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Water Dynamics at the Root of Metamorphosis in Living Organisms

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Received: 15 July 2010; in revised form: 10 August 2010 / Accepted: 23 August 2010 /

Published: 3 September 2010

Abstract: Liquid water has been recognized long ago to be the matrix of many processes, including life and also rock dynamics. Interactions among biomolecules occur very differently in a non-aqueous system and are unable to produce life. This ability to make living processes possible implies a very peculiar structure of liquid water. According to modern Quantum Field Theory (QFT), a complementary principle (in the sense of Niels Bohr) holds between the number N of field quanta (including the matter field whose quanta are just the atoms/molecules) and the phase Φ . This means that when we focus on the atomic structure of matter it loses its coherence properties and, *vice versa*, when we examine the phase dynamics of the system its atomic structure becomes undefined. Superfluid liquid Helium is the first example of this peculiar quantum dynamics. In the present paper we show how consideration of the phase dynamics of liquid water makes the understanding of its peculiar role in the onset of self-organization in living organisms and in ecosystems possible.

Keywords: water; coherence; quantum electrodynamics; dissipative structures; interfacial water; biological evolution; ecosystems

1. Introduction

A very long time ago, water was recognized to be the matrix of life; Thales [1] stressed this point, following maybe the teachings of more ancient traditions. In recent times, a huge amount of findings have been collected in regard to the role of water in living dynamics. In the years following the Second World War, many reports appeared showing that living organism's surfaces were coated by thick layers of a peculiar water substance exhibiting the properties of a "liquid ice"; these layers reached depths of up to hundreds of water molecule diameters [2]. In the 1950s, Albert Szent-Gyorgyi admitted that biologists were still unable to provide a formally satisfactory definition of the difference between "animate" and "inanimate" objects since "...biology has forgotten water or never thought of it" [3]. The main proposal of Szent-Gyorgyi [4,5] was that the organized water existing close to the biological surfaces was able to induce a very long lasting electronic excitation of the different molecular species present, thereby making their activation possible and selective mutual attraction. As a matter of fact, most biochemical reactions are redox reactions, which demand a supply of electrons. However, both biomolecules and isolated water molecules are not electron donors, since electrons are tightly bound to parent molecules with binding energies of several eVs.

In the conventional theory of liquid water, this paradox cannot easily appear, since the existence of the liquid is taken for granted (no description is provided for the dynamics of the phase transition vapor-liquid and the consequent large increase in density). Starting from an ensemble of molecules, which are already close enough to stay within the range of static interaction, the computer simulation calculates the shape of the network formed by a small number of molecules (at most one thousand). Hence, the probability of the movement of protons along the network is estimated through computer simulation; in this way it has been found [6] that it is possible to recover the mechanism introduced by Grotthuss [7] 200 years ago.

In the conventional approach the importance of the collective effects has been recognized. Stanley and Teixeira [8] for instance point out that "...a description of molecular behavior of water by an effective pair potential will never be completely realistic, because of the existence of many-body forces and the complexity of water". The difference between the conventional approach and the Quantum Field Theory (QFT) approach is just in the size of the aggregates of molecules. The aggregates emerging from the *ab initio* calculations, which use static interaction, only have a size of a few tens of Å at the most, whereas the water Coherence Domains (CD), as we will see in the following, span over 0.1 µm and include millions of molecules.

Computer simulations usually deal with regions whose size doesn't exceed some tens of Angstroms. The extrapolation of the results to more extended regions implies the assumption of the homogeneity of the liquid on larger scales, which is just the assumption to be proved. Moreover the problem of the condensation of the liquid, namely the transition from a rarefied vapor where the intermolecular distance is 36 Å to the dense liquid, where this distance falls off to 3 Å, is not addressed. What is the dynamic process that arises abruptly at 100 °C and 1 atm and brings the widely separated vapor molecules to a close distance? Why is this process not a gradual evolution but occurs in a discontinuous way at a given thermodynamic condition? Actually the problem of the dynamics of the phase transitions has not been addressed so far in the conventional model, which addresses only its thermodynamics. The solution to the problem implies the recognition of the long-range messenger

able to attract the initially separated molecules to a much closer distance, namely a messenger able to establish a communication among molecules which are 36 Å apart.

This messenger must be the electromagnetic field, which is the field that modern quantum physics considers responsible for the interaction between particles, in this case the molecules that are not at rest but are subjected to quantum and thermal fluctuations.

The conventional approach introduces the *a priori* not unreasonable approximation that only the static part of the interaction is relevant. The QFT approach includes also the non static interaction, which has a much longer range than the static one.

Let us come back to the problem of the electron transfer in liquid water. The ionization potential of a water molecule is 12.60 eV [9], an energy corresponding to soft X-rays. In this situation, what could be the source of the electrons supplying the redox reactions? Szent-Gyorgyi [5] was able to recognize that water at interfaces was just the electron supplier, but this would have demanded a deep reshuffling of the electron clouds of water molecules. Szent-Gyorgyi suggested that, at least in living organisms, there were two different electron energy levels of water molecules, the excited state and the ground state. According to this suggestion, a voltage should appear at the boundary between interfacial water and bulk water. He also suggested that this property should give rise to energy transfer in biological systems and to the long lasting electronic excitations which were observed.

