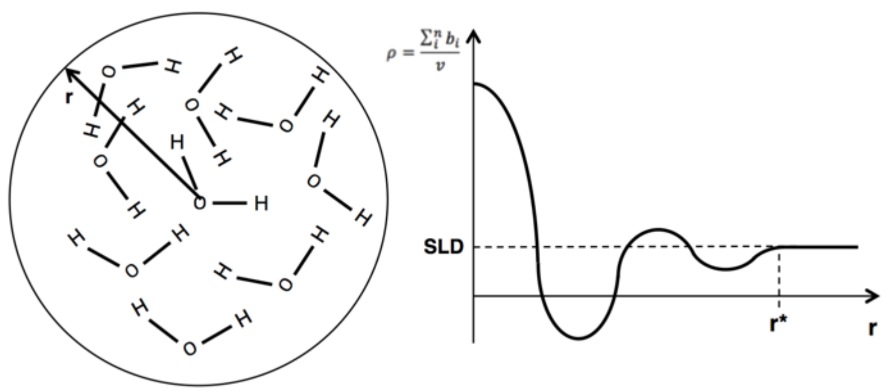
Interaction Spatial distribution

Scattering length and length density

- b_i quantifies the **interaction of radiation** with an atom.
  - X-rays – electron clouds.
  - Neutrons – nuclei.

$$\frac{d\sigma}{d\Omega} = \frac{1}{N}\left|\sum_{i}^{N} b_i e^{qri} dr\right|^2$$

- Treating mesoscopic structures from an **atomistic point of view** results very **complex**. Scattering length density (SLD) is the answer.



- Beyond a certain distance the **atomistic information is lost** – the density of the system remains constant.

Scattering length density and excess

$$SLD = \frac{\sum_{i=1}^{n} b_i}{V_m} = \rho N_A \frac{\sum_{i=1}^{n} b_i}{\sum_{i=1}^{n} RMM_i}$$

- SLDs are used to **quantify the scattering power** of the ensemble.
- The scattered intensity is proportional to the difference between the square of the SLD of the inhomogeneities and the SLD of the matrix – **scattering excess**.

$$I(q) \propto \Delta SLD^2 = \left(SLD_p - SLD_s\right)^2$$

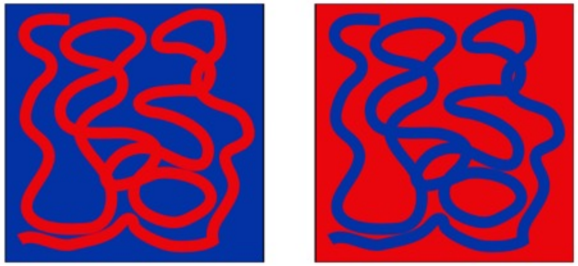
$$\frac{d\Sigma}{d\Omega} = \frac{N}{V}\frac{d\sigma}{d\Omega} = \frac{1}{V}\left|\int_V \rho(r) e^{qri} dr\right|^2$$

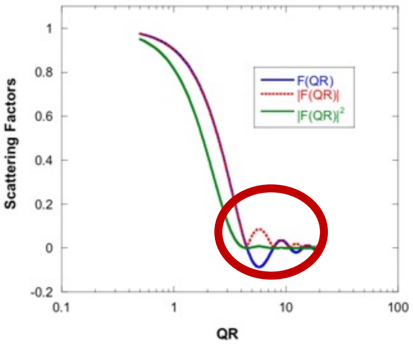
- The SLD may be modified through **isotope-labelling** (e.g. H/D exchange) **– contrast variation.**

The phase problem

- **Babinet's Principle** – in a two-phase system, two samples that have identical structure, but opposite SLD distribution, the coherent scattering is the same.

