Special Address

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Quantum Brain Dynamics and Quantum Field Theory

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ABSTRACT

An introductory exposition of Quantum Brain Dynamics (QBD) is presented in which the fundamental physical process of the brain can be described within the realm of quantum field theory. QBD is nothing else but Quantum Electrodynamics (QED) of the electric dipole field of dipolar solitons and water molecules with a symmetry property under the dipole rotation. The highly systematized functioning of the brain is found to be realized by the spontaneous symmetry breaking phenomena. Memory printing, recall and decay processes are represented by the fundamental physical processes standing for the phase transition process, the symmetry restoring process and the quantum tunneling process, respectively.

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1. Motivation

The problem of understanding the mechanism of memory in terms of fundamental physical processes providing the brain tissue with a highly systematized functioning (i.e., cybernetics) has been of particular interest from both physical and physiological points of view. Since only a restricted number of modern physicists have been interested in the problem, the conventional approach to it has remained of phenomenological and macroscopic nature. Indeed, the usual way for physicists and physiologists to understand the memory mechanism has been at most to consider the so-called neuronal network dynamics of transmembrane ionic transfer phenomena. The Waldeyer-Sherrington neuron doctrine has been believed widely without recourse to any further deep consideration. There, emphasis has been put on a belief that pathway conduction of neural impulses is the sole basis for signal transfer and information processing in the brain. Neural impulses are macroscopic membrane potential differences arising from the transmembrane ionic transfer phenomena.

Such a macroscopic and phenomenological approach to the problem has been shown increasingly to fail in several directions, and a further theoretical approach form a microscopic point of view has been expected. In a series of papers Umezawa and coworkers (Ricciardi and Umezawa 1967; Stuart et al. 1978; 1979) proposed a completely new framework of brain dynamics within the realm of quantum field theory. They considered the brain as a mixed physical system composed of the macroscopic neuron system and an additional microscopic system. The former consists of pathway conduction of neural impulses. The latter is assumed to be a quantum mechanical many-body system interacting with the macroscopic neuron system. There, they emphasized the importance to notice a fact that the long-range correlation of Goldstone mode type plays an essential role in making brain dynamics much ordered or systematized. Indeed, they developed a quantum field theoretical model of unlocalized memory in the brain in which a memory storage is nothing but a vacuum state of spontaneous symmetry breaking type. Such a vacuum state is realized as a spatial domain in which all the ingredients manifest a strongly correlated homogeneous configuration up to the quantum fluctuation. In other words, a memory is stored in an unlocalized domain of quantum field theoretical vacuum state just as the Bose-Einstein condensate in the superconducting media. It manifests, therefore, long-range correlation and long-term stability. These very characteristics of the quantum vacuum sate well explain both nonlocal presence and long-term stability of the memory.

The theory of mixed physical system proposed by Umezawa and coworkers seems to be the first approach to develop a physical framework describing the fundamental process of the brain information processing on the basis of conventional physical principles in quantum field theory. Therefore, it may be allowed to call the theory "Quantum Brain Dynamics" and abbreviate it by "QBD".

QBD is nothing but a quantum dynamics of a macroscopic many-body system of two different types of ingredients interacting with the macroscopic neuron system. The first ingredient is called a corticon and assumed to be the fundamental dynamical element of the microscopic system. Corticons are not spatially confined within each neuron. They are distributing both inside and outside of neuronal membrane and constitute rather a fuzzy region of dynamical exchange points. In other words, corticons manifest a global distribution in the whole cell assembly of the brain tissue. The second ingredient is an exchange boson. Corticons show a global distribution in the whole cell assembly of the brain tissue

Umezawa and coworkers have presented an interesting model of memory printing and recalling processes in terms of a long-range ordered vacuum state of the microscopic system of corticons and exchange bosons. Roughly speaking, the memory printing process is nothing but a phase transition process of the QBD vacuum state which is assumed to be of spontaneous symmetry breaking type. The recalling process is, then, merely a creation process of Goldstone mode (or equivalently Goldstone bosons), that is, long-range correlation waves with zero energy requirement.