In the following decades, however, mainstream Molecular Biology focused on the interactions among biomolecules [10-12], neglecting any possible role of water. Simultaneously, water investigations focused on the inner structures of pure water, which is actually an abstraction since there is no such thing in Nature as pure water, because water always contains other molecular species, first of all atmospheric gases. The problem of electron transfer [13] in the water of living organisms has not been addressed.

Recently, a surge of interest has arisen concerning the role of water in organizing structure, which makes the emergence of complex dynamics possible [14]. As an example, we quote here recent reports on the presence of coherent structures within organisms, which make specific biological functions possible. We refer in particular to the studies on photosynthesis [15-17]. In these articles, a very long time of coherence of chloroplasts is reported, possibly larger than predicted by the available theories of biomolecules. Since theoretical investigations based on Quantum ElectroDynamics (QED) have suggested the spontaneous emergence of coherence in liquid water [18,19], an appealing possibility is that the coherent electromagnetic field responsible for the coherent molecule structures in water, which are in principle very long lasting, could explain the peculiar coherence of chloroplasts.

An additional indication of the organizing role of water has been recently provided [20] in the frame of the investigations on the Belousov-Zhabotinsky (BZ) phenomenon, which is a regular time oscillation of the concentrations of chemical reagents within a suitably prepared system. It has been shown that the regular oscillation appears only when the amount of water bound to the surface exceeds a critical threshold; an indication emerges that water could play the essential organizing role.

In the present paper, we wish to discuss the requirements imposed by the structure of water to its ability of governing molecular dynamics within itself. In this frame we will try to understand the rather unique role of water in living organisms (actually water cannot be replaced by any other H-bonded liquid), and the differences between the normal bulk water and “special waters” such as those close to the surfaces, which mimic the water in biological systems.

2. Anomalous Phenomena in Liquid Water and Living Organisms

The anomalous properties of interfacial water were already known in the late 40s [2]. Water in living organisms could be considered interfacial water since there is almost no point in the organism that is farther than a fraction of a micron from a surface (cell membranes, macromolecule backbones, *etc.*). Interfacial water has been investigated by a number of researchers [21-23]. In particular, it has been discovered that thick layers of water contiguous to biological surfaces remain static when the surrounding fluid is vigorously stirred [24], and there is a relationship between the thickness of the layer and the intensity of the stirring of the surrounding fluid. Subsequently, Pollack and Clegg [25] suggested the existence of a linkage between these unstirred layers and the zones (EZ, Exclusion Zone) where solutes were unable to penetrate; whose existence in eukaryotic cells was pointed out for the first time by Mollenhauer and Morrè in 1978 [26]. Further contributions to the investigation on EZ water can be found in the bibliography of reference [25].

The properties of EZ water have been widely investigated by the group led by G.H. Pollack [27-31]. By using dyes dissolved in water as a probe, he was able to detect the existence of extended regions in the boundary between the liquid and the wall of the container, where the dyes were prevented from entering (exclusion zones, EZs), provided that the wall was an hydrophilic surface. The depth of EZs could reach a length of some hundreds of microns, much longer than the estimates of conventional studies on liquid water. For instance, in the computational scheme presented by Buch *et al.* [32] the interfacial layers are defined to contain 60 molecules, whose total size cannot exceed a couple of hundreds of Å, a length smaller than the observed depth of the EZ layer by four orders of magnitude.

The physical properties of EZ water could be summarized as follows:

- (1) EZ water is considerably more viscous than normal water (about ten-fold).
- (2) EZ water has a negative electric potential (up to 150 mV) with respect to the neighboring normal bulk water; thus the pair EZ water-normal water is a redox pile. This property of EZ water could account for the source of electron excitations looked for by Szent-Gyorgyi.
- (3) Protons concentrate at the boundary between EZ-water and bulk water
- (4) EZ water exhibits a peak of light absorption at 270 nm; it emits fluorescence when excited by light having this wavelength.
- (5) The illumination of EZ water by light (especially IR radiation) increases the depth of the layer.
- (6) As previously said, EZ water cannot host solutes.

The above list of properties appears quite mysterious in the frame of conventional ideas about liquid water. A possible objection on the nature of EZ water, namely that the observed EZ could be a network of filaments protruding from the wall within water, has been ruled out by careful experimental investigations [33].

EZ water appears to be a different phase of liquid water. The problem of how many phases liquid water is made of is a long standing problem. As far back as in 1892, Roentgen [34] proposed a two-phase model of liquid water, designed to fit the observed behavior of the coefficients of solubility of the good solutes with temperature. This model was generally accepted until the early 30s, when Bernal and Fowler [35] criticized it on the ground that the water molecule obeyed a well defined Hamiltonian which did not allow more than one phase within the same thermodynamic conditions.

However, only a few years later a model was proposed, in the frame of Quantum Field Theory (QFT), about superfluid liquid Helium [36], which was considered a two-phase liquid. The objection of Bernal and Fowler was circumvented since the liquid was no longer considered as a collection of single molecules; the so-called normal phase only was considered as such, whereas the superfluid phase was a collective state made up not only of molecules but also of an extended field responsible for the correlation between molecules. Of course, this field was closely connected to the existence of the collective state and disappeared with it. The correlating field becomes therefore a component having equal rights as the molecules. We will discuss this topic in the next section.