$$\left(SLD_{p1} - SLD_{s1}\right)^2 = \left(SLD_{p2} - SLD_{s2}\right)^2$$





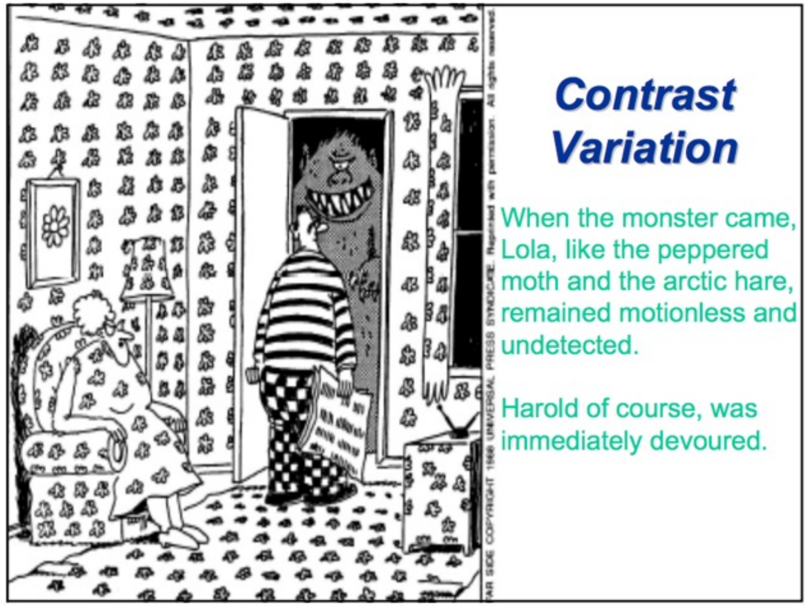
where SLD_{p1}=SLD_{s2} and SLD_{p2}=SLD_{s1}.

- The differential cross section is proportional to the **square of its amplitude**.

$$\frac{d\Sigma}{d\Omega}(q) \propto P(q) = F(q)^2$$

- The "negative" values are lost in the square function, so the inverse of the Fourier transform cannot be directly performed – ***ρ(r)* needs to be reconstructed**.

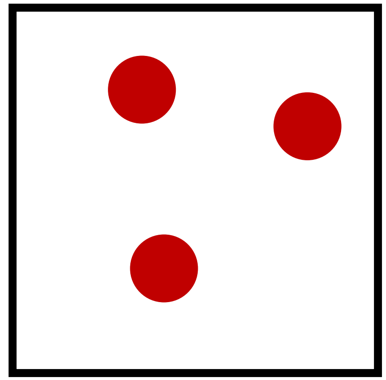
Contrast variation



- Common routine in SANS experiments – use of isotopically labelled compounds to change the SLD of different parts of the system.
- Helps to enhance the contrast of some **particular features**.
- Used to investigate **complex systems** (e.g. mixture of NP's, protein-detergent complexes, mixture of polymers).

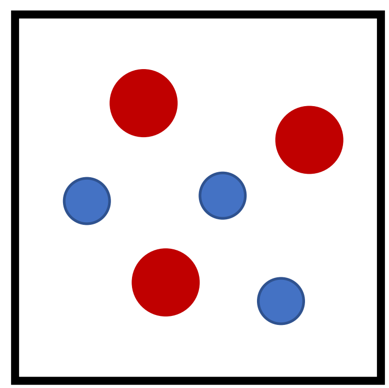
Neutron contrast conditions

- Finite contrast.

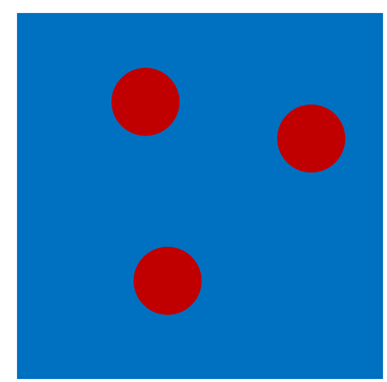


- Zero contrast.

- Multiple contrast.



