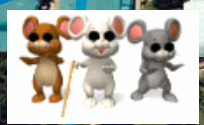
Basics of X-ray scattering by solutions

D.Svergun, EMBL-Hamburg

EMBL

EMBL Outstation at DESY, Hamburg

1974



EMBL integrated facility at upgraded Petra-3 ring (in operation from 2012)

2 MX beamlines
1 BioSAXS beamline

Biological SAXS @ EMBL-HH

Group leader: D. Svergun
Staff : M. Petoukhov, C.Blanchet, D.Franke, A.Kikhney, H.Mertens
Postdocs: A.Tuukkanen, M.Graewert , A.Spilotros, C.Jeffries, A.Panjkovich
Predocs: M.Kachala, E.Valentini, N.Hajizadeh

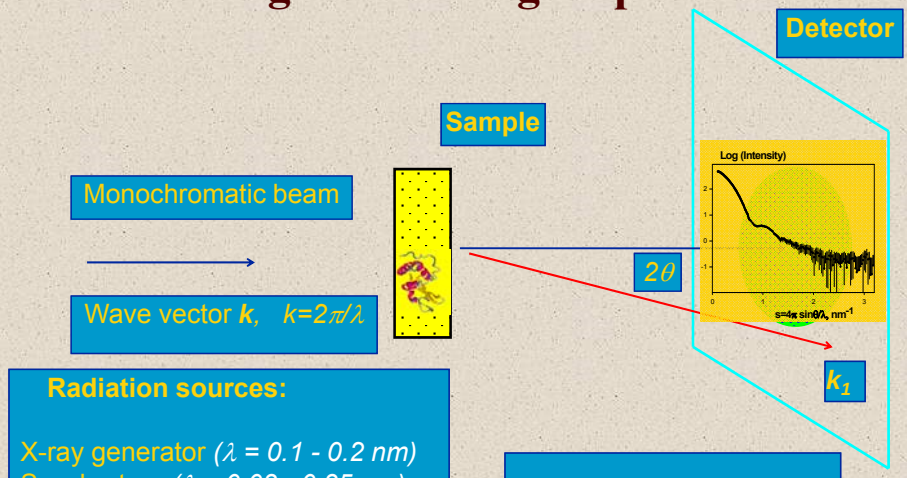
Major tasks:

- Development of data analysis methods
- Running and developing SAXS beamlines
- User support and collaborative projects
- Education and training

Modern synchrotron SAXS

General princples of solution SAXS

Small-angle scattering: experiment



Scattering by matter

- **X-rays** are scattered mostly by electrons
- **Thermal neutrons** are scattered mostly by nuclei
- Scattering amplitude from an ensemble of atoms $A(\mathbf{s})$ is the Fourier transform of the scattering length density distribution in the sample $\rho(\mathbf{r})$
- Experimentally, scattering intensity $I(\mathbf{s}) = [A(\mathbf{s})]^2$ is measured.

Notations

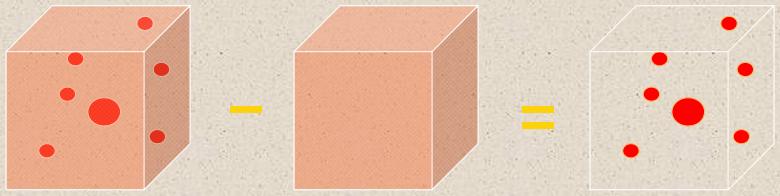
The momentum transfer (i.e. the modulus of the scattering vector is denoted here as $s=4\pi \sin(\theta)/\lambda$

There are also different letters used, like

$$Q = q = s = h = k = 4\pi \sin(\theta)/\lambda$$

Sometimes, the variable $S= 2\sin\theta/\lambda = 2\pi s$ is used, and to add to the confusion, also denoted as "s", or μ or yet another letter. Always check the definition for the momentum transfer in a paper

Small-angle scattering: contrast



$I_{sample}(s)$ $I_{matrix}(s)$ $I_{particle}(s)$

- To obtain scattering from the particles, matrix scattering must be subtracted, which also permits to significantly reduce contribution from parasitic background (slits, sample holder etc)
- **Contrast** $\Delta\rho = \langle\rho(r) - \rho_s\rangle$, where ρ_s is the scattering density of the matrix, may be very small for biological samples

