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Water States in Living Systems
I. Structural aspects

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Abstract: Formation and special consequences of water-ordering are studied and discussed. Based on the knowledge of the water states, a special dynamic clustering (called dynamic frustration) is suggested. This can be an essential mechanism for life processes. A frustration mechanism and its consequences are discussed.

WATER OFTEN HAD MYSTIC ROLES in human culture. It was the central theme in many philosophical essays (for example Thales and Herakleitos) (1), important in various religions (for example the Tao (2) and the Christian(3)). Although water has been the subject of numerous scientific investigations, its true nature is still not revealed (4) even after a full series (5) and other books (6) have been dedicated to water itself.

The importance of water can be formulated for different disciplines:

- For the *Biologist* water is the 'mother' of evolution, the matrix of life. Furthermore, it is the critical substance of biological energy production on Earth (photosynthesis):

$$2H_2O \Rightarrow O_2 + 4H^+ + 4^{e-} \qquad (1)$$

  which is proceeded by the radiating energy of the Sun. Without this process, life, as we know it, would not be possible.
- For the *Chemist* water is the final oxidized material: water cannot be further oxidized. It can be regarded as the final and ground state of the reactions in living systems (7).
- For the *Physicist* the driving force of life is the gradual energy loss of the electrons caused by the metabolic processes, during which highly energized electrons

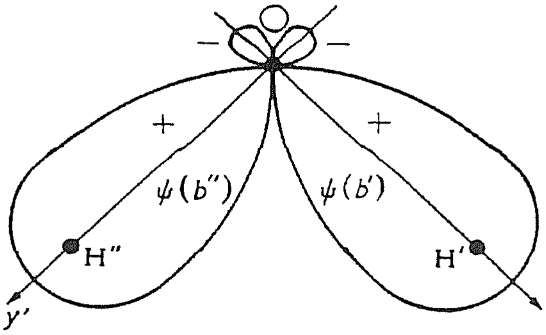


FIGURE 1. Schematic picture of the bonds in a water-molecule.

originating from the photosynthetic reaction eventually reach their lowest energy state. One of the most common products from this process is water (8).

Despite the simplicity of water it has unusual properties: abnormal thermodynamic parameters (melting point, boiling point,vaporization heat, fusion heat, etc. and all higher than would be expected of liquids composed of hydrogen and oxygen); structural properties (maximal density at 4°C decreases its viscosity with a pressure up to ~ 1000 atm.). All these physical abnormalities make water exceptional.

One must consider that so many human achievements are based on water and aqueous solutions, that they became a matter of fact. "As the fish forgets the water in the ocean," we often forget the important role of water in our life (9). The body of a human contains on average more than 60% water, making the molarity of the body less than one mole (taking the average molecular weight of 1000 Dalton). The water requirements of the human body are strict; missing about 2 litre (4.5%) is usually fatal. The water contents of the living cell is even higher: 80%(10). The cell can be regarded as a dilute salt solution according to the Membrane-Pump Theory, although Ling showed that 95% of the cell water exist in the form of polarized multilayers according to his Association-Induction Hypothesis (11). Life itself can be modelled as a fluid automat (12). In summary: life on Earth is tightly connected with water.

In the present paper we deal with the structural properties of water which probably cause these exceptional properties and what we suggest gives a basic mechanism for the living processes.

Water Structure

The water molecule (H_20) is rather simple in its chemical composition but requires a remarkable activation energy (104.2 kcal/mol) for its creation from oxygen and hydrogen elements. The quantum mechanical description of the bonds between the oxygen and the hydrogens is not very complicated either (13). A schematic drawing of the bonds are shown in Figure 1. There are four electron-pairs of which two are bonded to the hydrogen (proton) and two are not bonded (lone pairs, non-bonding pairs). Due to the electrostatic effects, the pairs are homogeneously distributed in a sphere around the oxygen. If the four electron pairs

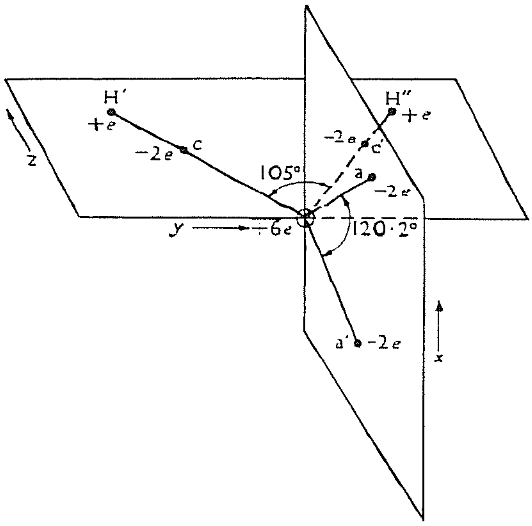


FIGURE 2. Geometrical construction of the water molecule.

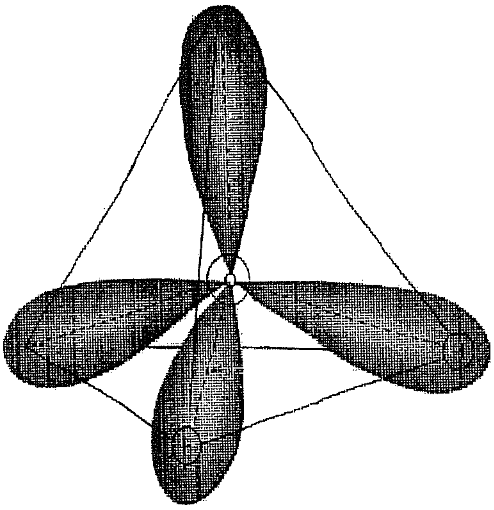


FIGURE 3. Water-tetrahedron in three dimensions.

would be identical, the angle between them would then be equal (109.5°). According to the nonequivalent bonds, the angle between the hydrogens is about 105° while the angle between the lone-pairs is about 120.2° (Figure 2). This structure, the singular water molecule, is a non-regular tetrahedron in the three-dimensional space (Figure 3).

This special geometry is accompanied by a special physical property: due to the non-

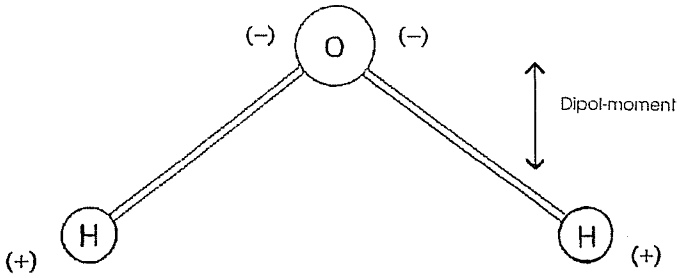


FIGURE 4. Origin of the dipole-moment of the water molecule.

uniform distribution of the charges in the molecule, the system has in its original form a resultant electrostatic dipole-momentum, without any external applied electric field (Figure 4). The water molecule is not a usual dipole, it is arranged like two simple dipoles having a common positive pole. This means that it has a more complicated electric field than a simple dipole. Over a distance (d), which is much larger then the bond-length between the oxygen and hydrogen atoms ($l = 0.9572$ nm, $d >> l$) (133), the dipole field is not observable and diminishes rapidly by $1/r^3$. If the effective distance is not so large, but remains considerably larger than the 1 ($d > l$), the dipole appears to be standard, having a double charge (a double dipole-field). However, when $d \approx l$, the situation becomes rather complicated: the field heterogeneity affects the interactions (Figure 5).