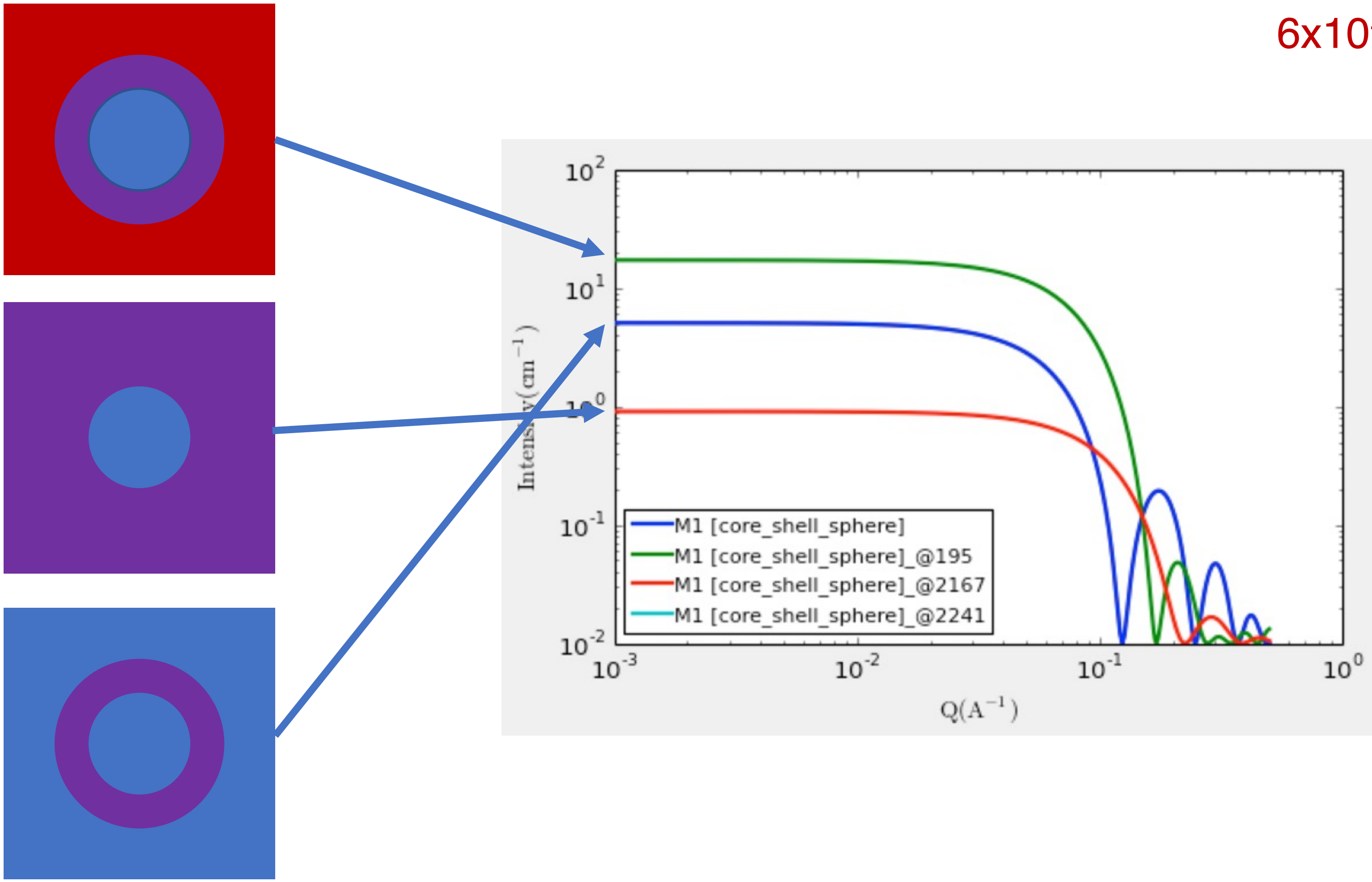
- Contrast match condition.



Contrast match experiments

- Varying solvent contrast (e.g. H_2O/D_2O ratio).

SLDs –
0x10^{-6} Å^{-2}
3x10^{-6} Å^{-2}
6x10^{-6} Å^{-2}



Contrast match experiments

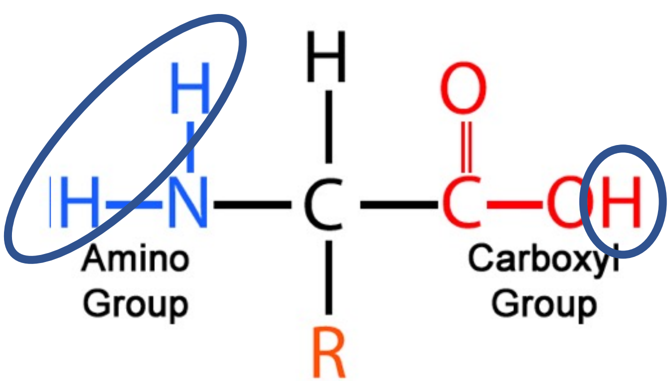
- Some calculated SLDs:

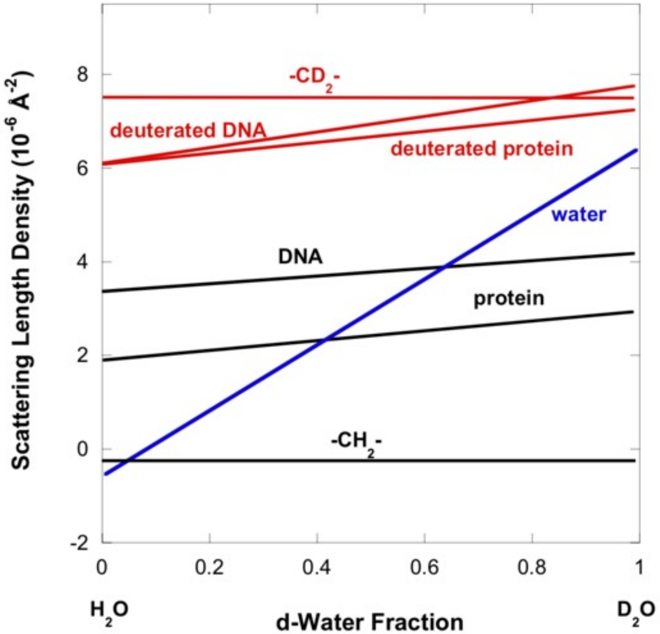
Component	SLD / x10^{-6} Å^{-2}
H_2O	-0.56
D_2O	6.37
Fe_2O_3	7.2
Lysozyme*	3.45

Component	SLD / x10^{-6} Å^{-2}
h-Phosphocholine	2.1
$NaSO_4$	3.7
$C_{12}H_{25}$	-0.35
$C_{12}D_{25}$	7.4

*Some systems go through **H/D exchange in deuterated conditions** – e.g. proteins.

- This modifies the SLD of the scatterer – **needs to be accounted for.**

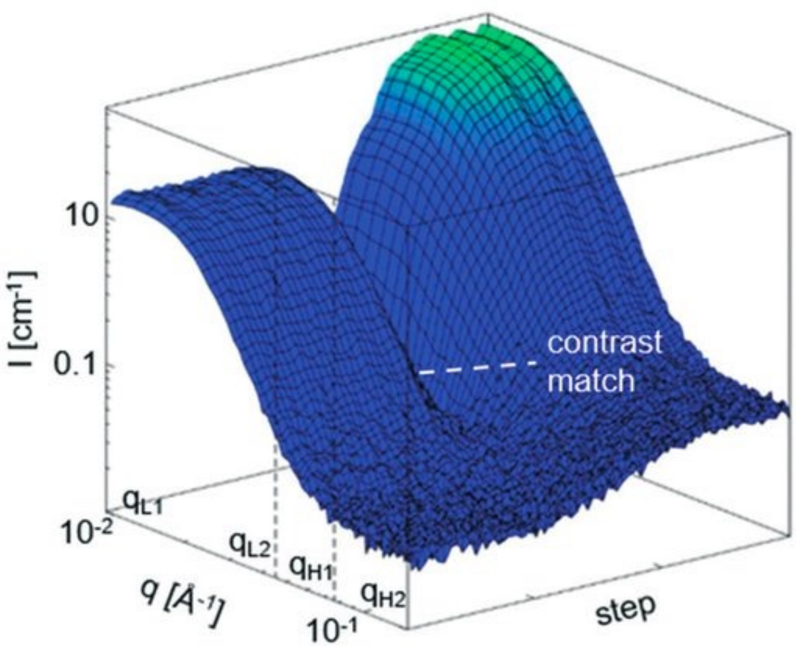




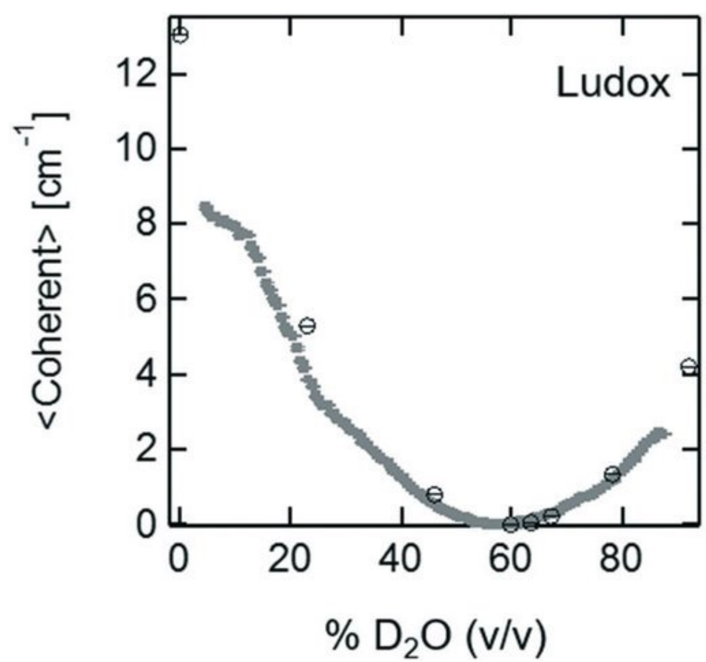
Contrast match experiments

- How to **find the contrast match point** of a scatterer experimentally.
- Yields to the **zero contrast condition,** i.e. ΔSLD²=0.