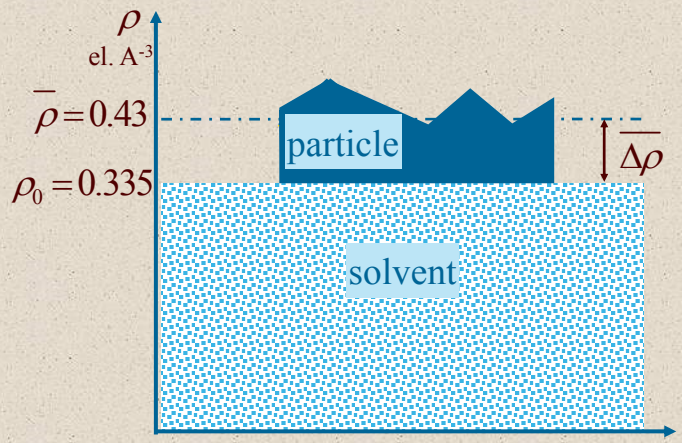
X-rays versus neutrons

- **X-rays:** scattering factor increases with atomic number, no difference between H and D
- **Neutrons:** scattering factor is irregular, may be negative, huge difference between H and D

Element	H	D	C	N	O	P	S	Au
At. Weight	1	2	12	14	16	30	32	197
N electrons	1	1	6	7	8	15	16	79
$b_X, 10^{-12}$ cm	0.282	0.282	1.69	1.97	2.16	3.23	4.51	22.3
$b_N, 10^{-12}$ cm	-0.374	0.667	0.665	0.940	0.580	0.510	0.280	0.760

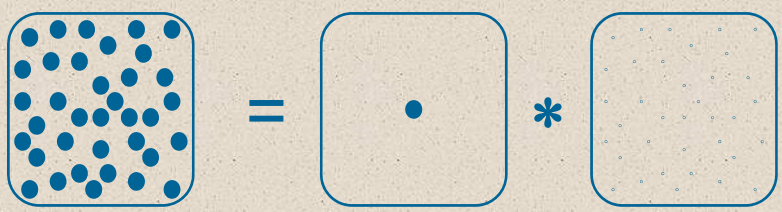
Neutron contrast variation

Contrast of electron density



In the equations below we shall always assume that the solvent scattering has already been subtracted

Solution of particles



Solution		Motif (protein)		Lattice
$\Delta\rho(\mathbf{r})$	=	$\Delta\rho_p(\mathbf{r})$	*	$d(\mathbf{r})$
$\mathbf{F(c,s)}$		$\mathbf{F(0,s)}$	*	$\delta(c,s)$
			•	

Solution of particles

For spherically symmetrical particles

$$I(c,s) = I(0,s) \times S(c,s)$$

form factor of the particle **structure factor of the solution**

Still valid for globular particles though over a restricted s-range

Solution of particles

- 1 – ***monodispersity***: identical particles
- 2 – size and shape polydispersity
- 3 – ***ideality*** : no intermolecular interactions
- 4 – non ideality : existence of interactions between particles

In the following, we make the double assumption 1 and 3

Ideal and monodisperse solution

$$A(\mathbf{s}) = \Im[\Delta\rho(\mathbf{r})] = \int_V \Delta\rho(\mathbf{r}) \exp(i\mathbf{sr}) d\mathbf{r}$$

Particles in **solution** => thermal motion => particles have random orientations to X-ray beam. The sample is ***isotropic.*** Therefore, only the ***spherical average*** of the scattered intensity is experimentally accessible.

Ideality and monodispersity $I(s) = N i_1(s)$

Crystal versus solution

$$\mathbf{I(c,s) = I(0,s) \times S(c,s)}$$

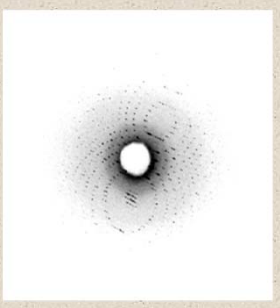
For an ideal crystal,
I (**s**) is the three-dimensional scattering intensity from the unit cell
S(**s**) is a sum of δ-functions along the directions of the reciprocal space lattice
s=(h**a***+k**b***+l**c***)

For an ideal dilute solution,
I(**s**)= I(s) is the orientationally averaged intensity of the single particle

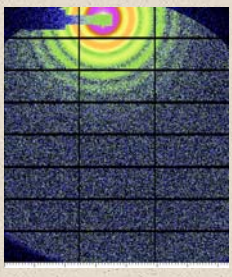
S(s) is equal to unity

Crystal versus solution

For an ideal crystal, measured signal is amplified into specific directions allowing measurements to high resolution ($d \approx \lambda$)



For an ideal dilute solution, I (**s**) is isotropic and concentrates around the primary beam (this is where the name "small-angle scattering" comes from): low resolution ($d >> \lambda$).



