Bio-SANS for modelers and experimentalists

(compiled by Anne Martel and Sergei Grudinin)

Similarly to small-angle X-ray scattering (SAXS), small-angle neutron scattering (SANS) measures the neutrons scattered by particles in solution. And, the way the scattered intensity varies with the scattering angle depends on the size and shape of the scatterer. However, the two methods have fundamental and technical differences that explain why they provide complementary data.

A- Fundamental differences and their consequences

The fundamental difference between the two radiations is that the X-rays interact with the electrons of the scatterers while the neutrons interact with their atom nucleus. Consequently, while X-rays "see" each atom with the volume of its electron cloud, neutrons "see" it as a point-scatterer. Another consequence is that X-ray scattering length (SL) of each atom is proportional to its number of electrons (Z), while the neutron scattering length is not. Figure1 shows the coherent scattering length of some atoms constituting biological molecules.

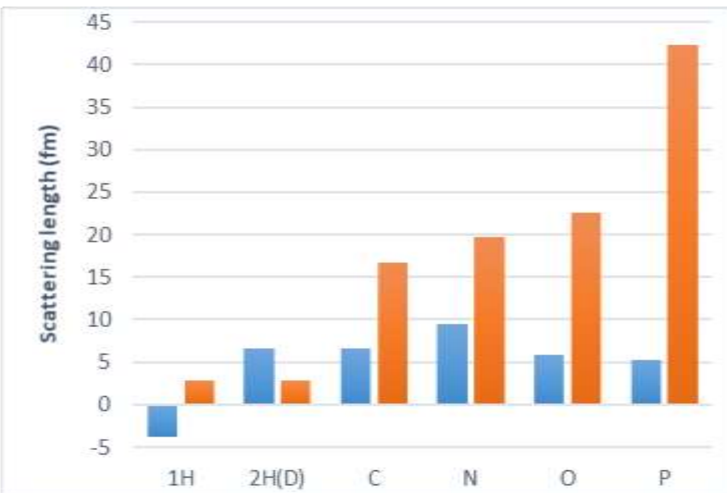

Figure 1: Graph of the Neutron (blue) and X-ray (orange) scattering lengths of the main atom of biological molecules.

Each molecule is characterized by its Scattering Length Density (SLD) which is the sum of the scattering length of all of its atoms divided by the partial specific volume of the molecule. The different types of biological macromolecules: proteins, nucleic acids, lipids and sugars, have different compositions and different hydrogen fractions. Therefore, they have different neutron SLD, although, being made of light atoms, they have about the same X-ray SLD. The SLD difference is called the contrast. From figure 1, note that deuterium, the isotope of hydrogen which nucleus contains one proton and one neutron (^{2}H or D), has exactly the same SL as the most common hydrogen isotope (^{1}H or H) in SAXS but a very different one in SANS, and even of different sign. This isotope effect is used to specifically label selected partner within a biomolecular complexes. This labelling is called *deuteration*. For instance, in a protein heterodimer, if both partners are non-deuterated, they will have a similar neutron SLD while if one of them is deuterated and the other one is not, their neutron SLD will be very different. Similarly, the SLD of the solvent can be tuned by preparing the buffer with different fractions of light water (H_2O) and heavy water (D_2O). In particular, the SLD of the solvent can be adjusted to match the SLD of a molecule. In this case, the molecule is "contrast-matched". Figure 2 (from Jeffries *et* *al.*, Nat Protoc. 2016 Nov; 11(11): 2122–2153) shows how the contrast variation technique, which consists in varying the solvent SLD, can be used to highlight successively each partner within a complex, while contrast-matching the other one.