a)



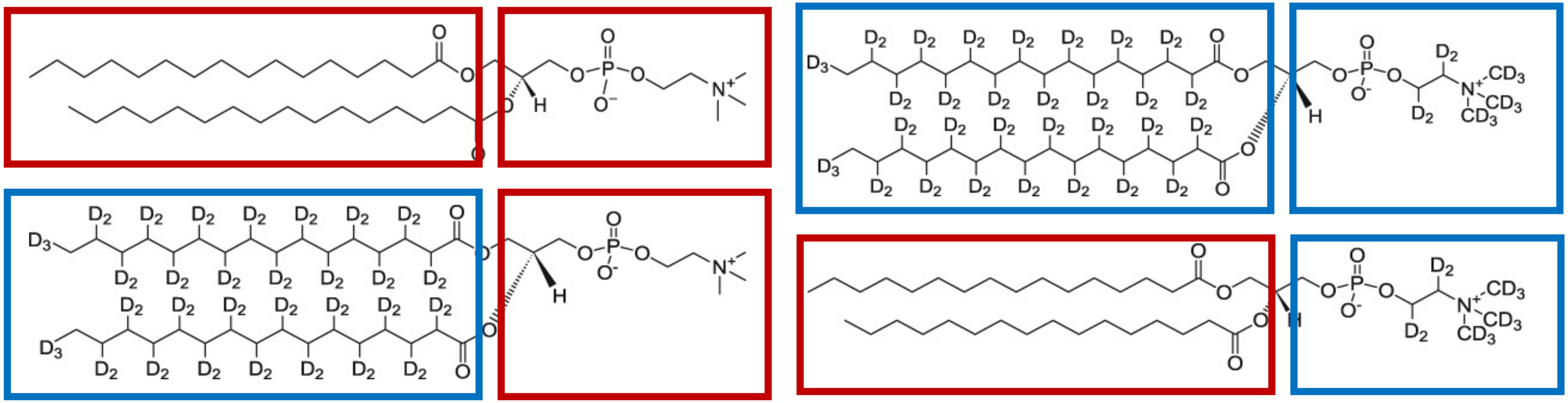
d) $I(q) \propto \Delta SLD^2$



Adamo *et al.*, Lab on a Chip, 2017.

Deuteration

- The SLD of the scatterers can be modified through **deuterium-labelling** – minimal impact on the chemistry of the sample.



- This allows the preparation of specific contrast conditions and **resolve more complex systems**.
- There is a wide range of commercially available deuterated compounds, but be ready to pay **$$$.**
- Neutron facilities have **deuteration facilities** willing to collaborate (maybe).

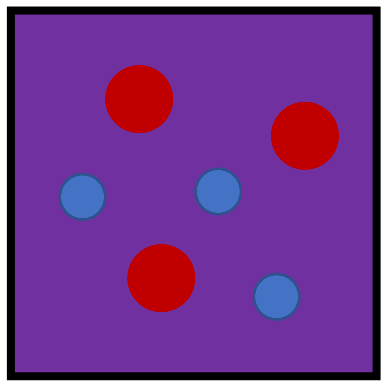
Zero average contrast condition

- Mixture of **protiated and deuterated scatterers** in a solvent where:

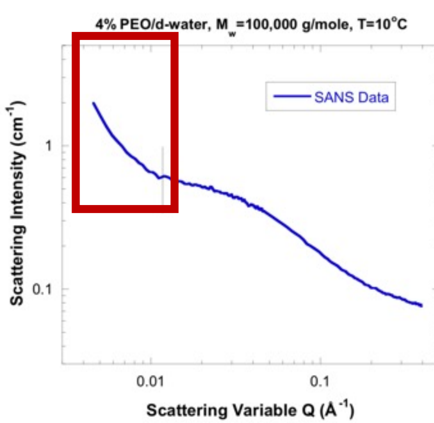
$$SLD_h - SLD_s = SLD_s - SLD_d$$

$$SLD_s = \frac{SLD_h + SLD_p}{2}$$

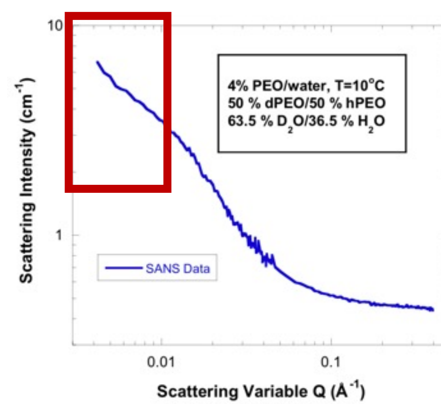
- In this condition, the **interaction term cancels out** and the single particle form factor can be calculated.