Unlike the liquid Helium, liquid water has been regarded for many decades [37] as a mere collection of single molecules kept together by static short range forces (H-bonds or else) whose binding was possibly counteracted by thermal collisions or by the oscillations of molecules endowed by the excitations of the low-lying states (less than 200 cm^{-1}) of the molecule spectrum. However, this picture hardly gives any room for more than one phase of liquid water. Consequently, water has been regarded for a long time as a one phase liquid. Actually, neutron scattering probes liquid water as a homogeneous liquid [38]; however, in recent times evidence has begun to be collected about an inhomogeneous structure of liquid water [39]. The results of experimental probings of the structure of water should actually be weighted in the light of the resolution time of the experiment, which is the duration of the elementary measurement of the scattering event. Should the two-phase structure give rise to a fast moving landscape, the actual observation of this structure would demand a resolution time shorter than the typical life-time of the landscape. Consequently, the departure from a homogeneous structure could not be observed until recent times, when the resolution time of the experimental probes became short enough. Vibrational spectroscopies have been suggested as a probe for detecting fast moving inhomogeneous structures since transition frequencies are sensitive to local molecular environments [40,41]. The existence of a plurality of phases of liquid water has recently received important corroboration. There have been reports that by submitting liquid water to well defined physical treatments (irradiation by electromagnetic waves, suspension of microspheres of inert materials, dissolution of fullerene macromolecules), special varieties of liquid are obtained having properties different than normal water and similar to EZ water [42-44]. Moreover, a variety of water-having properties similar to water present in biological organisms—has been obtained by performing particular biological processes in normal water, essentially connected with photosynthesis [45]. In this last case, viscosity was quite lower than in normal water, opposite to the case of EZ water. Other anomalous properties of the above varieties of water involve thermodynamics (strong decrease of the mixing heat with titrated alkaline solutions) [46] and electrochemistry (different shapes of the deposits of electrolytes on the electrodes) [42].

The co-existence of several phases of liquid water in the same thermodynamic conditions therefore can be no longer excluded. As said before, the contrary argument produced by Bernal and Fowler might be circumvented by assuming the existence of collective states of the water molecules which require the existence of a mesoscopic/macroscopic correlation field, like the one present in superfluid Helium. Should this correlation field be able to exist in many configurations, the possibility of many collective states of water, and hence many phases, could emerge. This possibility of course could not emerge in the conceptual framework of Quantum Mechanics where a collection of molecules interacting through static forces admits, according to the fundamental theorem of von Neumann [47], a

unique ground state (vacuum) and hence a unique phase at given thermodynamic conditions. It is therefore not surprising that the conventional *ab initio* approaches to water [48], based just on Quantum Mechanics, describe it as a monophasic liquid. On the contrary, the conceptual frame of QFT admits infinitely many ground states (vacua), each one corresponding to a particular function describing the expectation value of the involved field [49]. In the QFT approach, the quanta of the field correlating the molecules are components of the system on the same ground that the molecules; of course they would disappear when the system is dismantled. In QFT the interaction is considered an object as much as the basic components. Moreover, the tight binding between molecules and the correlation field produces new basic objects named quasi-particles and the conventional separation between matter and interaction is dropped out [49]. It is interesting to recall that a similar vision has been anticipated a long ago, in the conceptual frame of vitalistic biology, by the German botanist Julius Sachs [50], who pointed out that in living organisms, such as the plant cells, matter and energy are not separate but a unique substance he called *energid*, which means energized matter.

An important feature of the QFT approach is the fundamental role assumed by the physical variable, named the *phase* Φ of the field (which should not be confused with the thermodynamic phase). The *phase* Φ describes the rhythm of oscillation of the field and therefore the wavelike aspects of the system. The duality between particle and wave descriptions of the physical system is embodied by the uncertainty principle, between the number N of the quanta (which are the photons for an electromagnetic field, the atoms or molecules for the matter field, the quasi-particles for the interacting field) and the phase Φ (Equation 1) where h is the well known Planck constant.

$$\Delta N \Delta \Phi \geq h \quad (1)$$

This principle appears in Quantum Field Theory where the number of component particles is left undefined; this principle does not exist in the ordinary Quantum Mechanics where a phase is attributed to a definite number of particles. In this sense, ordinary Quantum Mechanics appears as a semi-classical approximation to a complete Quantum Physics, which is more correctly described by the Quantum Field Theory.

Inequality [1] has an analogous meaning of the Heisenberg relationship between the uncertainties of position and momentum and tells us that it is impossible to define simultaneously both the number of quanta (namely the microscopic structure) of the system and its phase, which, through the well defined mathematical function describing it, could have an information content. After all, it is well known that a talk, which carries an information, is nothing else than an ensemble of frequencies evolving in time according to a well defined law. What inequality [1], which summarizes the content of QFT, tells us is that an information content *evolving in time* (namely an information not given once and for all from outside), in other words a living information, cannot be attached to a well defined ensemble of molecules and quanta.

Since we know [51] that liquid water is the fundamental ingredient of living organisms, whose decrease below a concentration threshold destroys the possibility of life, we should conclude that the physical properties of liquid water, as understood in the conceptual frame of QFT, should mirror the above stated properties. In order to check this possibility, we need to describe water as a large ensemble of molecules (matter field) interacting through a long-range field (the only possible candidate is the electromagnetic field) and verify the existence of many solutions, corresponding to the

plurality of phases (in the thermodynamic sense) required by a living organism able to self-organize and therefore containing an information reservoir [52].