Main equations and overall parameters

Relation between real and reciprocal space

Using the overall expression for the Fourier transformation one obtains for the spherically averaged single particle intensity

$$I(s) = \left\langle A(\mathbf{s})A^*(\mathbf{s}) \right\rangle_\Omega = \left\langle \int_V \int_V \Delta\rho(\mathbf{r})\Delta\rho(\mathbf{r}')\exp\{i\mathbf{s}(\mathbf{r}-\mathbf{r}')\}d\mathbf{r}d\mathbf{r}' \right\rangle_\Omega$$

or, taking into account that $\langle exp(isr) \rangle_\Omega = sin(sr)/sr$ and integrating in spherical coordinates,

$$I(s) = 4\pi \int_0^{D_{max}} r^2 \gamma(r) \frac{\sin sr}{sr} dr$$

where

$$\gamma(r) = \left\langle \int \Delta\rho(\mathbf{u})\Delta\rho(\mathbf{u}+\mathbf{r})d\mathbf{u} \right\rangle_\omega$$

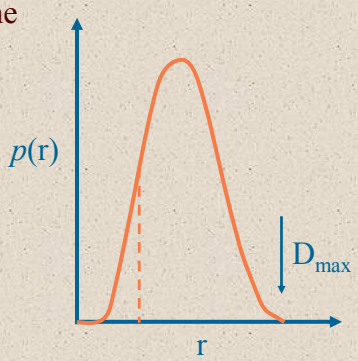
Distance distribution function

$$p(r) = r^2\gamma(r) = r^2\gamma_0(r)V\rho^2$$

$\gamma_0(r)$: ***probability*** of finding a point at r from a given point

number of el. vol. i $\propto$ V - number of el. vol. j $\propto 4\pi r^2$

number of pairs (i,j) separated by the distance r $\propto 4\pi r^2 V\gamma_0(r) = (4\pi/\rho^2)p(r)$



Debye formula

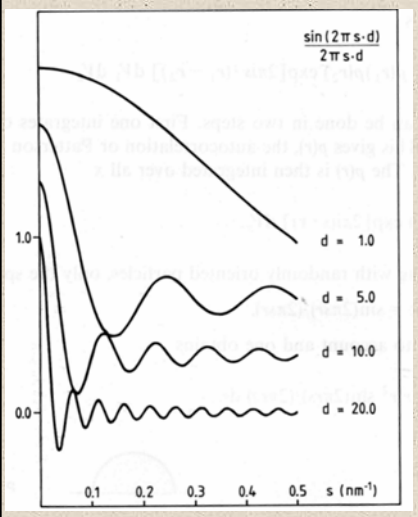
If the particle is described as a discrete sum of elementary scatterers,(e.g. atoms) with the atomic scattering factors $f_i(s)$ the spherically averaged intensity is

$$I(s) = \sum_{i=1}^{K} \sum_{j=1}^{K} f_i(s) f_j(s) \frac{\sin(sr_{ij})}{sr_{ij}}$$

where $r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$

The Debye (1915) formula is widely employed for model calculations

Contribution of distances to the scattering pattern

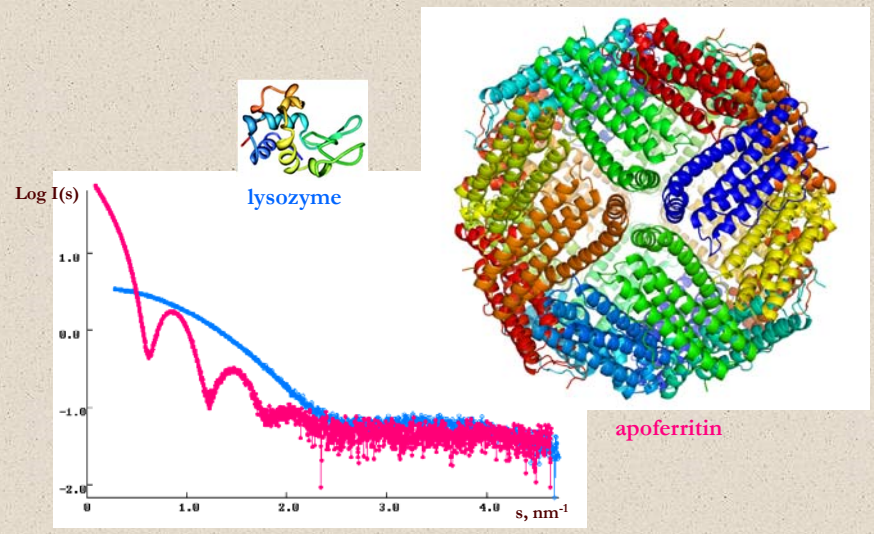


In isotropic systems, each distance $d = r_{ij}$ contributes a sinx/x –like term to the intensity.