Finite contrast



ZAC



Benmouna *et al.*, Prog Polym Sci, 1997.

Zero average contrast condition

- Uses a combination of **protonated and deuterated scatterers** and solvent where:

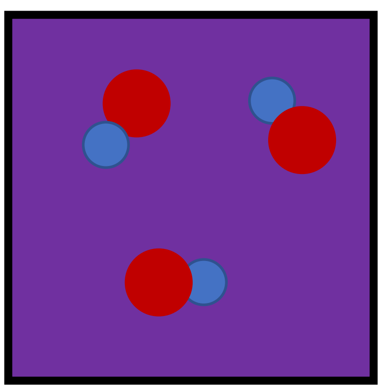
$$SLD_h - SLD_s = SLD_s - SLD_d$$

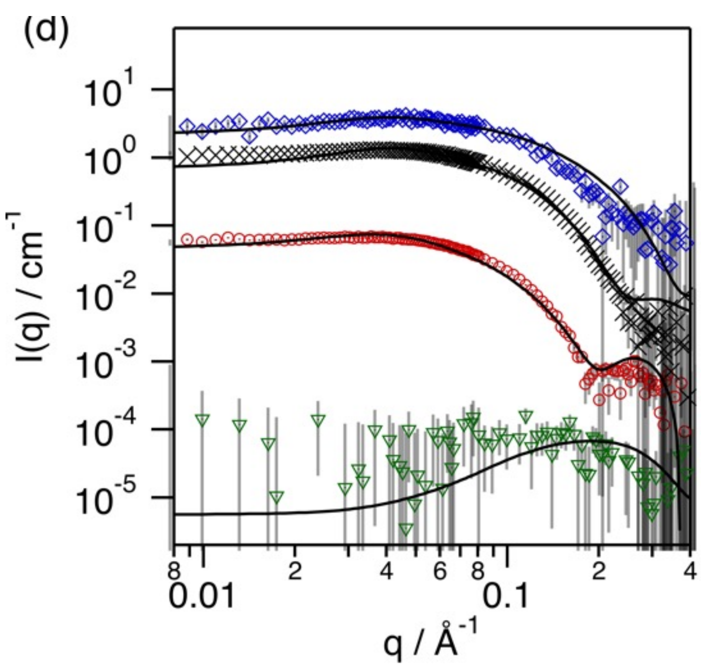
$$SLD_s = \frac{SLD_h + SLD_p}{2}$$

- Contrast condition to determine particle complexation.

$$SLD_s = \frac{SLD_{p1} v_{p1} N_{agg,p1} + SLD_{p2} v_{p2} N_{agg,p2}}{v_{p1} N_{agg,p1} + v_{p2} N_{agg,p2}}$$

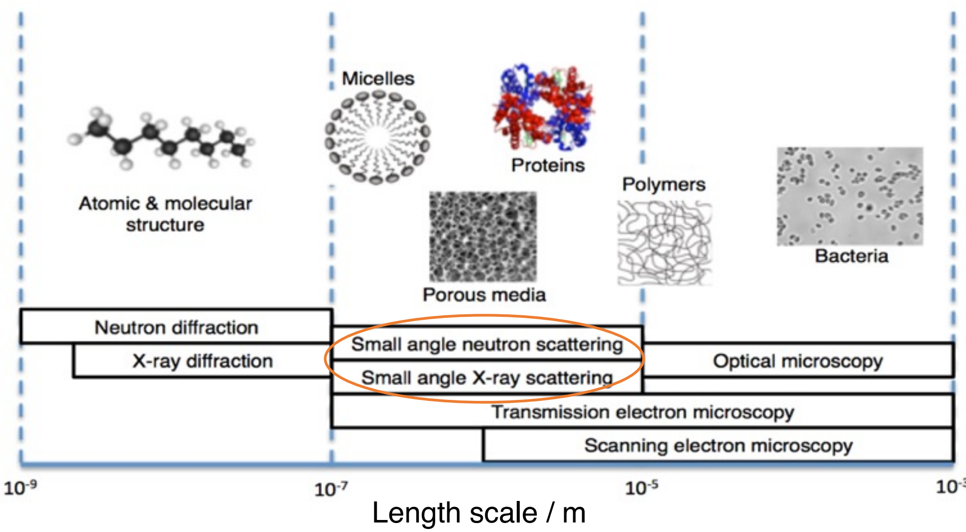
- Complexation – I(0)=0; peak related to the characteristic correlation length.