3. A Quantum Field Theoretical Description of Liquid Water

The process of condensation of matter, namely the transformation of an ensemble of uncorrelated molecules, a gas, in a collective of molecules performing in unison, a liquid or a solid, has presented a number of conceptual problems to the physicists. For a long time during the last century, condensed matter was regarded by most physicists as a dense gas where molecules became so close that short range static forces (van der Waals forces, Lennard-Jones forces, London forces, H-bonds) acquired the possibility of keeping them together. This approach reversed cause and effect since it didn't explain why molecules could have reached a distance where static forces became effective. In any case in this approach, which is not based on Quantum Field Theory, the phases of the components played no role whatsoever.

A different approach was conceived during the investigation of a liquid, the superfluid Helium, where the existence of a phase correlation among components is undeniable [36]. For a long time, this approach remained confined to liquid Helium as a consequence of the misconception that a macroscopic Quantum Physics could exist only at low temperature. In the last years, however, thanks also to the progress of Quantum Optics, the general problem of the interaction of a large number of microscopic components with an electromagnetic field (e.m.f.) has been addressed, achieving a number of non trivial results. Recently, in the theoretical frame of Quantum Optics, it has been discovered [53] that a closely packed ensemble of atoms is able to leak out photons (namely to give rise to a non vanishing e.m.f.), also in the absence of external driving, provided that the usual Rotating Wave Approximation (RWA), which is equivalent to neglect all the couplings between e.m. modes with different frequencies, is dropped. This result, which is derived rigorously from the basic equations of Quantum Optics, can be understood by recalling that in Quantum Physics the vacuum is able to exchange energy and momentum with matter, as shown by well known effects such as the Lamb-shift or the Casimir effect. Just considering the existence of the fluctuations of the quantum vacuum, as far back as in 1916, W. Nernst [54] suggested the possibility of tuning together the fluctuations of all the components of a system and therefore the appearance of a common phase.

This possibility has been checked in the framework of QED where the interaction among atoms mediated by the e.m.f. is addressed starting from first principles [55-57]. We will summarize here the main points of this approach, by avoiding all the difficulties of the rigorous mathematical treatments and the technicalities of QED. We will use intuitive arguments extensively to the benefit of non specialists, paying the price of some lacking precision in places.

Our starting point is an ensemble of a large number N of atoms (or molecules); For the sake of simplicity, we assume that they have two states only—the ground state and the excited state—whose excitation energy is $E = h\nu$. This assumption will be dropped eventually. The size of an atom is in the order of 1 \AA , whereas the size of the photon able to excite the atom is its wavelength $\lambda = c/\nu$, which, in the case of an excitation in the range, as usual, of 10 eV , would be in the order of about 1000 \AA . Therefore, the size of the object able to induce a transition in an atom is about one thousand times larger than the atom! Just this mismatch is at the origin of the possibility of producing extended

regions where component atoms are correlated. As a matter of fact, one (virtual) photon, which got out from the quantum vacuum because of Heisenberg quantum fluctuations, could excite an atom with a probability P in the order (according to the estimates based on the Lamb-shift) of $10^{-4} \div 10^{-5}$. The excited atom would decay after its typical decay time, giving back the photon, which could alternatively be reabsorbed by the vacuum or excite another atom. The relative probabilities of the two events would depend on the density $n = N/\lambda^3$ of the atoms present within the volume λ^3 of the photon. When the density n exceeds the threshold n_{crit} (Equation 2), the photon would never be able to reach again the vacuum and will bounce forever from one atom to another within the volume λ^3 .

$$P \lambda^3 n_{\text{crit}} = 1 \quad (2)$$

Therefore, the vacuum has given a photon to matter. This process would go on until many photons get trapped and a sizeable electromagnetic field (e.m.f.) is built in this region. This field produces two consequences:

- (1) it attracts co-resonating atoms, which are of course the atoms of the same species, producing a large increase of density, as observed in the phase transition vapor-liquid; the saturation density corresponds to the inter atomic distance at which hard core repulsion becomes important. So the observed density would depend on the short range forces.
- (2) it produces a common oscillation of all the trapped atoms giving rise to a common phase within the whole region, which for this reason is named Coherence Domain (CD). This common phase of oscillation does not coincide with the original phase of the free photon, since the time of oscillation of the photon involved in the common oscillation with atoms should be supplemented by the time spent within atoms in the form of excitation energy.

In this process, atoms and photons have lost their original identity, giving rise to energized matter (the *energid* of Sachs) made up of quasi-particles *entangled* among them in the CD. Just for this reason, photons cannot get out from the CD; their squared mass $m^2 = \hbar^2 v^2 - \hbar^2 c^2 / \lambda^2$, which is zero for a free photon, becomes negative for the quasi particle (self-trapped photon) because of the above mentioned increase of the oscillation period and hence of the decrease of the frequency. A negative value of the squared mass implies the impossibility of propagating and consequently the quasi-particle would remain trapped within the CD. This is quite a fortunate result since it guarantees the stability of the system, which would otherwise continuously lose energy.