The structure of an agglomeration of water molecules (in a liquid or solid state) is definitely complicated and exhibits many unusual properties:

- The hydrogen atoms, bonded to one oxygen, can jump over to another oxygen in another water molecule thus making connection though a lone-pair, bridging the oxygen atoms and creating a so-called hydrogen-bridge (which has a much weaker bond strength than the normal hydrogen-oxygen chemical bonds).
- The intermolecular dipole interactions and arrangements are not simply due to the above described V-shaped dipole structure.
- The non-regular tetrahedral shape of the water molecule changes the connected hydrogen bridge, so consequently the whole geometrical arrangement fluctuates due to fluctuating proton bonds.
- The water-tetrahedra cannot occupy the space properly: internal space (holes) between the tetrahedras must definitely appear.

The above mentioned remarks make the structure of water a very exciting problem. Let us now study these peculiarities in more detail.

Clustering of water

The hydrogen bridge is a special quantum mechanical effect based on the migration of the proton (hydrogen ion) between water molecules (Figure 6). This process means that the proton itself is highly delocalized (14) which gives the following chemical equilibrium:

$$2H_2O \Leftrightarrow OH^- + H_3O^+ \qquad (2)$$

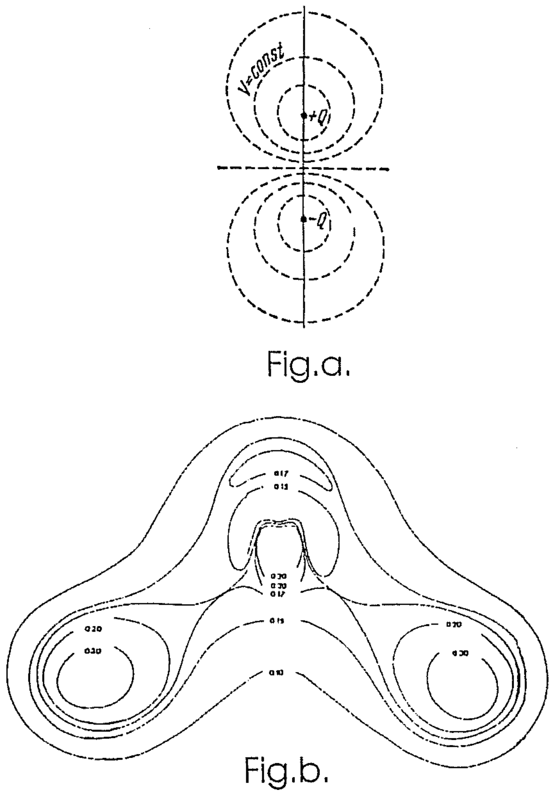


FIGURE 5. Fields of the dipole structure (the curves of the equal potentials): a) standard dipole; b) water-dipole.

Note that not only the protons but the electrons as well can be delocalized, forming the so called hydrated electron (15):

$$2H_2O \Leftrightarrow H_3O^+ + e^-_{aq.} + OH \qquad (3)$$

The existence of hydrogen-bridges is the most important organizing factor of the water cluster formation (Figure 7) (16). The clusters will be formed in such a way as to minimize their free energy. This type of ordering appears in the structures of ice which show a significant variability. Ice has eight main and several additional structures depending on the forming conditions (Figure 8) (17). Some characteristic ice-structures are shown in Figure 9 (13). These structures can be modified by rotating the water molecules, which is possible because of their V-like structure. Some of the characteristic rotated variations of the six-fold-rings (of the ice I. structure) are shown in Figure 10 (133). This extra variability can cause a special disorder in the actual ordered structure (Figure 11) (18).

In liquid water the order of the water molecules cannot stabilize because the thermal-energy destroys a huge fraction of the hydrogen-bridges. The bonding energy of the

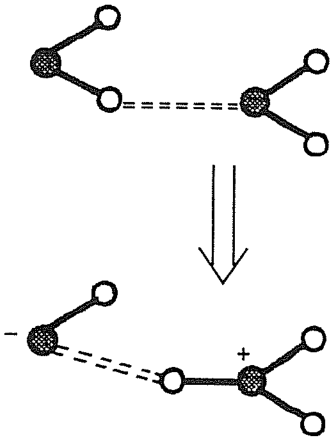


FIGURE 6. A schematic process of the hydrogen migration in water.

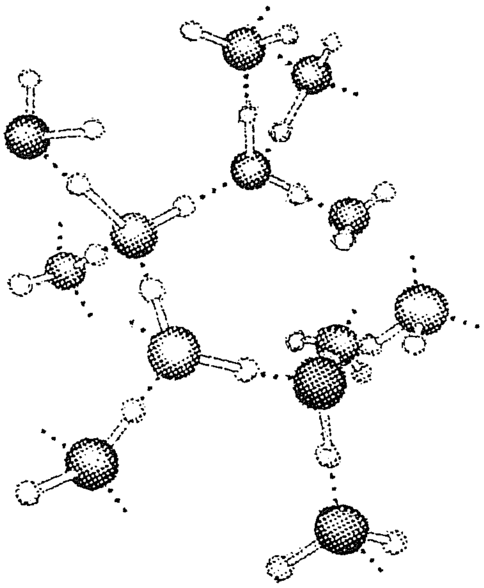


FIGURE 7. Hydrogen-bonds (bridges) between the water molecules (16).

hydrogen-bridges is only 0.17–0.29 eV/molecule (4–7 kJ/mol) which is only one order of magnitude larger than the thermal energy at room temperature (~ 0.025 eV at 20°C) while the molecular bond in water is 10 eV/molecule (242 kH/mol). This is about fifty times more than the average bonding in hydrogen-bridges. However, a remarkably large part of the hydrogen-bridges still exists in the liquid phase even at temperatures as high as the boiling point, Figure 12 (19–26).