Within the realm of QBD, it is also shown that the memory stored as a vacuum state of spontaneous symmetry breaking type is rendered unstable due to the quantum tunnel effect. The decay process of the memory is then described by the notion of instanton just as the recall process is by that of Goldstone boson.

The purpose of the present article is to provide the researcher in medical, biological and computer sciences with an introductory exposition of QBD. We avoid, therefore, the use of mathematical notations and equations, and try to make the conceptual aspect of QBD clearer.

2. Why Quantum Field Theory?

Any matter in macroscopic scale is made of as many atomic ingredients as Avogadro's number. It is, therefore, difficult to perform straightforward physical analyses starting from the most fundamental principle of dynamics for atomic ingredients, that is, quantum mechanics. Simpler systems like the harmonic oscillator, the hydrogen atom and the helium plus ion can be solved completely by means of the direct use of quantum mechanics. However, complex systems with more atomic ingredients cannot be solved. Of course, this does not mean incompleteness of quantum mechanics any more. Rather, it is our problem that we cannot find a proper mathematical way to solve the fundamental equation of quantum mechanics, that is, Schroedinger equation or Dirac equation for complex systems.

This difficulty in question has enforced physicists to find appropriate approximations so that certain physical aspect of macroscopic matter may be well understood qualitatively. Knowing or guessing a typical physical aspect of macroscopic matter, physicists look for an approximative way to solve the fundamental equation of quantum mechanics or to describe the typical physical aspect of macroscopic matter by certain phenomenological or heuristic equations easy to handle with. For example, most of the non-living matter in macroscopic scale have a common physical aspect to be described phenomenologically by good old thermodynamics. This typical physical aspect is said to be thermal equilibrium. Then, a systematic approximation adequate for describing or analyzing complex systems of atomic ingredients in thermal equilibrium has been obtained. It is called quantum statistical mechanics or equilibrium quantum statistical mechanics. Most of the theoretical results on physical analyses of non-living matter in macroscopic scale are given within the realm of quantum statistical mechanics. In other words, quantum statistical mechanics got much success in understanding the typical physical aspect of non-living matter in macroscopic scale.

It seems important to notice here what the success of quantum statistical mechanics means. The basic assumption of quantum statistical mechanics is to incorporate an approximative viewpoint that typical physical characteristics of macroscopic matter in thermal equilibrium are same as those of less complex systems of ideal disordered atomic ingredients without mutual correlation. The fact that quantum statistical mechanics got much success in understanding the typical physical aspect of non-living matter in macroscopic scale claims simply the absence of mutual correlation in such matter in actual circumstance. In other words, macroscopic matter in thermal equilibrium can be thought as a complex system of atomic ingredients manifesting completely disordered (i.e., uncorrelated or thermalized) dynamics so that quantum statistical mechanics happens to give appropriate approximations.

Encouraged by the success, quantum statistical mechanics has been a little enlarged so that it may cover complex systems out of but near thermal equilibrium. Then, chemical and biochemical reactions of atomic ingredients have become to fall into the competition of modern physical analysis from which recent molecular biology has been developed extensively. Namely, nowadays medical and biological sciences find their physical and theoretical foundation in quantum statistical mechanics, and provide us with detailed microscopic understanding of certain biochemical processes taking part in living matter. Since few physicists mention explicitly that quantum statistical mechanics is an approximative framework limiting its validity to complex systems of atomic ingredients without mutual correlation, the researcher in medical and biological sciences believes it as the most fundamental physical law also reliable in the analysis of living matter from the microscopic point of view of quantum mechanics.