The concentration of energy in a small number of microstates (in principle just one) from the original large number of microstates (corresponding to the many configurations of the uncorrelated atoms) implies a large curtailing of entropy, which would violate the Second Law of Thermodynamics unless a corresponding amount of energy is released outwards. This release of energy gives rise to an *energy gap*, which implies that the energy of the coherent state is lower than the energy of the original non-coherent state. The energy gap prevents the occurring of a Perpetuum Mobile; the energy lent originally by the quantum vacuum is given back through the above outflow of energy which is nothing else than the latent heat of the phase transition. The conservation of energy and the Second Law of Thermodynamics are consequently satisfied. It is apparent that the above Quantum Field theoretical predictions agree completely with the observed pattern of a vapor-liquid transition. In the conventional approach, computer simulation techniques have allowed investigation of the properties of water clusters made up of a small number of molecules and their stability [58]. In these investigations, it has

been recognized that many-body forces should play an important role. In other words, condensed matter cannot be described in terms of pair potentials only.

The electrodynamic attraction induced by the onset of coherence is supplemented in real systems by the short range static attractions which could play a role only after molecules are brought in close contact by QED attraction. We should point out that the static attraction does not occur between the molecules in their individual ground state but among molecules which are in the coherent state where there is a significant contribution of the excited state. We will see that this consideration is very important in the case of water.

In the real case of molecules having not just two internal configurations but many, the choice of the pair of states involved in the coherent oscillation demands, as discussed in [18], the estimate of the time required by the onset of the coherent regime. The pair of states which eventually gives rise to the coherent state is the one having the fastest rising time toward the state where the coherent oscillation appears. In the case of water, this time has been estimated to be in the order of 10^{-14} seconds [18].

At non-vanishing temperature T , the electrodynamic attraction is counteracted by the disruptive dynamics of thermal collisions which could push a number of molecules out of tune. In reference [18], a statistical derivation is given allowing to estimate, for each value of T , the fraction $F_{nc}(T)$ of molecules which have lost coherence because of the thermal noise. The two fractions $F_c(T)$ and $F_{nc}(T)$ of coherent and non-coherent molecules are tied, as in the case of superfluid liquid Helium, by the relationship:

$$F_c(T) + F_{nc}(T) = 1 \quad (3)$$

Equation (3) determines, for each T , the total number of molecules belonging to each phase, but each molecule crosses over between the two phases continuously in time. This phenomenon produces a landscape flickering in time, so that a measurement whose resolution time is longer than the typical time of flickering would detect a homogeneous liquid; only measurements having a resolution time short enough would detect the two-phase structure depicted above.

However the situation would change near a wall, where the attraction between the molecules of the liquid and the wall would be able to stabilize the coherent state, thus shielding it from the disruptive effect of collisions.

Let us discuss now the peculiar case of water. The above theory applies to all molecular species. However, as shown in references [18-20], in the case of water the excited state involved in the coherent oscillation (12.06 eV) lies just below the ionization threshold of the molecule (12.60 eV). An oscillation of 12.06 eV corresponds to a water CD size of 0.1 microns. The onset of the coherent oscillation gives rise to the appearance of one quasi-free electron in the coherent state; therefore, the CD becomes a reservoir of quasi-free electrons that are easily excitable. In reference [59], the spectrum of excitations of water CDs has been derived; each excitation corresponds to a coherent *cold* vortex of quasi-free electrons. Actually, quasi-free electrons belong to a coherent state so that an external perturbation that is smaller than the energy gap, cannot be received by any individual molecule, but is stored by the CD as a whole, giving rise to a collective excited state, which is still coherent. The analysis of reference [59] shows the existence of a huge number of excited states, characterized by their angular momentum L , whose energy spacing is in the order of radiowave energy (some tens of kHz). Since the vortices are cold, they cannot decay thermally, thus their lifetime depends on the

lifetime of the parent CD. Consequently, the excitations of CDs could last a very long time and, moreover, give rise to a sum of several subsequent excitations whose energy therefore becomes higher and higher. The possibility of the storage is increased by the coupling of the magnetic moments of the cold electron vortices with the Earth's magnetic field, which aligns them. The spectrum of the excited states of the water CDs, given in reference [59], is limited upwards by the energy gap which is 0.26 eV per molecule; since in a CD there are about six million molecules, it is apparent that the spectrum of an isolated water CD has practically no upper limit. This means that within the CDs it is possible to store amounts of energy that can reach the visible and the ultraviolet. In this way, the water CD would become a device able to collect the energy coming from the environment and transform it into energy able to induce electronic excitations in the biomolecules surroundings the CDs. This property, which emerges naturally in the scheme of QFT, implements the requirement of Szent-Gyorgyi [3-5] made long ago on purely biological grounds. This result opens new perspectives in the investigation of important natural phenomena such as lightning. A lightning blot emerges from clouds, which are ensembles of droplets of water suspended in air; nothing else. In spite of this simplicity, huge amounts of energy and electric charge are carried by the lightning. Since we have proved that a water CD can easily release electrons and can store huge amounts of energy, we are faced by the appealing possibility that we could learn something about the dynamics of lightning by using the QFT approach.

We conclude this section by discussing the structure of the short range static forces among the coherent water molecules. As shown in reference [18], the excited state appearing in the coherent state of water is a 5d state, namely, in this state there is a very decentralized electron having a high angular momentum ($L = 2$). The electron cloud in the excited state assumes, therefore, a torpedo like shape; the average shape of the electron cloud in the coherent state is the combination of the shapes in the two component configurations between which the coherent molecule oscillates. As discussed in reference [60], the contamination of the electron configuration of the excited state induces the appearance in the ground state electron cloud of two protuberances oscillating with the same frequency of the collective oscillation of CD. This produces the observed phenomenon of the H-bonding, which becomes therefore an effect of the existence of the coherent regime. So the H-bonded network of water molecules is the phenomenological appearance of the coherent fraction.