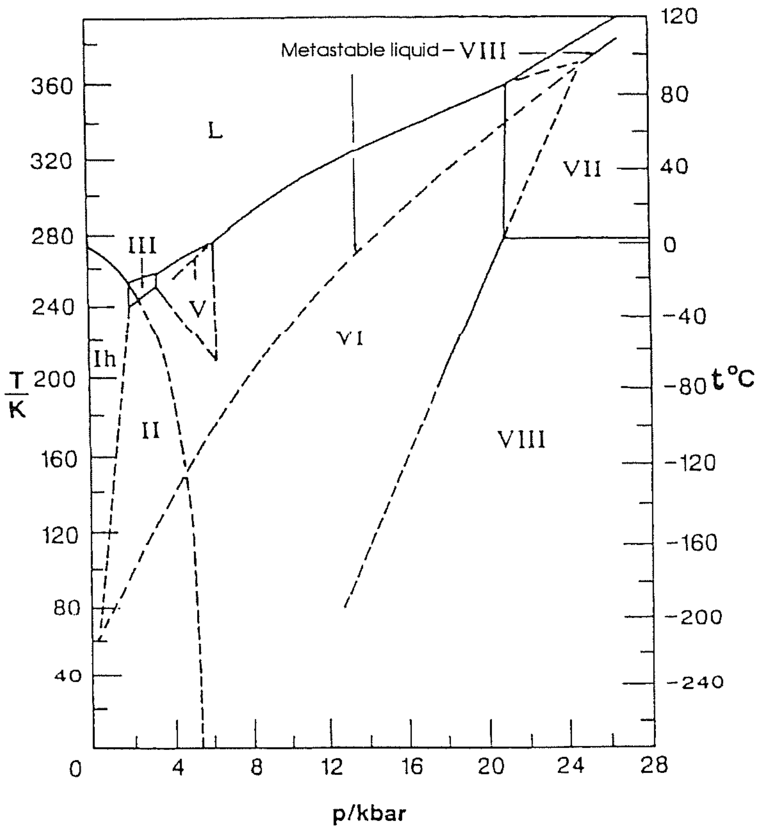
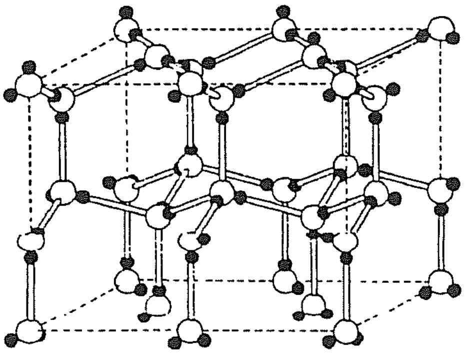


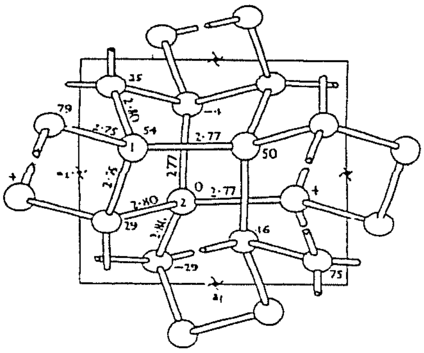
FIGURE 8. Water phase-diagram (177).

The existence of the clustering of water is revealed by the radial distribution function measured by X-ray diffraction (Figure 13) (13). These measured hydrogen-bridges show that the "ice-structure" does not vanish at once during the melting process. The effect on the melting point is only that some domains (clusters of water) are disconnected from each other (like islands). When increasing the temperature, these domains are gradually broken down into the smaller and smaller ones. These domains are not static structures, their size fluctuates, but the average is definitely characterizing the actual state. This means that normal water, gradual melting from ice, has two structurally different phases: the monomer water-molecules and the water-clusters (Figure 14) (27). Moreover the water clusters in this phase-mixture can have a large variability depending on the their actual structure and phase-transitions. This fact emphasizes the complexity of the normal liquid water which mostly can be subscribed to the hydrogen-bridges.

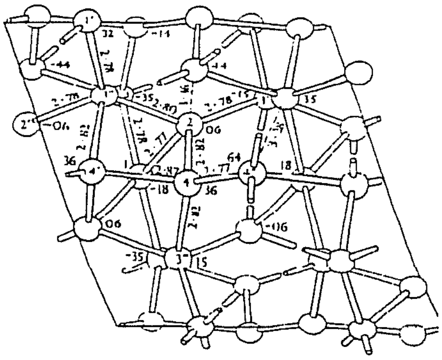
Numerous models, taking into account these peculiarities, were formulated for liquid-water: the quartz like structure (based on tetrahedral units) (28), the dodecahedral (chlatrate) model (associated to the special hydrogen bond rings) (29), the bent-hydrogen-bond model (calculates the bent chain of the hydrogen bonds) (29); as well as the cluster-models: the



Ice I.



Ice III.



Ice V.

FIGURE 9. Some characteristic ice-structures (13).

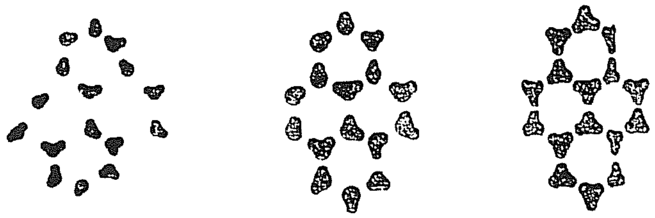


FIGURE 10. Characteristic variation of the six-fold rings in ice I (13).

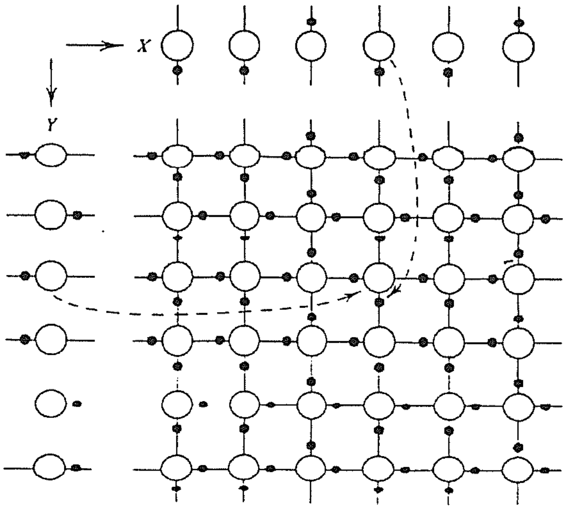


FIGURE 11. Disorder in ordered structure (two dimensional schematic drawings) (18).

flickering cluster model (30), the solid-like model (31), etc. These models reasonably follow the actual systems but fail to yield to the density maximum at 4°C.

A more-or-less adequate model was suggested based on the coexistence of two types of clusters in the liquid (32), so that the water in this model consists of three phases. (Note that other structural phases, which are represented in the different crystalline forms of ice, are not excluded in the generalization of this model.) One cluster structure was chosen similar to ice-I and the other to ice-III. These clusters are in dynamic equilibrium and their molecules can be transported from the one cluster to the other:

$$\text{molecules(ice-I)} \Leftrightarrow \text{molecules(ice-III)} \quad . \qquad (4)$$

The different water phases have, of course, different physical and chemical properties, for instance the solubility, surface tension. The complex forming ability and connected processes are not identical in the various clusters or monomer water. The dielectric permeability is sharply changed by the structure: for the ice-like order it varies from 4 to 200 (depending on the actual structure, the temperature and the measuring field-frequency) (33),