When famous mathematician von Neumann

saw scientists investigating dynamics of water by using the Euler equation for perfect fluid without viscosity, he laughed and said it as dynamics of "dry" water. Similarly, we should keep it in mind that the picture of living matter investigated by molecular biology and biochemistry in terms of quantum statistical mechanics is not a real one but that of "dry" living matter. The meaning of this warning is that living matter is not a complex system of atomic ingredients without mutual correlation but those with strong mutual correlation. As it has been pointed out by Schroedinger in his famous monumental lecture, (Schoredinger 1944) living matter is characterized to produce negentropy without recourse to incoming information gain. In other words, living matter decreases entropy and increases order even under the supply of energy in completely thermalized and disordered form, whereas non-living matter in thermal equilibrium is with maximum entropy (i.e., disorder). To investigate the correct physical aspect of living matter, therefore, another approximative framework is needed in which complex systems of atomic ingredients with strong mutual correlation can be well described from the fundamental point of view of quantum mechanics. It may be opposite, in a sense, to quantum statistical mechanics in which mutual correlation of atomic ingredients is completely neglected.

The above quite important fact was first emphasized by a physicist H. Umezawa in the early 1960's. He clamed the necessity of emergence of quantum field theory in describing and investigating the typical physical aspect of living matter, because complex systems of atomic ingredients with strong mutual correlation like living matter can not be treated by quantum statistical mechanics but only by quantum field theory. In 1967 he published a monumental paper with one of his Italian colleagues, L. M. Ricciardi in Kybernetik. (Ricciardi and Umezawa 1967) There, focusing on the highly systematized functioning of the brain tissue as the most elaborated example of typical aspects of living matter, emphasis is put on the role of collective mode and Goldstone mode in quantum field theory of complex systems of atomic ingredients with strong mutual correlation. Just as the thermal equilibrium is the key concept in approximative physical analyses of complex systems of atomic ingredients with vanishing mutual correlation by means of quantum statistical mechanics, collective mode and Goldstone mode are the key concepts in those with strong mutual correlation.

3. A Brief History of QBD

Before proceeding to the conceptual exposition of QBD in the succeeding sections, we give here a little bit of history after the original proposal of Umezawa (Ricciardi and Umezawa 1967). Slightly later, another physicist H. Froehlich pointed out also that collective mode or long-range coherent dynamics of atomic ingredients in macroscopic scale may play an essential role in energy storage of biological systems. (Froehlich 1968) Coherent dipolar wave propagation is shown to exist in cytoskeletal structure of the biological cell and exchange energy with the external electromagnetic field. Such a coherent dipolar wave propagation is nothing but a collective mode of many dipolar oscillations maintained by nonlocalized electrons trapped in the one-dimensional chains of protein molecules as well as hydrogen bonds recurring therein. Due to Froehlich's estimation, the coherent dipolar wave propagation realizes a branch of longitudinal electric modes in a frequency region between 10^{11} and 10^{12} sec^{-1}, called Froehlich frequency. Then, it is concluded that energy larger than Froehlich frequency times Planck's constant supplied to the cytoskeletal structure of biological cells is not completely thermalized but stored in a highly ordered fashion. Notice that thermalized energy or heat is the form of energy characteristic to complex systems of atomic ingredients with vanishing mutual correlation.

In 1970's, Umezawa proceeded to developing his original idea to describe the typical physical aspect of living matter in terms of collective mode and Goldstone mode in quantum field theory so that the memory printing and recalling process in the brain can be well investigated with the use of known facts in quantum field theory. In two succeeding papers with his colleagues, C.I.J.M.Stuart and Y. Takahashi, he presented an interesting physical picture of fundamental processes of memory printing and recalling: (Stuart et al. 1978; 1979)

Memory printing is maintained by a physical process of phase transition from disordered dynamics to ordered one of the brain tissue (i.e., cortex) seen as a complex system of atomic ingredients called corticons. Memory recalling is maintained by a physical process of symmetry restoring typical in the ordered dynamics which can be considered as a creation process of Goldstone mode or Goldstone boson. Phase transition from disordered dynamics to ordered one as well as the symmetry restoring process are both central concepts to understand the collective mode and Goldstone mode in quantum field theory.