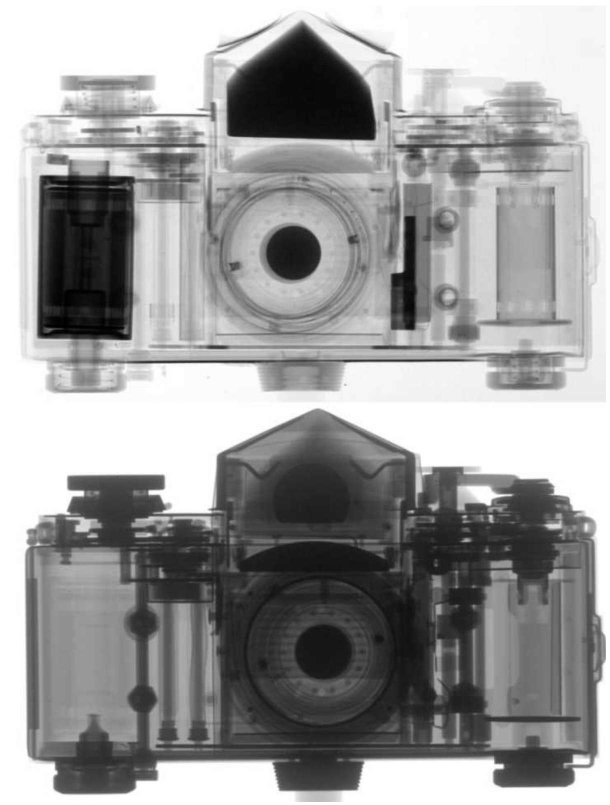




SANS and SAXS – a love story

- X-ray and neutrons **interact with matter in a different way**.
  - X-rays – **electron clouds**.
  - Neutrons – **nuclei**.
- **Same length scale** – different contrast.
- Both can provide **complementary information** of the same system – co-refinement of SANS and SAXS data.

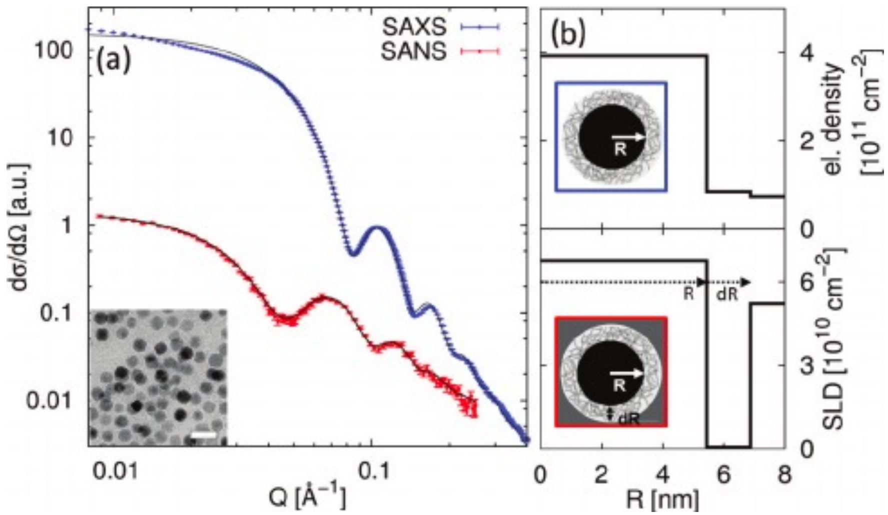




SANS and SAXS – a love story

- Contrast variation can be also exploited **between techniques**.

Fe_2O_3 – oleic acid – d-toluene



Disch *et al.*, Phys Rev B, 2014.