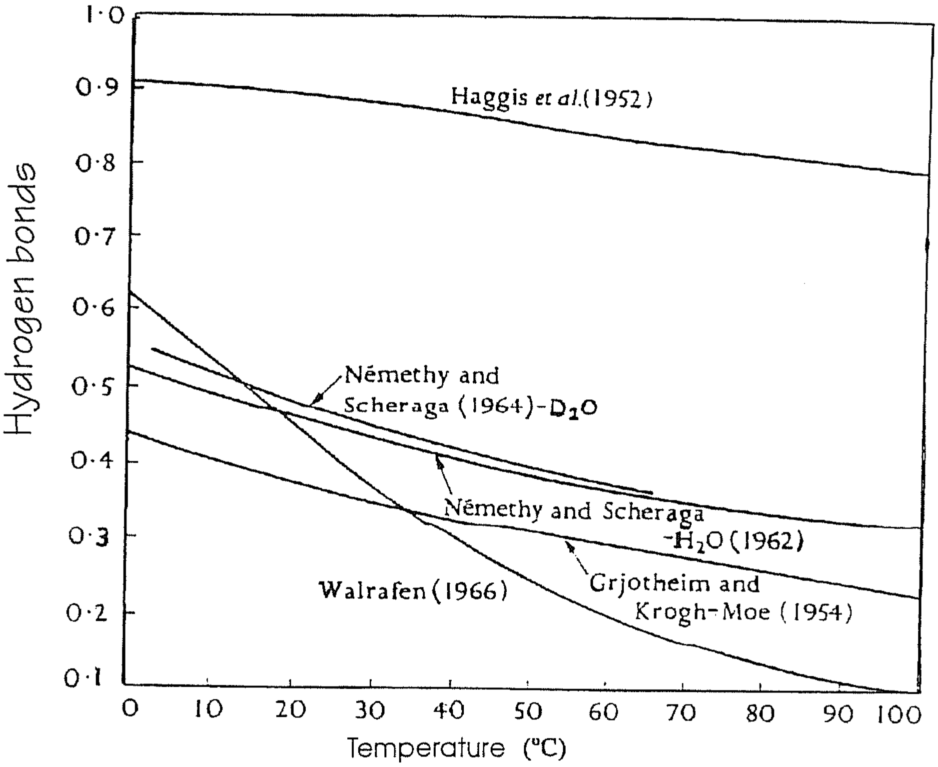


FIGURE 12. The temperature dependence of the percentage of hydrogen bonds (100% in ice), according to different approximations (19–23).

(see Table I), while for the mixture of the phases (liquid water) $\varepsilon = 70 - 90$ in the same temperature range (34). The electric field at the oxygen atom is also drastically different in the ordered and disordered state (34). This behavior allows the physical properties of the solution to change without changing the material itself: only the structural rearrangement is enough for drastic (e.g. one order of magnitude) changes in the dielectric properties.

A dynamic effect: frustrated connections

It is well known that the chemical equilibrium in aqueous solutions is based on a dynamic balance of the reagents. Water itself also defines a chemical equilibrium of the OH^- and H_3O^+ ions (see Equation 2).

There are some dynamic effects responsible for the actual structure of water:

1. One of the most important dynamic equilibrium is included in the hydrogen-bridges. The hydrogen ion (proton) which is involved in the bridge, migrates between the two oxygen molecules. It is in fact bounded in a double-well potential and does not strictly belong to one molecule alone. This means that the proton is 'frustrated': the tetrahedral bond-structure becomes bifurcated (34). This effect offers paths in the hydrogen network with lower energy barriers than the hydrogen bonds. This process reconstructs the

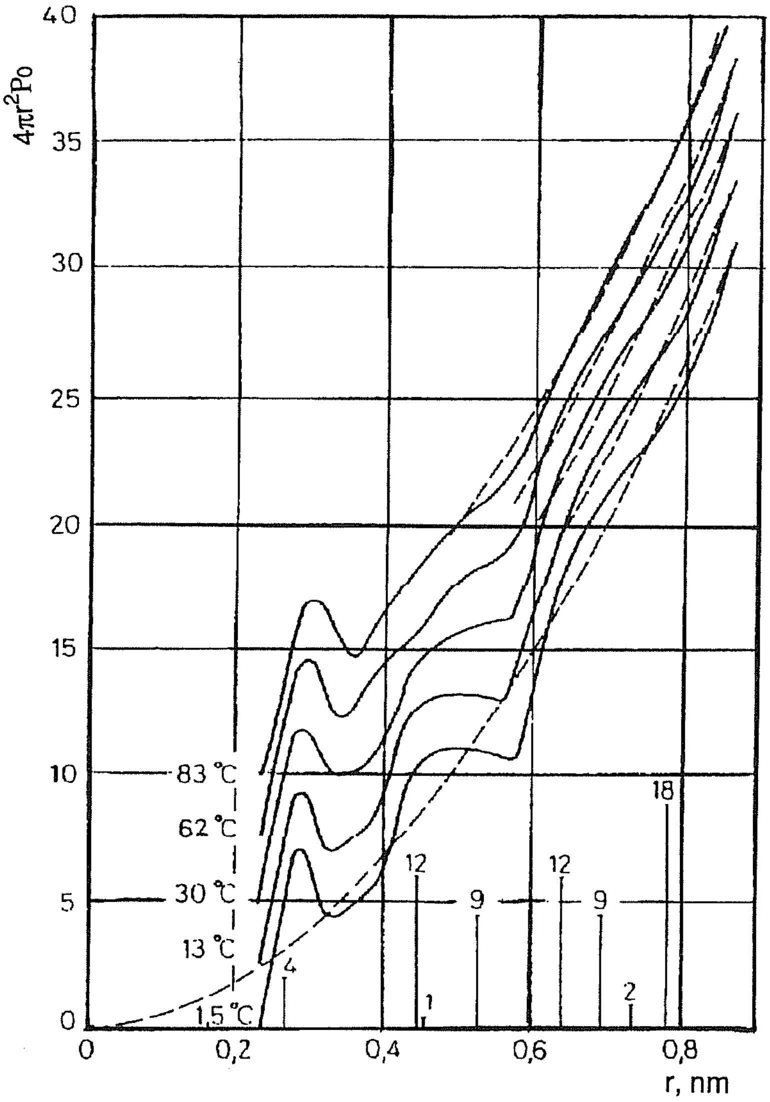


FIGURE 13. Radial distribution function of the water on various temperatures. The totally amorphous (no hydrogen bonds and clustering at all) function is dashed (13).

actual network effectively and relatively fast (34). The frustration process can be so intensive that the proton migration becomes delocalized over a large area (35), giving an instability in liquid-water (36). The structure of water, from the point of view of the proton localization, is similar to a gel structure (37) which, regarding quantum mechanical effects, can be considered to be in a so-called quantum-gel state (38). Consequently, water itself is not homogeneous in this meaning of hydrogen-bond either (39).

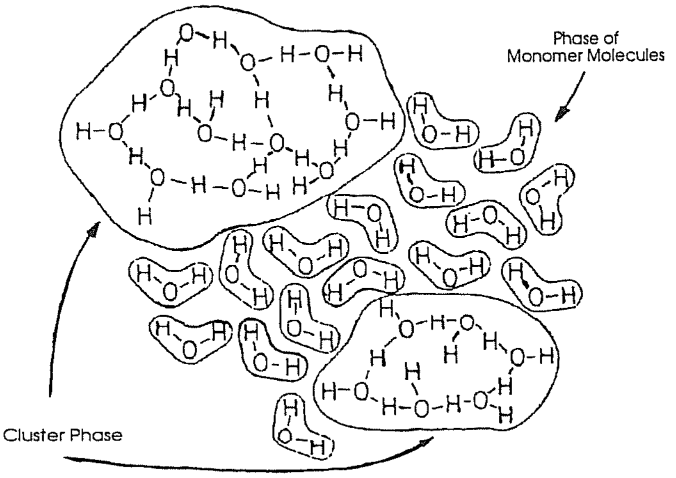


FIGURE 14. Two phases of the normal water: the monomer molecules and the phase creating by the clusters (27).