Much inspired by those results of incorporating quantum field theoretical method of physical analysis into the investigation of living matter initiated by Umezawa and Froehlich in 1960's, several physicists have begun to consider in 1980's biological systems of living matter as complex systems of atomic ingredients with strong mutual correlation in which energy transfer does not suffer from Maxwell's demon, that is, thermalization. They have continued to apply quantum field theory to physical analyses of various fundamental processes taking part in biological systems of living matter and ensured Umezawa's and Froehlich's original ideas. (Davydov 1982; Del Giudice et al. 1982; 1985; 1986; 1988; 1992; Sivakami and Srinivasan 1983; Jibu and Yasue 1993; 1995; 1997a; 1997b) Thanks to those extensive research activities, we are nowadays in the best position to understand various typical physical aspects of living matter from the very fundamental point of view of quantum field theory. QBD is one of many examples of understanding such aspects.

The secondary aim of the present article is, henceforth, to sow in the field of medical and biological sciences the seed of this physicists' new picture of living matter in terms of collective mode and Goldstone mode characteristic to complex systems of atomic ingredients with strong mutual correlation and highly systematized order.

4. Fundamental and Metabolizing Systems of Living Matter

Most of the living matter are known to manifest a specific form of existence, that is, biological cell. It may be understood as the most fundamental element of biological systems. In other words, most of the biological systems including of course the human body are made of biological cells. For the purpose of making our discussion as general as possible, we will consider a typical form of biological system as a macroscopic assembly of biological cells and call it a cell assembly. A biological cell is also a macroscopic structure of living matter which can be considered as a complex system of quite a large number (i.e., Avogadro's number) of atomic ingredients with strong mutual correlation.

From a macroscopic point of view, the biological cell can be regarded essentially as a living matter called cytoplasm confined within a spatial region of macroscopic scale by another living matter called cell membrane. Of course, there exist other macroscopic structures embedded in cytoplasm such as cell nucleus, Golgi apparatus and mitochondria. However, they may be thought as other biological cells cooperating inside the biological cell in question. From a microscopic point of view, cytoplasm is a complex system of water molecules and protein molecules, and cell membrane is that of lipid molecules and protein molecules. The former manifests a dense and dynamical three-dimensional network structure of protein filaments (i.e., one-dimensional chain of protein molecules) called cytoskeletal structure surrounded by water molecules, and the latter a double layered two-dimensional surface structure of lipid molecules patched from both inside and outside by a dynamical two-dimensional network structure of protein filaments. There are many protein molecules embedded in the lipid bilayer of cell membrane which plays the role of active gates for the ionic metabolism of the biological cell. The functioning of those protein gates has been investigated intensively in molecular biology. Nowadays, they are known to control the diffusion process of various ions between inside and outside of the biological cell.

Such a diffusion process of ions is a typical example of completely thermalized (i.e., disordered or incoherent) dynamics of atomic ingredients well described by quantum statistical mechanics. It has been supposed, therefore, to be the most fundamental physical process of living matter in medical and biological sciences. This may be the limit of conventional analyses of biochemistry and molecular biology. For further investigation of the typical physical aspect of living matteruch as the cell assembly, the truly most fundamental physical process should be considered from the fundamental point of view of quantum mechanics.