Large distances correspond to high frequencies and only contribute at **low angles** (i.e. at low resolution, where particle shape is seen)

Short distances correspond to low frequencies and contribute over a large angular range.
Clearly at **high angles** their contribution dominates the scattering pattern.

Small and large proteins: comparison



Guinier law

Near *s=0* one can insert the McLaurin expansion *sin(sr)/sr≈1-(sr)²/3!+...* into the equation for I(s) yielding

$$I(s) = I(0)\left[1 - \frac{1}{3}R_g^2 s^2 + O(s^4)\right] \cong I(0)\exp\left(-\frac{1}{3}R_g^2 s^2\right)$$

This is a classical formula derived by Andre Guinier (1938) in his first SAXS application (to defects in metals). The formula has two parameters, forward scattering and the radius of gyration

$$I(0) = \int_V \int_V \Delta\rho(\mathbf{r})\Delta\rho(\mathbf{r}')d\mathbf{r}d\mathbf{r}' = 4\pi \int_0^{D_{max}} p(r)dr = (\Delta\rho)^2 V^2$$

$$R_g = \int_0^{D_{max}} r^2 p(r)dr \left[2\int_0^{D_{max}} p(r)dr\right]^{-1}$$

ideal monodisperse

Intensity at the origin

$$i_1(0) = \int_{V_\mathbf{r}} \int_{V_{\mathbf{r}'}} \Delta\rho(\mathbf{r})\Delta\rho(\mathbf{r}')dV_\mathbf{r}dV_{\mathbf{r}'}$$

$$i_1(0) = \Delta m^2 = (m - m_0)^2 = \left[\frac{M}{N_A}\overline{v}_P(\rho - \rho_0)\right]^2$$

$c = \frac{NM}{N_A V}$ is the concentration (w/v), e.g. in mg.ml^{-1}

$$I(0) = \frac{cMV}{N_A}\left[\overline{v}_P(\rho - \rho_0)\right]^2$$

ideal monodisperse

Intensity at the origin

If : the concentration c (w/v), $\overline{v}_P$,
the partial specific volume v_P,
the intensity on an absolute scale,
i.e. the number of incident photons
are known,
Then, the **molecular weight** of the particle can be determined from the value of the intensity at the origin

In practice, MM can be determined from the data on relative scale by comparison with I(0) of a reference protein (e.g. BSA, lysozyme or cytochrom C)

ideal monodisperse

Radius of gyration

Radius of gyration : $$R_g^2 = \frac{\int_{V_r} \Delta\rho(\mathbf{r}) r^2 dV_r}{\int_{V_r} \Delta\rho(\mathbf{r}) dV_r}$$

R_g is the quadratic mean of distances to the center of mass weighted by the contrast of electron density.
R_g is an ***index of non sphericity***.
For a given volume the smallest R_g is that of a sphere : $$R_g = \sqrt{\frac{3}{5}} R$$

Ellipsoid of revolution (a, b)

$$R_g = \sqrt{\frac{2a^2 + b^2}{5}}$$

Cylinder (D, H)

$$R_g = \sqrt{\frac{D^2}{8} + \frac{H^2}{12}}$$

ideal monodisperse

Virial coefficient

In the case of moderate interactions, the intensity at the origin varies with concentration according to :

$$I(0,c) = \frac{I(0)_{ideal}}{1 + 2A_2 Mc + \ldots}$$

Where A_2 is the second virial coefficient which represents pair interactions and $I(0)_{ideal}$ is $\propto$ to c.
A_2 is evaluated by performing experiments at various concentrations c.
A_2 is $\propto$ to the slope of c/I(0,c) vs c.