2. The proton migration effectively changes the geometry of the water-tetrahedron, (recall that the angle between the two bonded hydrogen connected to the oxygen is approximately 105° while between the hydrogen bridges it is approximately 110° and between the lone pairs approximately 120°). In this way the water-tetrahedron is not a fixed geometrical arrangement but its edges are vibrating in accordance to the proton migrations. Consequently it can be regarded as a 'smeared' or 'soft' polyhedra in the duration of a considerably longer time period than the characteristic migration time.
3. The situation becomes even more complicated when taking the geometrical incompatibilities of the water structure into account. The tetrahedral structure is the most dense packing of spheres possible in a small cluster (40). Tetrahedron of water is not so dense (the oxygen atom is in the center) but it is the most stable clustering of these molecules. Five tetrahedra sharing a common edge constructs an almost compact polyhedra (Figure 15). The missing space for compatibility is resolved by deformation of the spheres or by the migration of the 'hard' tetrahedron (apposing the soft sphere as described above in point 2, so a sphere with a fixed geometrical arrangement but now with the proton migrating). The same situation occurs at the next stage of closest packing: twenty tetrahedra sharing one vertex form (by a small deformation and/or migration) an icosahedron (Figure 16) (41). These clusters are the most dense, so they represent the smallest amount of free energy (42) among the possible clusters. These polyhedra have five-fold symmetries: they have five-fold identical rotational transformation around symmetry axes through their vertexes. A crucial problem arises when trying to continue packing the spheres: icosahedra, despite their compactness and highest stability, do not occupy the space properly, leaks (the space between the adjoining icoshedra) between the units demand another arrangement, Figure 17. (This situation is strictly formulated in the solid state physics: no solid crystalline material has a five-fold symmetry in its structure, so the polyhedra having five-fold vertexes are not

Temperature [°C]	Structure	ε(60kHz)	ε(20kHz)	ε(5kHz)	ε(1kHz)	ε(0.5kHz)	ε(0.3kHz)	ε(0kHz)
-70	ice	2.98	2.97	2.99	3.33	3.59	4.00	-
-50	ice	3.02	3.04	3.21	3.82	4.65	6.17	-
-30	ice	3.04	3.15	4.06	14.6	31.3	46.2	-
-10	ice	3.33	5.46	24.4	69.4	73.6	74.8	-
-3	ice	4.2	10.4	46.3	72.4	73.5	74.2	-
-1	ice	4.3	12.3	51.6	72.5	73.6	73.7	-
	ice-I	-	-	-	-	-	-	105
	ice-III	-	-	-	-	-	-	125
	ice-IV	-	-	-	-	-	-	~4
	ice-V	-	-	-	-	-	-	155
	ice-VI	-	-	-	-	-	-	195
	ice-VII	-	-	-	-	-	-	~150
	ice-VIII	-	-	-	-	-	-	~20
20	water	-	-	-	-	-	-	80.3
25	water	-	-	-	-	-	-	78.4

Table I.
The dielectric permeability of the water phases (33, 34).

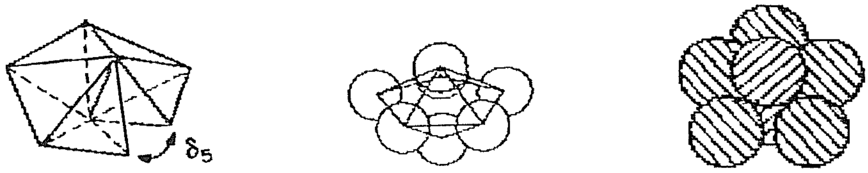


FIGURE 15. Compact polyhedron, constructed by five tetrahedra sharing a common edge (92).

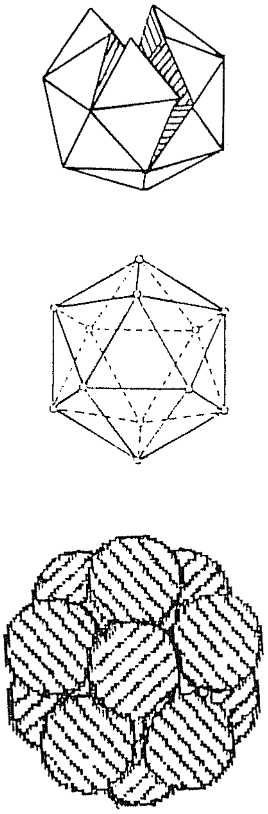


FIGURE 16. Compact polyhedron, constructed by twenty tetrahedra sharing a common vertex (41).

allowed to construct a regularly ordered crystalline structure.) (It is noteworthy that a calculation with a special (Lennard-Jones) potential indicates a change of the five-fold symmetries in the packing at about the ninth coordination sphere (43). Other potentials, of course, give other possible shell numbers.)

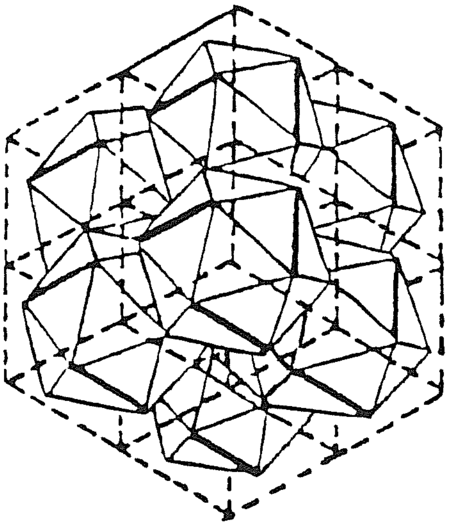


FIGURE 17. A compact arrangement of icosahedra in the space. Note the improper space-filling in the system.

Geometrical frustration

To arrange the water molecules in space the energy minimization has to be done cluster independent (microscopic or short-range order) or for the total system, (macroscopic or long-range order) which means a search for a crystalline structure. The microscopic equilibrium initially creates five-fold symmetries (pentagons) and continues this process. But in short-range, the process of ordering would freeze-in if there wasn't the macroscopic equilibrium to consider. This causes improper space occupation with the five-fold construction because this state is strictly prohibited (44), and thus causes frustration.