Since we are not interested in completely thermalized dynamics of the ionic diffusion process as the fundamental physical process of living matter, we look for another possibility starting from the original ideas of Umezawa and Froehlich. Let us neglect all the atomic ingredients taking part in the completely thermalized dynamics of cell assembly, that is, the lipid bilayer of cell membrane and protein molecules embedded therein. Then, a living matteruch as the cell assembly becomes to manifest rather simpler microscopic structure of a huge and dense three-dimensional network of protein filaments surrounded by and interacting with water molecules. We call this structure as the fundamental system of living matter. Comparatively, we call the molecular biologically well-known structure maintaining the completely thermalized dynamics of cell assembly as the metabolizing system of living matter. Thus, the living matter is a mixed system composed of the fundamental system and the metabolizing system. The latter manifests completely thermalized (i.e., disordered and incoherent) dynamics of atomic ingredients playing the role of heat engine to supply energy such as the ATP cyclic process, and well described by quantum statistical mechanics. The former manifests conversely non-thermalized (i.e., ordered and coherent) dynamics of atomic ingredients with strong and long-range mutual correlation the role and characteristic of which is the scope of quantum field theory. The idea that the living matter is from a fundamental point of view of physics a mixed system of coherent dynamics and incoherent dynamics is due to Umezawa. (Ricciardi and Umezawa 1967; Stuart et al. 1978; 1979) There, the fundamental system of the brain tissue as a typical living matter is called the microscopic system, and the metabolizing system is called the macroscopic (physiologically nonclassical) neuron system.

It seems worthwhile to notice here again that both fundamental and metabolizing systems of living matter are made of as many atomic ingredients as Avogadro's number. In this sense, they are both macroscopic systems of extremely many microscopic (i.e., atomic) ingredients. The difference between them appears only in their dynamical characteristics. Namely, the fundamental system manifests ordered dynamics of atomic ingredients with strong and long-range mutual correlation which may be well described by quantum field theory. The metabolizing system manifests disordered dynamics of atomic ingredients with vanishing mutual correlation such as ionic diffusions which has been well investigated by quantum statistical mechanics.

5. Physical Picture of the Fundamental System of Living Matter

Let us investigate the essential characteristic of the fundamental system of living matter. First, we visualize relevant degrees of freedom of the fundamental system of living matter, that is, a huge and dense three-dimensional network of protein filaments surrounded by and interacting with water molecules. Although the network of protein filaments changes its form and connectivity due to spatial motion of protein filaments, such degrees of freedom belong no longer to the fundamental system. This is simply because such a dynamical change of the network structure is driven by disordered dynamics of protein filaments and belongs to the metabolizing system of living matter. Indeed, the dynamical change of the network structure of protein filaments (i.e., cytoskeletal structure) results in protoplasmic streaming. We may be allowed, therefore, to regard dynamics of the fundamental system. Thus, the first degree of freedom we are looking for in the fundamental system of living matter may be found as an internal degree of freedom of the background three-dimensional network structure of protein filaments free from thermalization (i.e., Maxwell's demon).

In 1979 such a degree of freedom was found by Davydov as a coherent dipolar solitary wave propagation along the one-dimensional chain of protein molecules such as the protein filament. (Davydov 1979) In quantum field theory, a coherent solitary wave propagation is considered as a localized degree of freedom maintaining and carrying energy without loss due to thermalization, and it is called Davydov soliton or dipolar soliton. Namely, energy incoming from the metabolizing system of living matter through the ATP cyclic process to the fundamental system of living matter induces first dipolar solitons localized in each protein filament. As a specific character of soliton in quantum field theory, energy stored in soliton form is kept free from thermalization and belongs to the fundamental system of living matter, though creation of soliton is triggered by incoherent and disordered interaction with the metabolizing system. In other words, the creation and annihilation process of dipolar solitons plays the role of a gateway between metabolizing and fundamental systems. The dipolar soliton is a collective mode of many dipolar oscillations maintained by nonlocalized electrons trapped in the one-dimensional chain of protein molecules and may be regarded as the first degree of freedom of the fundamental system of living matter. It is a quantum mechanical degree of freedom representing electric dipole moment localized in each background protein filament. In the case of brain tissue, Stuart et al. (1978; 1979) called it corticon. In the general case of cell assembly, we call it simply dipolar soliton. Thus the first degree of freedom of the fundamental system of living matter is found to be the dipolar soliton localized in each protein filament of the background three-dimensional network structure. It may be well visualized from physical point of view by a quantum mechanical variable representing nonvanishing electric dipole moment localized in each protein filament.