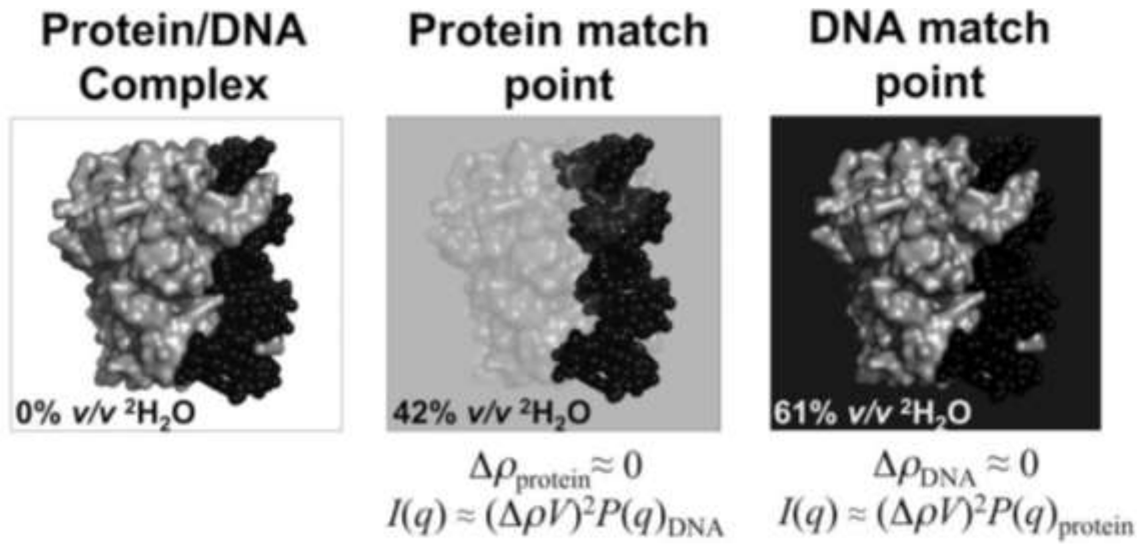

Figure 2: Scheme illustrating the use of natural contrast between protein and DNA for the determination of the low-resolution structure of a protein-DNA complex by SANS through the measurement of a contrast variation series. While in protonated buffer, the two partners are visible with different contrasts, in 42% deuterated buffer, the protonated protein is contrast-matched and only the DNA is visible. And in 61% deuterated buffer, the protonated DNA is contrast matched and only the protein is visible.

B- Technical differences and their consequences

Technical differences between SAXS and SANS mainly impact the sample preparation, but also the data format. X-rays are easier to produce and more widely available than Neutrons. As a consequence, scientists will opt for SANS only for specific projects, requiring the contrast variation, which cannot be realized with SAXS, i.e. when they want the relative position of partners within a hetero-oligomer.

In SAXS, the X-ray flux is very high compare to the Neutron flux in SANS, therefore, SAXS scientists can afford selecting a very small beam and a very narrow wavelength range (monochromatic beam). However, in SANS, to gain some flux, we select a beam with a large footprint (several mm diameter) and a wavelength spread of 10 to 20%. Furthermore, detectors for X-ray and neutrons also rely on a very different detection technologies and while X-ray detector pixels are a few µm wide, Neutron detector pixels are several mm wide. All together, these technical specificities result in data being smeared by a “resolution function”. And **Neutron data files contain 4 columns**:

1: Q value (usually in $Å^{-1}$),

2: Intensity (in cm^{-1}),

3: Intensity error (these 3 columns are common with the SAXS data files) and

4: the resolution in the 4^{th} column. The number given in the 4^{th} column is actually the “sigma” value of the Gaussian function by which data is smeared and is calculated, at each q-value using the instrument geometry parameters and the wavelength spread. The model has to be smeared the same before fitting to the data.

The neutron detector being real “neutron-counting”, the SANS signal is normalized to the incident neutron flux and therefore, the data are provided in absolute intensity. This means that, in particular, the intensity extrapolated at Q = 0 can be used to estimate sample molecular weight (as long as the concentration is known) and therefore to estimate its oligomerization state.

In order to maximize the flux across the whole required Q-range, the samples are often measured at several instrument configurations, resulting in several data files which are merged during the data reduction.

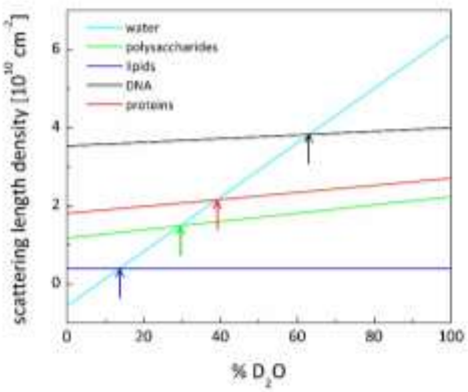

Figure 3: Graph showing the evolution of biomacromolecules SLD according to the D_2O content of the buffers. The arrows show the match point of these molecules. At a given D_2O content, the difference between the water and the molecule SLD is the contrast.