This contradictory situation leads to the so-called geometrical frustration (45). This is essentially the same effect as the proton-frustration, also a dynamic process, balancing the cluster between the short- and long-range energy minima. To demonstrate this effect in two dimensions we covered a sheet with regular pentagons (demonstrating that the most compact units in a three-dimensional space are icosahedra) having special rhombuses between them (Figure 18). Non-regular pentagons, of course, are able to cover the sheet without any leaks between them (Figure 19) but this construction is against the energy minimization in the cluster-level (in the short range). This is a demonstrative contradiction between the short- and long-range energy minimization requirements. However, there is a solution made possible by the frustrated atoms (Figure 20) which dynamically satisfies both, statically not harmonizable, requests: the bounded atoms migrate. The same can be constructed in the real three-dimensional systems: the clusters are in a dynamic equilibrium (by vibration like breathing and/or tilting of the polyhedra, (46)) for which a simple example is shown in Figure 21.

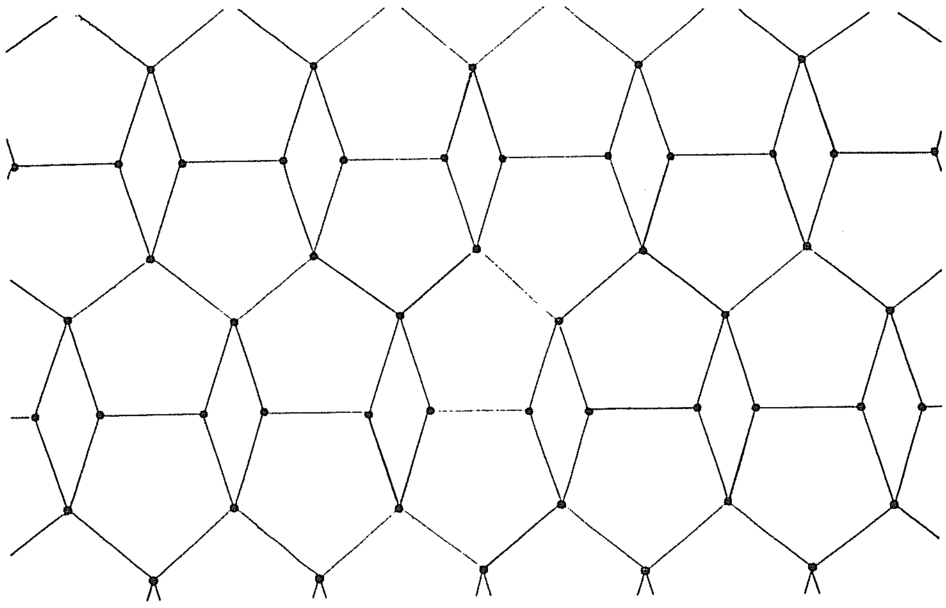


FIGURE 18. A possible tight tessellation of regular pentagons. Note that rhombuses are needed to cover the area in the figure.

The geometrical "frustration" of the material makes a special transport phenomenon possible (47): if a cluster stabilizes itself on microscopic level then its neighborhood becomes instable because of the larger fitting incompatibilities than average. In this way the stable cluster is destroyed by its neighbors in order to lower the total (long range) energy of the system. The lowered energy in the neighborhood makes the microscopic stabilization possible for those clusters which, in their turn, will be destroyed by their neighbors. The stable clustering is sliding towards the next cluster and pushes away the stable cluster-bag without any particle transport. It can be visualized by a standing row of domino stone: if the first rakes then gradually all the others will be raked, falling down in a line, without any transport of the dominoes themselves, the energy is transported. Another analogy would be the moving of waves in a wheat field caused by the wind. A moving "stability-bag" allows a possible special transport in the cluster arrangement (48). This phenomenon is very similar to the explanation of high-temperature superconductivity (49) and can be important for the transport and information exchange in living systems, including electron transport (change transfer) in metabolic processes.

Life: cooperative phenomenon

Living systems, even its smallest but unbelievably complicated microscopic functional units: the proteins, are extremely complex. It is not trivial that these massive, large units could present such flexibility in their responses as we observe in the living state. The proteins are so intricate and complex that a considerable 'inertia' in their responses has to be expected.

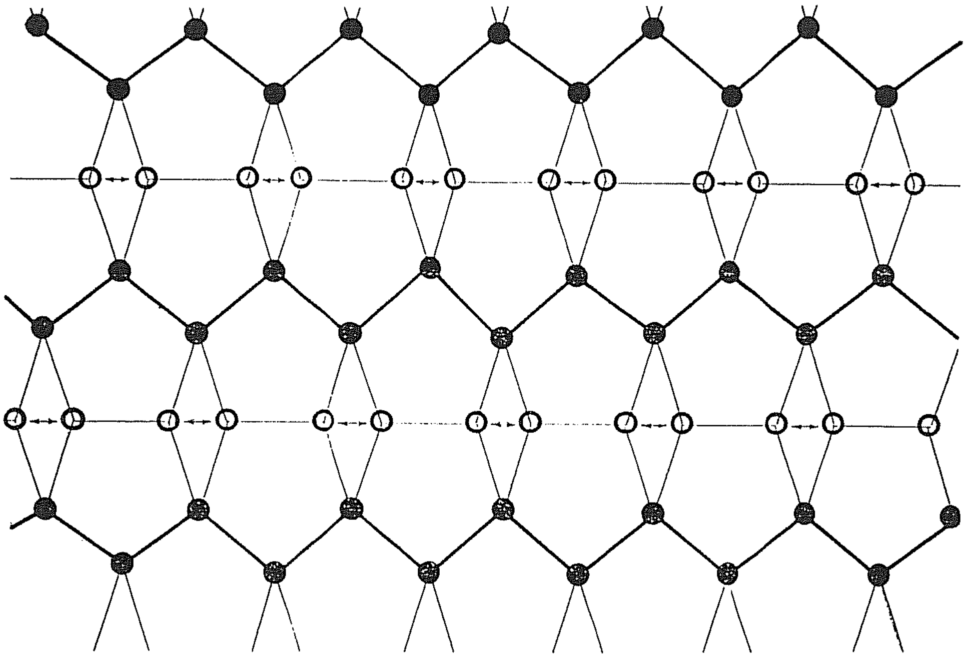


FIGURE 19. Proper tessellation on the plain sheet by non-regular pentagons.

Any of the living systems must be regarded as a unit (50), since its properties cannot be additively composed from the properties of its parts and it is not possible to divide it into parts carrying the properties of the whole system. The living reactions are special processes which are cooperative, collective phenomenon expanded over the whole living unit (protein, cell, etc.) depending on the level of the interaction. The cooperativity in the living state is the essence of the phenomenon. Some synchronized effects characterize life (for example the growth or the dividing of cells) which have to have a general controller in the system. But until now such an overall chemical and/or physical control parameter is not recognized. Some cooperative mechanisms have been ascribed to the living state: for example, chemical (51), solid-state electronic and ionic transfer (52), as well as fractional charge-transfer (9). These considerations have indeed had success in the explanation of different special proteins (for example enzymes) or whole cells. For example an ionic concentration (pK) has also been introduced (51), governing and explaining the collectivity of some special processes.