To obtain I(0, s), this extrapolation to infinite dilution is performed for different angles

Guinier plot example

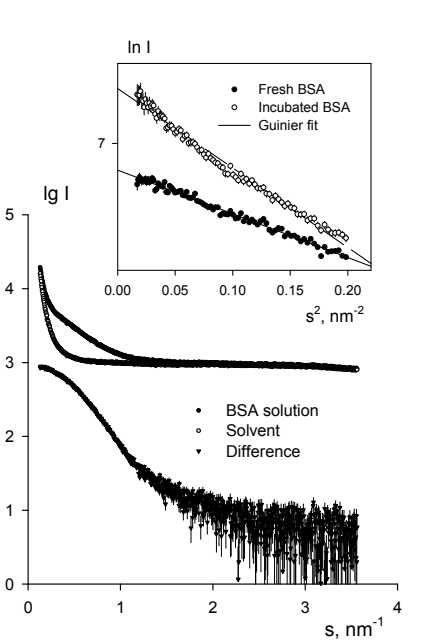
The law is generally used under its log form :

$$\ln[I(s)] = \ln[I(0)] - [sR_g]^2/3$$

A linear regression yields two parameters : I(0) (y-intercept)
R_g from the slope

Validity range :
$0 < sR_g < 1.3$

ideal monodisperse



Rods and platelets

In the case of very elongated particles, the radius of gyration of the cross-section can be derived using a similar representation, plotting this time sI(s) *vs* s^2

$$sI(s) \cong I_C(0)\exp\left(-\frac{1}{2}R_c^2 s^2\right)$$

In the case of a platelet, a thickness parameter is derived from a plot of $s^2I(s)$ *vs* s^2 :

$$s^2 I(s) \cong I_T(0)\exp\left(-R_t^2 s^2\right)$$

with $R_t = T/\sqrt{12}$ T : thickness

ideal monodisperse

Distance distribution function

$$p(r) = \frac{r^2}{2\pi^2} \int_0^\infty s^2 I(s) \frac{\sin sr}{sr} dr$$

In theory, calculation of p(r) from I(s) is simple.

Problem : I(s) - is only known over [s_{min}, s_{max}] : truncation
- is affected by experimental errors and possible instrumental distorsions due to the beam-size and the bandwidth $\Delta\lambda/\lambda$ (neutrons)

$\Rightarrow$ Fourier transform of ***incomplete and noisy data*** is an ***ill-posed problem***.

Solution : Indirect Fourier Transform (suggested by O. Glatter, 1977).
p(r) is parameterized on [0, D_{max}] by a linear combination of orthogonal functions, where D_{max} is the particle diameter.
Implemented in several programs, including GNOM (part of ATSAS)

ideal monodisperse

Distance distribution function

The radius of gyration and the intensity at the origin are derived from p(r) using the following expressions :

$$R_g^2 = \frac{\int_0^{D_{max}} r^2 p(r) dr}{2\int_0^{D_{max}} p(r) dr} \quad \text{and} \quad I(0) = 4\pi \int_0^{D_{max}} p(r) dr$$

This alternative estimate of R_g makes use of the whole scattering curve, and is much less sensitive to interactions or to the presence of a small fraction of oligomers.
Comparison of both estimates : useful cross-check

ideal monodisperse

Porod invariant and volume

Following the Parseval theorem for Fourier transformations

$$Q = \int_0^\infty s^2 I(s) ds = 2\pi^2 \int_V (\Delta\rho(\mathbf{r}))^2 d\mathbf{r}$$

Q is called the Porod invariant, which is computed from the intensity but provides the mean square electron density contrast.

For homogeneous particles, $Q=2\pi^2(\Delta\rho)^2V$, and, taking into account that $I(0)=(\Delta\rho)^2V^2$, the excluded volume of hydrated particle in solution (Porod volume) is

$$\mathbf{V=2\pi^2 I(0)/Q}\ .$$

The asymptotic regime : Porod law

Integrating the Fourier transformation for I(s) by parts and using that for particles with a *sharp interface* $\gamma'(D_{max}) = 0$, one has

$$I(s) \cong 8\pi s^{-4}\gamma'(0) + O_1 s^{-3} + O_2 s^{-4} + o(s^{-5})$$

where O_1, O_2 are oscillating trigonometric terms of the form *sin* (sD_{max}). The main term responsible for the intensity decay at high angles is therefore proportional to s^{-4}, and this is known as Porod's law (1949). For homogeneous particles, $\gamma'(0)$ is equal to $-(\Delta\rho)^2S/4$, where S is the particle surface.