(from nmi3.eu website)

Figure 3 shows a plot of the Scattering Length Density of different biomolecules as a function of the D_2O content of their buffer, and enables to visualize the contrast one can expect with the buffer. Some of the hydrogen atoms of biomolecules are labiles and exchange with the hydrogens of the buffer. These are the ones bond to an oxygen, a nitrogen or a sulfur atom. This exchange explains why the SLD of the biomolecules increases with the D_2O content of the solvent. The others hydrogen atoms, i.e. the ones bond to a carbon atom, are non-labile. To change them for deuterium, the molecules have to be produced in deuterated conditions.

As seen above, the usual **Bio-SANS sample is a complex.** For instance, it can be

- a membrane protein with a detergent belt
- a deuterated protein with a protonated one
- a protein and a nucleic acid

The partners must be at least 10 kDa each. Because of the low flux, the amount of sample required for a SANS experiment is larger than for a SAXS experiment. **Each sample must be at least 200 µL of 2mg/mL** concentration of the non contrast-matched component(s). Fortunately, Neutrons do not cause any radiation damage. Therefore, the same sample can be buffer-exchanged to vary the contrast (by desalting size exclusion chromatography preferentially, or by dialysis), re-concentrated and re-measured. Then, once the SANS experiment is done, the sample can be re-used for another kind of measurement (SAXS, for instance). The contrast match point of the partners can be estimated (Isis

PSLDC calculator: http://psldc.isis.rl.ac.uk/Psldc/), as well as the intensity extrapolated at Q = 0, to prepare the experiment. But it has to be precisely measured before measuring the complex SANS data.

Here, we present two examples of samples for SANS measurements:

Case1: Membrane protein with a detergent belt:

Not all detergents can be contrast-matched. LMNG does. To measure its match point, one should prepare 5 samples having exactly the same mass concentration of LMNG, and as high as possible (for instance 20 mg/mL), but 5 different D_2O contents, for instance 0%, 20%, 40%, 60%, 80% and 100%. (This measurement has already been done and LMNG match point is 21.4 % D_2O.) Then the protein sample, containing the protein with its detergent belt and some free detergent micelles, has to be prepared in a buffer, whose D_2O content corresponds to the detergent match point. Consequently, the SANS measurement will reveal the low resolution structure for the protein alone in solution, without contribution of the detergent. Co-factors or substrates of the protein can be added to the sample (without changing the D_2O content) to see their effect on protein structure. Recently, specifically deuterated β-DDM has been chemically synthetised to be matched out at 100% D_2O (Mitgaard *et al.*, FEBS J. 2018 Jan;285(2):357-371.).

Case2: Protein-protein complex with one deuterated partner:

A protonated protein is contrast-matched around 42% D_2O, as shown in Figure 3. A perdeuterated protein (i.e. a protein whose all hydrogen atoms are replaced by deuterium) cannot be contrast matched as its SLD is higher than D_2O. A 75%-deuterated protein is contrast-matched around 100% D_2O. Protocols to produce deuterated protein to a given rate are published (Dunne *et al.* European Biophysics Journal 46, 425-432 (2017)), usually mastered by NMR experts or can be realized with the help of facilities such as the D-lab of Institut Laue Langevin. The match point of each partner has to be measured accurately: Similarly as above for the detergent, 5 samples with different D_2O contents and the same protein concentration have to be measured for each partner. Then, the complex will be measured at the contrast match point of each partner and at least one other contrast. For instance, a sample in 0% D_2O is usually easily available. At the average D_2O content between the two contrast match points, the two partners will have the same contrast with the buffer (of opposite sign) and therefore, the scattering data will be comparable to the data that can be obtained by SAXS.

The sample preparation quality checks are the same as for SAXS: the sample must be perfectly monodisperse and free of interparticle interaction (attractive or repulsive), at least the non contrast-matched part. This mean that the protein must be pure and at a concentration where no aggregation is observed by dynamic light scattering. This has to be checked for the highest D_2O content that is planned to be measured as D_2O tend to favor hydrophobic interactions.

The 2-dimensions scattering patterns are isotropic and reduced in a similar way as SAXS data.

In conclusion, SANS is used to determine the relative position of some partners in a complex, or the low resolution structure of a protein that you cannot obtain without detergents. The absence of radiation damage makes it also a good technique to study very sensitive protein or photo-reducible molecules for which SAXS is not adequate.