4. Liquid Water Close to Surfaces

A conclusion in the previous section was that normal liquid bulk water is a combination of a coherent phase and a non-coherent phase, whose amounts depend on temperature; however each molecule crosses over continuously between the two phases according to the typical time scale of the thermal noise so that we get at last a flickering space picture. Near a surface, the interaction between molecules and walls introduces a new factor into the dynamics. Should the water-wall interaction be strongly attractive as in the case studied by the Pollack group [27-31], the disruptive role of thermal collisions gets neutralized and the whole interfacial water is allowed to stay coherent, mimicking the case of low temperature water ($T \leq 200$ K) which is fully coherent as shown in reference [61]. In fact, a fully coherent water appears as a glass since it is impossible to touch a molecule without affecting all the others; viscosity consequently increases as observed experimentally. It is interesting to observe that water in living cells, where each water molecule is no more distant from some surface than some

hundreds of Ås, assumes a glassy appearance [62], which plays an important role in biology. As Pagnotta and Bruni [63] observe: *“interfacial and intracellular water is directly involved in the formation of amorphous matrices, with glass-like structural and dynamical properties. We propose that this glassiness of water, geometrically confined by the presence of solid intracellular surfaces, is a key characteristic that has been exploited by Nature in setting up a mechanism able to match the quite different time scales of protein and solvent dynamics, namely to slow down fast solvent dynamics to make it overlap with the much slower protein turnover times in order to sustain biological functions. Additionally and equally important, the same mechanism can be used to completely stop or slow down biological processes, as a protection against extreme conditions such as low temperature or dehydration”*.

Let us compare now the QED predictions on coherent water with the observed properties of EZ water [27-31]. The absence of solutes in fully coherent water (glassy state) could be easily understood by considering that in the coherent state, water molecules are tightly packed together as much as they can. However, the density of coherent water is lower than that of normal water since coherent molecules are spatially wider than non-coherent molecules because they are a combination of the ground state and of a much more extended excited state. Consequently, coherent water is a low density liquid, but its molecules are simultaneously so packed inside that the entrance of external molecules is not allowed, which could only crowd on the surface. The strange property of the exclusion of solutes from the interfacial water thus becomes understandable in the QED framework.

Moreover, in the coherent water, electrons are kept oscillating from a ground state, where they are tightly bound and cannot escape at room temperature, to an excited state, where one electron is loosely hanging out of the electron cloud core. The ensemble of quasi-free electrons gives rise to two main consequences:

- (1) it could give rise, as discussed in the previous section, to excited cold vortices.
- (2) it could release electrons out of the CD, either by a quantum tunnel effect or by a mild external perturbation.

The second consequence accounts for the presence of electron transfer properties on the surface of coherent water. The interface between fully coherent interfacial water and normal bulk water becomes therefore a redox pile, as demanded by Szent-Gyorgyi [3-5]. These same properties have been observed in the EZ water [27], corroborating the assumption of its identification with the coherent interfacial water.

In reference [20], the jump of electric potential existing on the interface between coherent and non-coherent water has been estimated to be in the interval $55 \div 120$ mV, in good agreement with the observed values of electric potentials on cell membranes and on EZ water.

We conclude this section by observing that in a living organism, water, which accounts for about 70% of the total mass and 99% of the total number of molecules, could be considered as fully interfacial water since each molecule is always closer than a fraction of a micron from some surface or macromolecule backbone, whereas the observed depth of EZ water is much greater.

5. Coherent Liquid Water as a Dissipative Structure

The possibility of coherent excited states of water CDs opens a fascinating perspective: the possibility of coherence among water coherence domains! In this way, many coherent regions—each having a size of 0.1 microns—could give rise to much more extended coherent regions, as in living organisms. A hierarchy of nested organized regions would emerge. In fact, this possibility holds only for liquids where the excited component of the coherent state lies just below the ionization threshold and this is just the peculiar case of water. However this perspective could become real only if a number of conditions are fulfilled.

We have seen that water CDs can be easily excited; water CDs are able to collect a large number of small external excitations (low grade, high entropy energy) producing single coherent vortices whose energy is the sum of all the small excitation energies but whose entropy is small (high grade, low entropy energy). This collective energy, however, cannot be released outwards in a thermal way and this explains the long lifetime of the CD excited states. In order to produce coherence among coherence domains, it is necessary to make CDs oscillate, which means that CDs should be able to discharge energy outwards.

A possible way out could be a chemical discharge of energy. Let us examine this possibility in detail. First of all, we observe that, should an external nonaqueous molecule contain in its own spectrum a frequency close to the oscillation frequency of the water CD, this molecule could become a *guest* participant in the water coherent dynamics and would settle on the surface of the CD. The difference of frequencies between CD and guest molecules should be smaller than the level kT of thermal noise, so that the molecule could match the frequency of the CD by stealing the needed energy to the thermal bath. This is a phenomenon well known in Quantum Optics, where it is denoted by the name *laser cooling* [64]. This condition determines which molecules could become guests of water CDs at a given value of T (and become consequently biomolecules). By calling $\nu_{CD}(T)$ the frequency of the water CD (which depends on the number of components that depends in turn on T), ν_i the frequency of the i -th molecule mode, the condition becomes:

$$|\nu_{CD}(T) - \nu_i| \leq kT \quad (4)$$

Inequality (4) suggests a possible criterion for selecting the molecules able to participate in a biological process. For instance, it is known that Nature selects 20 amino acids only to be used in living organisms, out of a total of one hundred. The possibility arises that the explanation of the above puzzle could reside just in the Inequality (4). The frequency of oscillation of the electromagnetic field trapped in the CD is 0.26 eV at $T = 0$ in the ground state of the CD [18]. When the CD stores energy this frequency changes; moreover the frequency, which depends on the number of coherent molecules, decreases when this number decreases with an increase in temperature. We have not yet calculated the rate of such a decrease that should conceivably give a frequency of about 0.2 eV at room temperature; it is interesting that amino acids involved in living organisms exhibit spectral lines near this value. We think that the above conjecture deserves an investigation.

