

## The Structural Components of Living Matter: Water, Nucleic Acids, Proteins.

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### 1. What does *living matter* mean?

Any material taking part in the construction of living organisms. The word matter implies not only a certain chemical composition but a well defined form of occurrence as well as environment.

### 2. What is the meaning of structure?

organization, order, system, periodic repeat

molecule vs. macromolecule

small molecules show noticable thermal motion affecting the complete mass of the molecule while macromolecules (i.e. big molecules) show thermal motion only detectable on the submolecular level.

Constitution, Configuration, Conformation

Constitution: the order of connection between atoms within a molecule. Constitution may be altered only through the breakup of chemical bonds. The structural formulas are used to represent constitution.

Configuration: The relative sterical position to each other of atoms bound to a certain atom. Configuration can only be changed by the breakup of chemical bond(s). A number of stereochemical formulas are used to represent configuration (see also: Polarimetry practice). In most organic chemistry and biochemistry context the configuration around carbon and, to lesser extent, nitrogen atoms is important.

Conformation: the momentary spatial position of atoms of a molecule. Conformation may change without the breakup of bonds.

### 3. "Reality" vs. "Artists Impression"

The molecular world is often depicted with images and models appearing quite tangible, however, it always have to be kept in mind that object are not visible or otherwise percieveble in an everyday manner at this level. Therefore, if we see an image, our task is not simply to understand what it tries to explain, but also how the information was acquired and how was it made depictable. For this reason I try to indicate the most important research methods.

### 4. The properties of water with their importance for the living organism.

Water is the compound of oxygen formed with hydrogen. The life on Earth was most probably formed in the aqueous medium of the World Ocean, which fact made its

imprint on all organisms (including terrestrials) to modern times. Biochemical reactions all happen in aqueous medium that is why it is important to know the physical and chemical characteristics of water and its biological role.

#### 4.1. The characteristics of one single water molecule

The water molecule consists of one oxygen and the adjoined two hydrogens. The H–O–H angle is 104.5 degrees, so the molecule has a "V"-like shape. The deviation from the linear 180 degrees is caused by the non-binding electron pairs: the hydrogens and the non-binding electron pairs are positioned on the vertices of a tetrahedron. The deviation from the 109 degrees characteristic of regular tetrahedron is caused by the larger space demand of non-binding electron pairs.

The O–H bond length is 96 pm, which – compared to the 152 pm and 120 pm van der Waals radii of oxygen and hydrogen – means that the hydrogen is literally buried in the electron cloud of the oxygen (Fig. 1. left).

The electronegativity of oxygen is 3.44 while that of hydrogen is only 2.20 so the O–H bond has a resting dipole. This combined with the non-linear arrangement of the two O–H bonds causes the water molecule to have a permanent dipole and namely, the oxygen side has a negative partial dipole.

#### 4.2. Interactions between water molecules

The colligative properties of water molecules show many anomalies, especially when compared to the hydrogen compounds of non-metal elements adjacent to oxygen in the periodic system. Compare for example their melting and boiling points:

methane: CH <sub>4</sub> –182 °C –164 °C	ammonia: NH <sub>3</sub> – 78 °C – 33 °C	water: H <sub>2</sub> O 0 °C + 100 °C	hydrogen fluoride: HF – 84 °C + 19.5 °C
		hydrogen sulfide: H <sub>2</sub> S – 82 °C – 60 °C	

The explanation of the phenomenon is that water is able to form hydrogen bonds (in contrast with hydrogen sulfide), and it can serve both as a proton donator and acceptor in the same number of bonds per molecule (in contrast with the other elements in the period). This enables the formation of strong intermolecular cohesive interactions, which then increases melting and boiling temperatures.

The bond length of hydrogen bonds formed between two water molecules (i.e. the equilibrium length of the hydrogen and oxygen nuclei) is 177 pm, which – considering the above mentioned 152 and 120 pm van der Waals radii – means the extensive overlap of the electron clouds of the two non-covalently bound atoms as well (Fig. 1. right).

The presence of water in solid, liquid and gaseous forms in nature can also be attributed to the high melting and boiling points.

In ice, water is found in its crystalline form which is a structure of high range and high degree order. The structure is defined by the tetrahedral arrangement of hydrogen bonds. The space filling of water in ice is not "packed", even foreign molecules can be trapped into the crystal to form the so called water clathrates. The structure of ice was discovered by the X-ray crystallography method, which is sensitive to periodic orderedness.

In the liquid phase water can be understood as the remnant of a disrupted tetrahedral crystals. Recently however, there is high emphasis on the investigation of water clusters, i.e. more or less stable associates of water molecules in the liquid phase (Fig. 2). Understanding these clusters is still a vivid research field, for example, with the help of infrared spectroscopy, a method capable of describing binding characteristics.