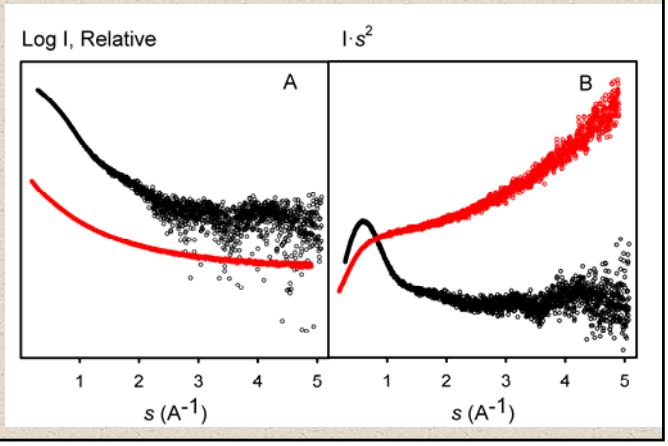
ideal monodisperse

Kratky plot

A plot of $s^2I(s)$ vs s provides a sensitive means of ***monitoring the degree of compactness*** of a protein.

Globular particle : bell-shaped curve

Unfolded particle: plateau or increase at large s-values



Summary of model-independent information

I(0)/c, i.e. molecular mass *(from Guinier plot or p(r) function)*

Radius of gyration R_g *(from Guinier plot or p(r) function)*

Radii of gyration of thickness or cross-section *(anisometrc particles)*

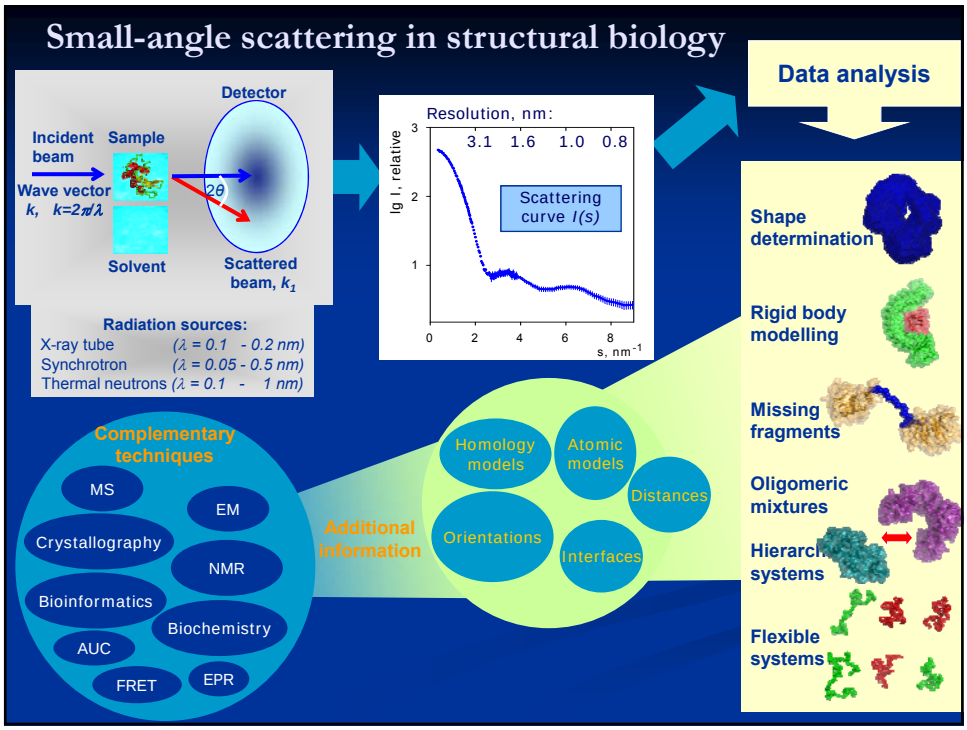
Second virial coefficient A_2 *(extrapolation to infinite dilution)*