However, the differences between the radiative dipole moments of the guest molecules and of the water molecules could, in principle, disrupt the total coherence, unless the number of guests is small with respect to the number of water molecules. Using a metaphor, a dozen of singers chanting very

loudly would not disturb a chorus of one thousand singing children, but would be a nuisance in a chorus of, say, fifty children. This consideration could help us to understand why water is so abundant in a living organism (99% of the total number of molecules). It is conceivable that water CDs would be unable to govern a larger number of guest molecules.

Therefore, if a water coherence domain was to accept a small number of guest molecules among its participants, then the excitation energy stored in the CD would become available to the guest molecules. When the amount of stored energy matches the activation energy of the guest molecules, it would be transferred to them, simultaneously producing their chemical activation, the energy discharge of the CD and a chemical reaction array; the CD would then behave as a multimode laser [18,56]. A number of consequences arise:

- (1) the CD has completed an oscillation, whose duration depends on the rate of energy storage, on the height of the required activation energy and on the rate of chemical reaction. The inverse of this time is the frequency of oscillation of the CD. Should many neighboring CDs be in the same chemical and thermodynamic environment, they could enter in a collective coherent oscillation that would in turn increase the degree of coherence (which is the width of the coherent oscillation frequency) of each of the participant CDs.
- (2) the chemical reactions, which occur on the surfaces of CDs and can benefit also from the electron transfer available there, are no longer governed by diffusion but are governed by electrodynamic attraction. According to a theorem of QED, two molecules oscillating with frequencies ν_1 and ν_2 within a region filled by an electromagnetic field oscillating with a frequency ν_0 develop a very strong attraction when the three frequencies coincide. This long range attraction replaces diffusion as the molecule interaction agent. The existence of codes governing the array of biochemical reactions could therefore be understood [65].
- (3) the energy output of the chemical reactions is released because of coherence as an excitation of the electromagnetic field trapped in the CD and is absorbed by the water CD. A corresponding shift of the CD frequency is produced, changing in turn the molecular species able to be attracted and opening consequently a new biochemical cycle. Each cycle is therefore opened by the outcome of the previous one. The possibility of an ordered array of biochemical reactions emerges.

Two correlated dynamics are therefore at work:

- (a) the emergence of an extended coherence among coherence domains depending on the frequency of the CD oscillation governed by the energy charge and discharge processes.
- (b) the emergence of a time-ordered biochemical array governed by selective attractions among molecules.

The two dynamics are tightly interconnected so that one could say that biochemistry is the tool necessary to keep water organized on a long range.

The onset of coherence among coherence domains stabilizes the coherent fraction of water since the energy gap of the additional coherence adds up to the energy gap of the single CDs, providing an additional protection against the disruptive effect of thermal noise. Consequently, liquids endowed with this extended coherence exhibit a less flickering internal landscape, giving rise to the possibility of a bulk water showing coherent patterns. This is exactly what is observed in the special waters produced recently [42-45]. We observe also that coherence among coherence domains is not equivalent to glue the CDs together but implies simply that separated domains oscillate in unison.

Consequently, contrary to the case of EZ water where CDs get glued together through the common attraction to the wall, in this case we can have a less viscous liquid as observed in superfluid Helium and in the special water described in reference [45].

The formation of an ensemble of CDs is accompanied by the expulsion of the solutes, including the atmospheric gases, from their inside so that in the very moment of CD formation in the bulk liquid a microbubble should appear also. In normal bulk water, microbubbles appear and disappear in a flickering way, mirroring the flickering space distribution of CDs. On the contrary, in the special waters where the extended coherence is established, the space distribution of CDs becomes much less flickering and this is mirrored by a non-flickering ordered space distribution of microbubbles. This is exactly what is observed in *Neowater* described in reference [42]. Therefore, the transition between flickering and ordered arrays of microbubbles in liquid water reflects the transition between coherence and non coherence of the water CDs.

Let us conclude this section by describing the energetics of the water extended coherence. By collecting energy from a large number of degrees of freedom (large value of initial entropy S_{ini}) the system produces an extended coherent system having a small value of the final entropy S_{fin} . The quantity $T(S_{fin} - S_{ini})$ is negative so that the Second Law of Thermodynamics requires the release of a corresponding amount of energy that the system could use for performing work. The coherent array of water CDs becomes then a candidate to be a dissipative system *à la Prigogine* [66].