The possible count of hydrogen bonds (one molecule may form 4 bonds, i.e. 2 bonds / molecule) is not equivalent to the average number of non-broken hydrogen bonds (1.2 bond /molecule @ 100 degrees), moreover, the bonds are not even stable in time ( $10^{10}$  breakup / second @ zero degrees).

Besides the transient breakup of hydrogen bonds, the autoprotolysis of water is also significant, which forms the basis of pH calculations in aqueous solutions.

#### 4.3. Interaction of water with other molecules

The central role of water is also indicated by the fact that the solubility (or miscibility) of all other materials is determined relative to water: hydrophylic and hydrophobic.

Water forms dipole (electrostatic) interactions and (in the presence of suitable pillar atoms) hydrogen bridge, which explains the solvation abilities of water and its role in the stabilization of the structure of macromolecules.

In case of hydrophobic materials, the major role is not assigned to the bond formed with water but rather to the higher orderedness of water along the interface (entropic effect), which favors the decrease of such surfaces (hydrophobic interaction, micelle formation).

### 5. Structure of nucleic acids

#### 5.1. Primary structure: constitution (and configuration)

Nucleic acids are directed copolymers with nucleotides as their monomers. Way of notation: phosphate-5'-pentose(+ base) – 3'. Its determination is carried out with X-ray crystallography. (Fig. 3.)

#### 5.2. Secondary structure: base pair formation (Fig. 4)

DNA: antiparallel double helix (B) model (Watson and Crick, 1953, Fig. 5)

A-DNA: right handed helix (C3' endo): low water content, homopurine, homopyrimidine (RNA double helix)

B-DNA: right handed helix (C2'-endo): most frequent

Z-DNA: left handed helix: high salt concentration, bacterial DNA

(Fig. 6)

5.3. Tertiary structure: superhelix (Fig. 7)

5.4. Quaternary structure: e.g. chromatin, ribosome

## 6. Proteins

Proteins are directed copolymers built up from the biogenic amino acids as monomers. Amino acids are bound to each other with peptide bonds.

### 6.1. Primary structure: constitution (and configuration)

Amino acid sequence. Three and one letter notations are used. Drawing starts from the amino end (N-terminal), like Ser-Gly-Ala. In this case, the carboxylate of the serine forms a peptide bond with the amine of the glycine.

It was a long lasting problem whether proteins are macromolecules or something else (e.g. loosely associated macromolecular complexes), it was doubted for a long time that covalent bonds can hold together such an enormous molecule. The first evidences on the existence of stable proteins with a definite molar mass was acquired with ultracentrifugation and electrophoretic studies (Fig. 8). The actual amino acid sequence is usually identified by chemical sequencing (first the insulin by Sanger in 1951).

### 6.2. Secondary structure of proteins: short range intramolecular conformation

Secondary protein structure means a short range (min. 3 amino acid residues) order in the polypeptide chain stabilized by the hydrogen bonds between the backbone atoms of the chain. The dihedral (torsion) angles of the  $-N-C\alpha-C-N-$  bonds (Fig. 9) have extraordinary importance: these angles can only have certain values because of steric limitations, this is represented in the Ramachandran plot (Fig. 10). Most important structures: parallel and antiparallel beta sheet, alpha helix (right handed:  $1 + 4 \rightarrow i$ ), beta turn (Fig. 11). These structures can be determined with X-ray crystallography and CD (circular dichroism) spectroscopy.

### 6.3. Tertiary protein structure: long range intramolecular conformation

The tertiary structure means the total three-dimensional spatial structure of the polypeptide chain forming the protein, it is primarily stabilized by hydrophobic

interactions. It is determined with X-ray crystallography and NMR technique (Fig. 13).

#### 6.4. Quaternary protein structure: intermolecular conformation

It is only defined for proteins composed of many polypeptide chains (so called subunits). Determination: same as for the tertiary structure (Fig. 14).

#### 6.5. Formation of the protein structure: folding

Folding occurs in vivo and can be investigated in vitro. The protein structure is formed from many possible conformational structures (Levinthal paradoxon). The protein passes through an energy landscape from the denatured state toward the native form through various conformation states (Fig. 12).

### 7. Summary

7.1. Where do biomolecules come from? Biomolecular evolution (RNA → DNA and proteins)

7.2. Biomolecular homochirality: most chiral biomolecules occur only in one of the enantiomer forms (L-amino acids, D-sugars). The reason of this asymmetry is obscure.

### 8. Calculation problem

Consider a one kilogram cube-shaped water "droplet" floating in a spacecraft (i.e., no gravity). What is the energy released/absorbed (in millijoules) upon its transformation into a sphere? How much does the temperature (in kelvins) of the water change?  $\gamma = 72 \text{ mJ/m}^2$ ,  $c = 4180 \text{ J/(kg}\cdot\text{K)}$ ,  $\rho = 1 \text{ g/cm}^3$ .

Result:  $\Delta E = -0.8381 \text{ mJ}$ ;  $\Delta T = 2 \cdot 10^{-7} \text{ K}$