- NP's scattering excess in X-ray: ~1142
- Ligand scattering excess in X-ray: ~0.64
- NP's scattering excess in neutrons: ~2.25
- Ligand scattering excess in neutrons: ~40

$$\Delta SLD^2 = \left(SLD_p - SLD_s\right)^2$$

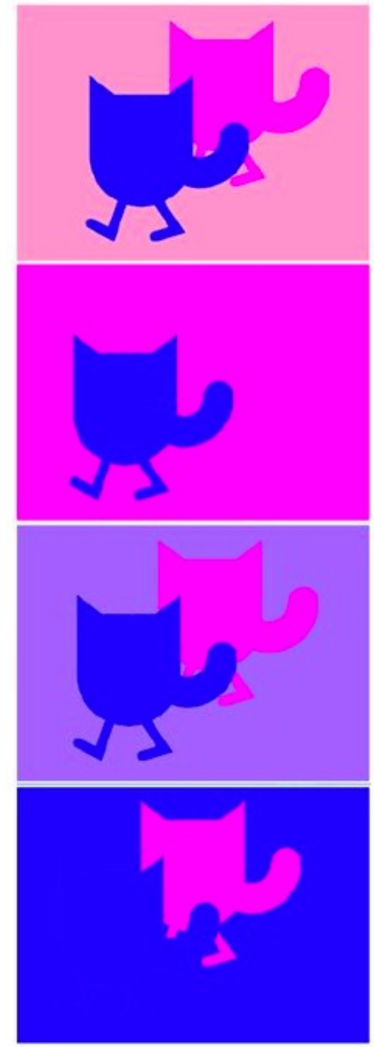
- NP's scattering/total scattering in X-rays: ~0.999
- Ligand scattering/total scattering in neutrons: ~0.946

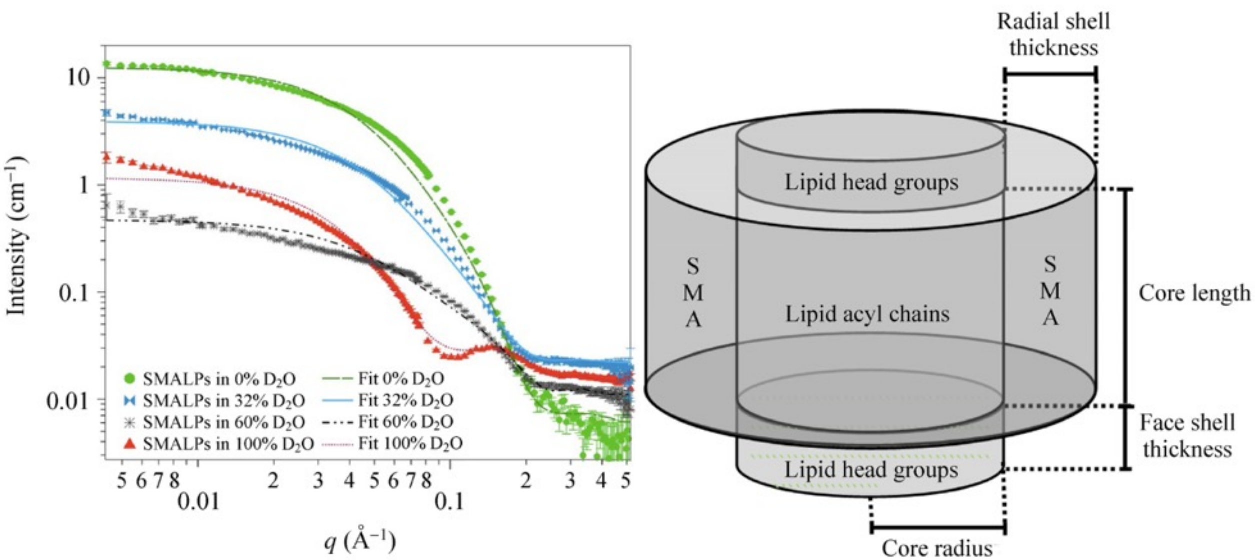
Simultaneous fitting of contrasts

- Measuring several contrasts (including X-rays), allows a **more accurate validation of the model**:
  - **Co-refinement of several contrast** to a single model.
  - **Introducing constraints** from simplified models.

- **Get rid of the phase problem** – one model to rule them all.

- Be careful, **isotopic effects** may affect the characteristics of the sample – stick them in a X-ray machine!





Jamshad *et al.*, Nano Res, 2015

Some final considerations

- **Know your system** – do I need neutrons? how can the system be simplified using contrast variation?
- **Consider the isotopic effect** – differences in the CMC, CAC, protein folding, isoelectric point, hydrogen bond effects…
- Where will you get the **d-chemicals**? not everyone has perdeuterated cotton candy in the lab.
- For more information: **The SANS toolbox – Hammouda**.