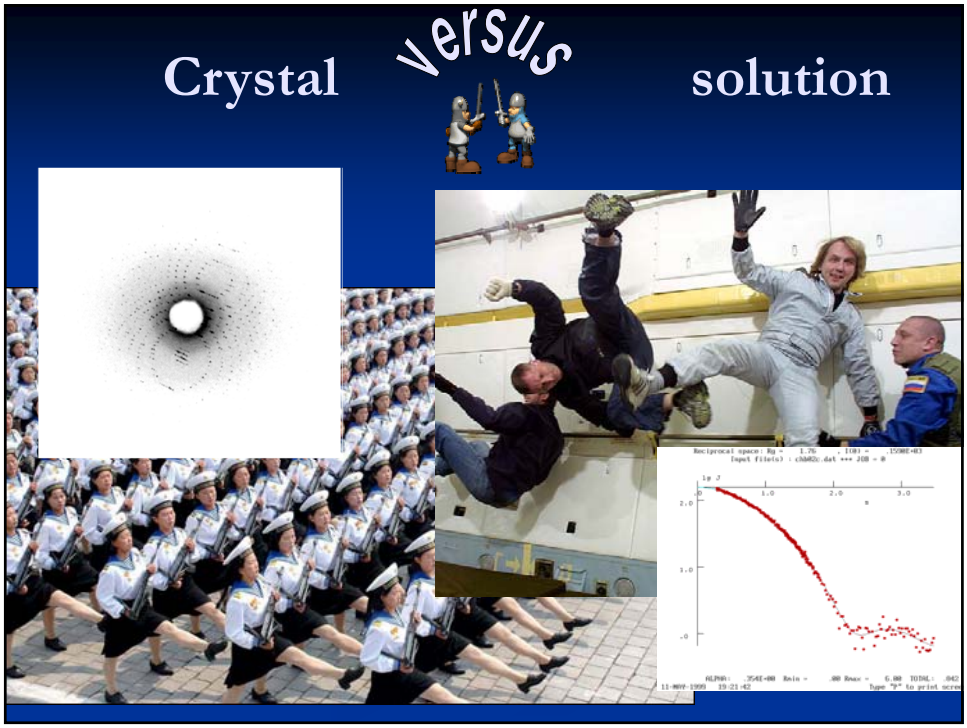
Maximum particle size D_{max} *(from p(r) function)*

Particle volume V *(from I(0) and Porod invariant)*

Specific surface S/V *(from I(0), Porod invariant and asymptotics)*

Globular or unfoded *(From Kratky plot)*


Small-angle scattering in structural biology
Detector
Incident beam
Sample
Wave vector
k, k=2π/λ
2θ
Solvent
Scattered beam, k1
Radiation sources:
X-ray tube (λ = 0.1 - 0.2 nm)
Synchrotron (λ = 0.05 - 0.5 nm)
Thermal neutrons (λ = 0.1 - 1 nm)
Resolution, nm:
3.1 1.6 1.0 0.8
lg I, relative
Scattering curve I(s)
s, nm-1
Data analysis
Shape determination
Rigid body modelling
Missing fragments
Oligomeric mixtures
Hierarch systems
Flexible systems
Complementary techniques
MS
EM
Crystallography
NMR
Bioinformatics
Biochemistry
AUC
FRET
EPR
Additional information
Homology models
Atomic models
Distances
Orientations
Interfaces