6. The Dialog between Liquid Coherent Water and the Environment: the Emergence of Time Evolving Information

The existence of a dissipative structure made up by the coherent array of water CDs, whose extended coherence depends on the presence of non-aqueous guest molecules in water, endows this liquid with the capability of communicating with the environment. Long ago, Giorgio Piccardi [67-69] reported that significant changes in the physical properties of molecular systems suspended in liquid water occurred simultaneously with cosmic or environmental events. For instance, he detected changes in the precipitation rates of colloids following the time evolution of sunspots or climatic events. As a matter of fact, water appeared as an accurate probe for a large number of external events. This property shed possible light on the capability of living organisms, which we know to have a dominant content of water, to perceive external events; more surprising, water and living organisms are shown to be able to perceive very subtle events, also below the resolution threshold of technical devices. We like to quote in this context the research of V. L. Voeikov and his Russian colleagues [70,71], who were able to detect peaks in the amount of photons emitted by water added with bicarbonates and Luminol coinciding with Sun and Moon eclipses, and also earthquakes occurring very far from Moscow where the lab was located. It is important to keep in mind that pure water has not such a property of sensitivity, but only water containing solutes or suspended particles, like colloidal solutions. This property recalls very much the conditions necessary in the QED theoretical approach for getting extended coherence in water.

The surprising properties found, among others, by Piccardi and Voeikov, do not appear surprising at all in the QED approach. Actually, water CDs contain trapped electromagnetic fields which produce a magnetic vector potential \mathbf{A} in the surrounding space, whose rotor—and hence the magnetic field—is

zero [we recall that $\mathbf{H} = \text{rot } \mathbf{A}$]. \mathbf{A} extends on a much longer range than \mathbf{H} , since this last field is given by the space derivatives of \mathbf{A} . There is, therefore, a coupling between the vector potential produced by the water CDs and the vector potential originating in the electromagnetic dynamics occurring in the environment, like the electromagnetic radiation produced by sunspots, cosmic events, atmospheric events and movements in the terrestrial crust. This situation is exactly what could give rise to the *Bohm-Aharonov effect* [72], according to which the phase of the system is changed by the magnetic vector potential. As a consequence of this effect, coherent systems in general and aqueous systems, including living organisms in particular, are very sensitive detectors of weak magnetic fields through the detection of their magnetic potential. The role of the magnetic potential in the onset of communications among living organisms and in the organization of ecosystems has been discussed in reference [73]. The evidence collected for many years of the impact of weak magnetic fields on aqueous and living systems, so far unexplained, could find at last a rationale in the existence of electromagnetic structures in the supramolecular organization of liquid water. Very recently, the group led by L. Montagnier has been able to detect experimentally the presence of electromagnetic signals originating in the water surrounding biomolecules [74].

Since the onset of the extended coherence of liquid water depends on the presence of nonaqueous molecules, a useful non-biological model system is provided by rocks containing some water. According to the dynamics described in the previous section, the water in the rocks, through the chemical reactions among the carbonates and the atmospheric gases, produces water having higher coherence than plain bulk water. The strange phenomena observed in water coming from springs located in caves could be analyzed just in this context. A very interesting article from Balk *et al.* [75] reported that at the rock-water interface very interesting oxidative phenomena and also oxidative stresses appear analogously to what occurs in living organisms. Actually, rocks and living organisms have in common the presence of an interfacial layer of coherent water, which appears as a reasonable candidate to be the actor of the reported effects. A contribution along this line was provided by Spinetti [76] who analyzed the role of rocks in the dynamics of a particular ecosystem, the garden.

Another significant model system has been provided by Tedeschi [45], who was able to observe changes in the physical properties of liquid water, triggered by biological events occurring inside it. These events were the response of vegetable leaves and algae, thinly triturated and therefore biologically *irritated* in order to enhance as much as possible their living dynamics. According to the Montagnier findings [74], it is conceivable that in these conditions electromagnetic signals could be emitted by the living system, thus changing the phase of the water CDs. It has been reported in reference [45] that water treated in the above way keeps its properties for a long time and, moreover, becomes able to respond to the environment much more than untreated water. It is possible that this last property would signal the emergence of a higher level of internal coherence. Through its coupling with the environment, this water becomes an efficient method for transmitting information to living organisms.

7. Conclusion and Outlook

Quantum Field Theory has produced a vision of liquid water as a medium, which for a peculiarity of the molecule electron spectrum reveals as an essential tool for long-range communications, being able to change its supramolecular organization according to the interaction with the environment. The electromagnetic fields trapped in the coherence domains and in their coherent arrays produce electromagnetic potentials governing the phase of the whole system, which in turn gives origin to selective attractions among the solute molecules. In this way, an array of biochemical reactions (soma) and time-evolving information simultaneously evolve, leading to the appearance of the self-consistency, which opens a new perspective for self-maintaining and stability of the systems under study.

However, evidence is growing in favor of the physical grounds of the approach proposed here. We limit ourselves to quote the fascinating experiment of the formation of the *floating water bridge* [77-84] where surprisingly water gets self-piped in presence of high voltages and becomes able to flow in the absence of any container from one beaker to another. A possible explanation of this effect along the lines of the QED approach has been proposed [85].

Acknowledgement

We dedicate this article to our late friend Enzo Tiezzi, who has been along his whole scientific life a supporter of the basic role of water in the organization of life. We wish also to thank our friends Larissa Brizhik, Vittorio Elia, Elmar Fuchs, Roberto Germano, Livio Giuliani, Nadia Marchettini, Luc Montagnier, Elena Napoli, Jerry Pollack, Giuseppe Vitiello and Vladimir Voeikov for the passionate discussions that have contributed to the emergence of the point of view presented in this article.

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