The first suggestion of a solid-state-type electronic process in living systems as one of the possible collectivity in proteins and DNA was made by Szent-Görgyi (53) in 1941. An early calculation (54) strongly suggested the existence of a conduction band in proteins. This was indeed proven experimentally (55), observing a semiconductive behavior with a forbidden gap of 2–3 eV (56). The measured conductivity in wet proteins (57, 58) (there is no effect at all in dry ones (59)) supports this idea. The kinetic theory of electron transport

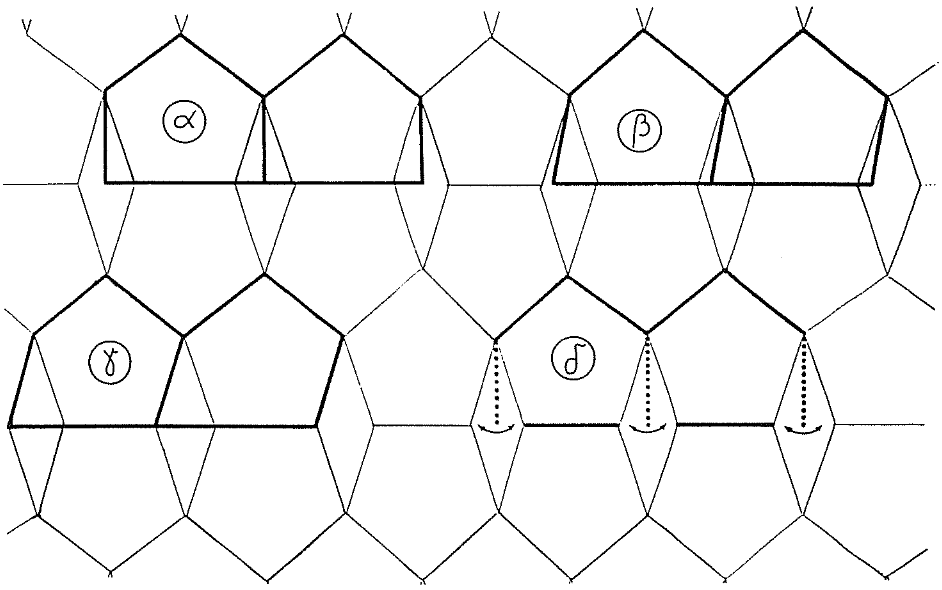


FIGURE 20. Dynamic solution of the tessellation by regular pentagons: α, β and γ are possible distortions of the five-fold symmetry, thus becoming non-regular units. With δ the regular five-fold symmetry is kept; the geometric frustration cuases the units to vibrate (if these units are composed of water, the hydrogen bridges will vibrate).

in biological processes is based on this solid state conception (52) supported by an electrical-mechanical cross-effect, the piezoelectricity, which was observed in the cell as well (60). According to these "bioelectronic ideas', the protein provides a background in life processes (they have a role as 'stage' in the 'theatre of life') offering a special conductor of the information and charge transfer. The flow of information is realized by this conception mainly by the controlled electron (or more general by charge) transfer.

However, the living system is not an ordered solid where the cooperativity is easily introduced (contrary to crystals (61)): it is an aqueous solution. However in the living state water is mostly well ordered, nearly crystalline (semi-crystalline (62)). A polarized multilayer of water was described which can be considered to be in a quasi-crystalline state (10, 11, 63, 64). This relative order formed 'dilute salted water' in the system having entirely different mechanical, chemical, physical behaviors than the normal aqueous solutions. Indeed, the important role in the living systems of the so called ordered water was pointed out in the middle of the nineteen sixties and was later proved (65). At first the ordered water was suggested to be as much as 50% of the total amount of water in the living bodies (66) but systematic investigations approximated more ordered water (67) than was expected before. Ling suggests that at least 95% of the cell water is bonded to fully extended proteins (68), while in other relevant systems this can be 75% (69).

The living process is the gradual loss of the electron energy of incoming compounds (nutriments, foods) by a multi-step oxidation having very little energy changes in one step. The typical metabolic energy-step is in the range of the hydrogen-bridge bond. Consequently it is possible energetically to rearrange the water structure (70) and with this drastically

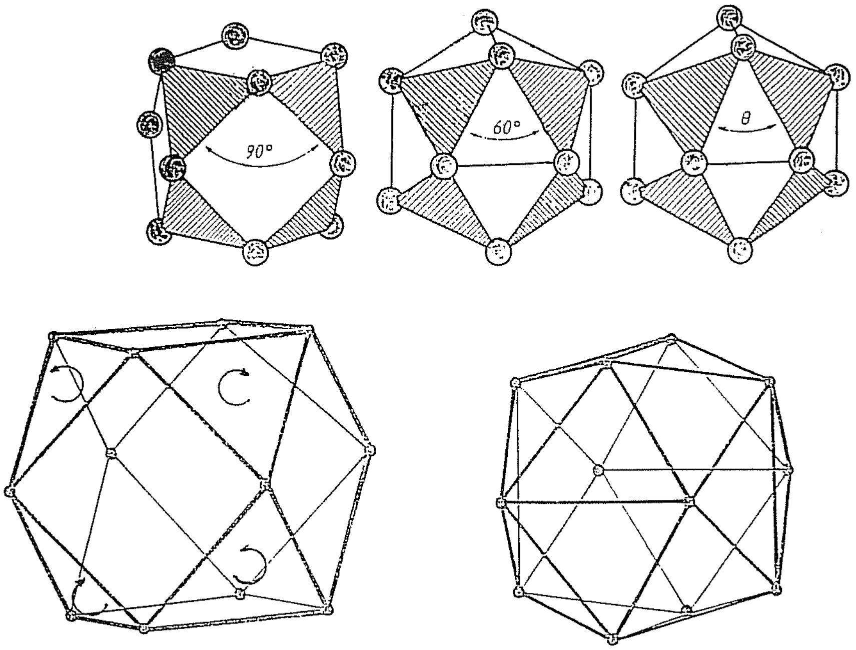


FIGURE 21. Geometrical frustration in three dimensions: a) breathing like; and b) tilting like; changes in the icosahedral cluster.

change the physical properties (for example the dielectric constant) of the material without changing the composition (only the microscopic ordering) of the medium itself.

Metastable, dynamic equilibrium of protein systems

The protein is a huge molecule. It is difficult to interpret it because it is dynamic and it is "screaming and kicking . . ." (71). However, the dynamic motion of the proteins has been proven both theoretically (72, 73, 74), and experimentally (75, 76).

The *protein in vitro* is an insulator in which electrons are at the lowest possible energy filling up the closed common electron-shells (valence-bands). The protein *in vitro*, in an insulating state, is not able to transfer any information, having only coupled electrons in almost localized bonds. (The protein *in vitro* has no ESR signal (77)). Due to the inert protein the cohesion forces between these molecules are not as large as *in vivo*. The system can in fact relatively easily decay in its non-living form.

The *protein in vivo* is different. It has a strong ESR signal (77) representing uncoupled electrons and is a conductor having a common band with other proteins nearby. The cohesion forces in this system are strongly enhanced in comparison to their *in vitro* counterpart.

Many native globular proteins with their NH and CO groups are locked in α-helix or other intramacromolecular, making them in general an insulator. The isolation of these islands of protein molecules is enhanced by the adsorbed water (52). The adsorbed water coverage *in vitro* (and also in cancer-tissues) is almost randomly distributed on the boundary of the protein molecule producing an insulating layer with large dielectric permeability (65, 66, 78). To make a material having a collective intermolecular transport the disordered structure must be rearranged.