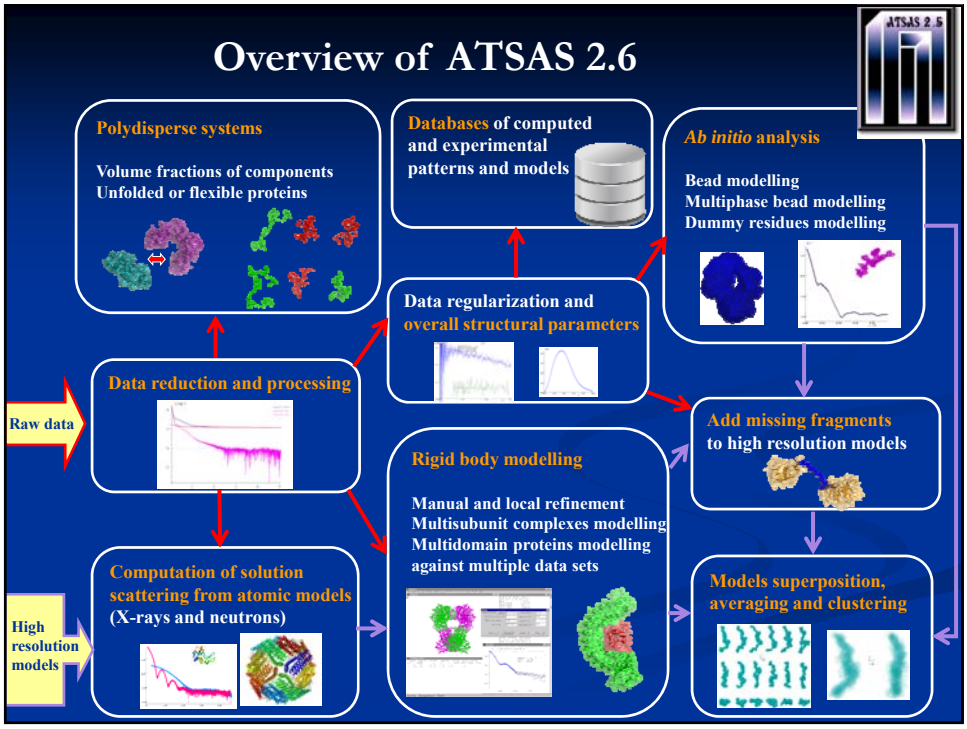

Crystal
versus
solution

Crystal versus solution

- In solution, no crystallographic packing forces are present

- For SAXS solution studies, one does not need to grow crystals
- SAXS is not limited by molecular mass and is applicable under nearly physiological conditions
- Using solution SAXS, one can more easily observe responses to changes in conditions
- SAXS permits for quantitative analysis of complex systems and processes

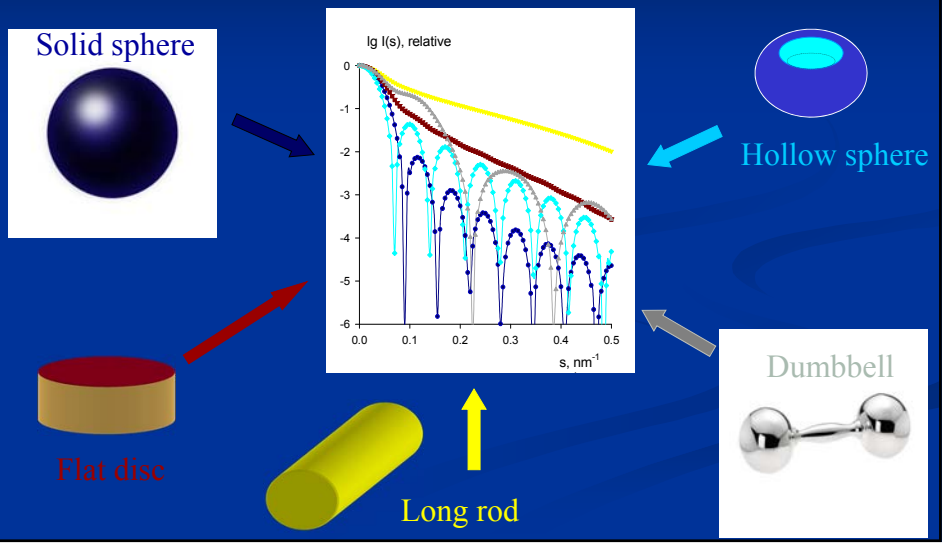
Overview of ATSAS 2.6



Data processing

PRIMUS: data manipulations
GNOM: distribution functions
BODIES: simple shapes

The scattering is related to the shape (or low resolution structure)



Recent reviews on solution SAS

Blanchet CE, Svergun DI (2013) Small-angle X-ray scattering on biological macromolecules and nanocomposites in solution. Annual Review of Physical Chemistry 64(1): 37–54.

Schneidman-Duhovny D, Kim S, Sali A. (2012) Integrative structural modeling with small angle X-ray scattering profiles. BMC Structural Biology 12(1):17.

Graewert MA, Svergun DI (2013) Impact and progress in small and wide angle X-ray scattering (SAXS and WAXS). Curr Opin Struct Biol 23: 748-754.

Rambo RP and Tainer JA (2013) Super-resolution in solution X-ray scattering and its applications to structural systems biology., Annu Rev Biophys. 42, 415-441

Books on SAXS

" The origins" (no recent edition) : Small Angle Scattering of X-rays. A. Guinier and A. Fournet, (1955), in English, ed. Wiley, NY

Small-Angle X-ray Scattering: O. Glatter and O. Kratky (1982), Academic Press. PDF available on the Internet at http://physchem.kfunigraz.ac.at/sm/Software.htm

Structure Analysis by Small Angle X-ray and Neutron Scattering. L.A. Feigin and D.I. Svergun (1987), Plenum Press. PDF available on the Internet at http://www.embl-hamburg.de/ExternalInfo/Research/Sax/reprints/feigin_svergun_1987.pdf

Small Angle X-Ray and Neutron Scattering from Solutions of Biological Macromolecules. D.I,Svergun, M.H.J. Koch, P.A.Timmins, R.P. May (2013) Oxford University Press, London.