In the living state there is a considerably smaller dielectric permeability around the proteins because of the ordered adsorbed water (65, 66, 78) while much larger cohesion forces were observed (65, 66, 78). In the living state the strict isolation as well as the electronic saturation of the macromolecule has been lost (62), desaturated proteins do appear. The system is an insulator *in vitro* becomes semiconductive *in vivo*. The desaturation is produced by an electron acceptor turning away the molecule from the stable, static equilibrium. We suggest that a strong charge transfer, which driving force is the metabolic process itself, is responsible for the living state, giving the possibility for a special type of collectivity and cooperativity in the system.

The essential mechanism of life on this submolecular level is the electron-desaturation of proteins by various reagents. The desaturation is going through the electron acceptors. The living process is realized in a charge-flow making the final oxidation through various steps by different reagents (oxidation process). The oxidation goes step-by-step transferring only a fraction of the electron charge in each step. This mechanism of the charge transfer is the life. The collectivity appears in the conduction chain of information between the protein molecules. The stable non-conducting protein-state has been destabilized *in vivo* and the molecules try to stabilize themselves seeking to fill up their shells to an electronically closed, stable situation. The non-saturated macromolecules seek to reach their stable, saturated form. The molecules in the neighborhood of the one which saturates itself will be more unstable due to the missing charge. (The charges, the electrons, that are transported here can be very small. They are not like a ball jumping from protein to protein but only a fraction of the charges can move in this process. The process can be visualized by the standard quantum-mechanics where an electron is 'smeared' between the atoms involved in molecules, compounds or alloys: the electron wave functions overlap each other.)

Seeking stability on the microscopic level (seeking a molecule configuration for the stable insulation state) contradicts the global (macroscopic) stability requirements. These are stabilized by the transported charge (semiconductor) due to the metabolic process which causes by its nature, non-corresponding electronic charges in the process. Consequently the non-stable, saturated molecules are produced in this process. In the living system, the local and global energy requirements compete with each other resulting in a geometrical frustration. It is supposed that their balance has a central role in the formation of the actual phases (47).

The high electronic stability is connected with the perfect saturated state which is missing a small amount of charge because the electron acceptors, responsible for the oxidation driving force in the living state, transport this charge. On the other hand, the long-range requirements are opposite: the effective long-range could be created only by the large correlation length which requires non-saturated, well interacting molecules. The momentarily optimal short-range order cannot be frozen-in because its neighborhood becomes more instable by the stabilization of the given short-range unit (protein). The incompatibility of energy minima of the short- and long-range orders creates an instable situation. The material (on this level too) has to be frustrated. The non-saturated proteins fit the long-range requirements well, but in the short-range the search for the saturated situation will dominate, contradicting the global tendencies. Again a 'stability-bag' will be formed moving through the material (8). This is one of the forms of frustration discussed above. If the short-range forces are favored in the total system, the long-range order does not balance (or vice versa), life would disappear.

The frustrated system has a set of insulating islands in a non-equilibrium state and the balance of the local and global stability criteria determines the real dynamics of the charge distribution. Seeking electronic saturation, the stable local environment becomes the driving force for charge transfer. A charge wave can be frozen-in if the local forces are strong enough to stabilize the cluster, ignoring the global (long-range) stability requirements. If this freezing of a cluster doesn't happen, then, due to the frustration, a locally stable cluster can travel through the system. This is a dynamic equilibrium as a solution of the frustration effect.

The apparent contradiction of the local and global stability requirements depends on the effective ratio of the areas of local and global arrangements. The range of the interactions (short-, medium- or long-range), can control the process which, depending on the effective interaction length (correlation length), have to become intermolecular and/or intramolecular. The intermolecular interaction only starts at a definite medium-range order which is the direct limit between the living and non-living state on the molecular level. The long-range interactions, satisfying the global stability energy requirements, are very limited because the material is not in a solid-state nor a band-structure and no definite quasi-particles (as for example the quasi-Bloch states in amorphous metals (79)) exist. Only the short-range interactions could freeze-in the charge-transport starting a motion in some saturated proteins. Observations of electric conductance and the colored homogeneous matter *in vivo* indicated a non-frozen-in system. Consequently, a medium-range interaction is in action in the living state. This is the origin of the frustrated state. A delicate balance in the effective interaction length stabilizes the dynamic frustration which is, we suggest, the basic behavior of life.

The dynamic frustration of the living protein is a possible explanation for the "screaming and kicking . . ." (71), but in any case responsible for the long-range interactions, the cooperative and collective behavior of the living processes. The transported charges in the frustration are one of the important components of the cohesion forces and without it life itself vanishes.

About the connections

For the real interactions of proteins to occur, an effective transmitter between them is required. Ordered water can probably function as an information exchanger between the protein molecules and even partly between the larger units (e.g. cells), communicating with the aid of the hydrogen-bridges. Dielectric permeability is drastically lowered in this ordered state. Consequently the information exchange due to the enhanced proton migration is promoted. The importance of the change of dielectric permeability, first recognized and experimentally proven by Szent-Györgyi (77), was postulated much earlier (80, 81). (Note that some actual switching mechanisms (for example the function of black-melanin) are also based on water (82) and connected with its reordering (83)).

The ordered water is able to do a very quick switching with the time constants ranging up to 10^{-12} sec (84). The quick energy (and/or disturbance) transport can mainly be brought into connection with the tetrahedral structure of the water molecule (34) and consequently with the geometrical frustration (as was discussed earlier).

Biological charge transfer requires a close connection between the donor and acceptor. If they are as far from each other as 2 nm, the charge-donation could effectively be decreased by 10^{-12} (85). Due to the close vicinity of the proteins, the ordered water makes the charge transfer between them possible (51). Very recently it was observed that hemoglobin binds 60 water molecules during its oxygen transport (86). This picture is expanded to some other switching systems (87). Although it is not clear yet (88) why there are a definite number of water molecules connected with one of the biological processes. One possible explanation is that biological processes are connected to ordered water. (Note, that the very small energetic effect in the hemoglobin action (8 kcal/mol) (89) is exactly in the range of the hydrogen-bridge energies.)

The total process described above is collective and cooperative (90) for which the driving force, the gradual loss of the incoming electron energy in the living system (91), forces a special dynamic equilibrium. This dynamism appears in the frustration process which starts with water clustering and effects the total living system, making the living system special: "screaming and kicking . . .".

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1. The only material (the final formatter) in the Thales's philosophy, and one of the four base-materials according to Heracleitos's views.
2. According to the Tao (China) philosophy, the water is one of the five base-materials constructing the universe.
3. Holy water for celebrations and protection.
4. For example: the "magnetized" water for preventing scales in boilers and water cooling systems; (it has no widely accepted explanation yet, but has been applied with success); and the so called π-water (life-water) helping (?) the living processes, (this effect has no solid evidence, a lot of psychological and 'mystery' effects hide the real facts for scientific observation.)
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