Let us look for the second degree of freedom of the fundamental system of living matter. From materialistic point of view, the fundamental system of living matter is composed of a huge and dense three-dimensional network of protein filaments and enormously large number (i.e., Avogadro's number) of water molecules surrounding it. The former has been thought of as a mere background structure for the fundamental system and plays the role of supporting the existence of the first quantum mechanical degree of freedom, that is, dipolar solitons. The latter is of purely quantum mechanical nature and an enormously large number of atomic ingredients, that is, water molecules, enforces us to rely on quantum field theory. Water molecule, H_2O, is a typical molecule simple in its form but rich in its physical characteristic. The origin of richness can be found, however, in simpleness of its form. Namely, due to the spatial geometric configuration of two hydrogen atoms relative to one oxygen atom, the water molecule manifests nonvanishing electric dipole moment. Thus, the totality of enormously large number of water molecules can be well described from a physical point of view by a quantum mechanical degree of freedom of electric dipole moment moving and rotating freely. This is the second degree of freedom of the fundamental system of living matter. We call it the water dipole moment.

Finally, we have obtained a physical picture of the fundamental system of living matter. It is essentially a quantum mechanical many-body system described by two different degrees of freedom interacting with each other, that is, dipolar solitons localized in the background three-dimensional network structure of protein filaments and water dipole moments surrounding them.

6. What is Quantum Brain Dynamics?

Having obtained a physical picture of the fundamental system of living matter, we are now in the best position to make a conceptual exposition of quantum brain dynamics, QBD. Identifying the corticon in Umezawa's original viewpoint with the dipolar soliton of the fundamental system of brain tissue as a typical living matter, we may visualize the most fundamental physical process providing the brain tissue with a highly systematized functioning within the realm of quantum field theory. Thus, QBD is a completely new theoretical framework to describe the fundamental physical process of the brain dynamics that makes man human on the basis of quantum field theoretical analysis of the fundamental system of brain tissue.

Let us start from the physical picture of the fundamental system of brain tissue with two different degrees of freedom standing for dipolar solitons localized in the background three-dimensional network structure of protein filaments and dipole moments of surrounding water molecules. The first degree of freedom, that is, the dipolar soliton arises from a coherent solitary wave propagation of nonlocalized electron along each protein filament. The dipolar soliton is created at the end of each protein filament by energy gain from the metabolizing system through, for example, the ATP cyclic process.

If we focus on the mere electric dipole moment of the dipolar soliton, we may consider an electric dipole field confined on each protein filament. Once created, such a confined electric dipole field is kept conserved there as long as there exists no other electric dipole moments nearby. However, in the fundamental system of brain tissue, we have the second degree of freedom, that is, electric dipole moments of water molecules surrounding the protein filaments. Then, it is most likely that the electric dipole field on each protein filament is no longer kept conserved and confined thereon but propagate into the spatial region occupied by water molecules. This suggests us the following fact:

As long as we look at the fundamental system of the brain tissue in terms of the electric dipole field, both dipolar solitons and water dipole moments can no longer be different degrees of freedom. In other words, the fundamental system of brain tissue can be well described by a single degree of freedom of electric dipole field spanning the spatial volume of the brain tissue.

Astonishingly, QBD is now translated into QED (i.e., quantum electrodynamics) of the electric dipole field which may be easily supposed to fall into the competition of quantum field theory.

It is found that the principal degree of freedom of QBD, that is, corticon is not merely the dipolar soliton as was expected at first sight but also the water dipole moment surrounding the protein filaments. The corticon in QBD is now fully described by the electric dipole field (of both dipolar solitons and water dipole moments) spanning the spatial volume of the brain tissue. In this sense, we may call the fundamental system of brain tissue simply as the system of corticons, hereafter. Considering the physical background of the electric dipole field as those of dipolar solitons and water dipole moments, we may assume that the electric dipole field manifests symmetry under rotation. Namely, even if the electric dipole field on each position is rotated by any spatial angle, the total energy of the system of corticons is kept invariant. In quantum field theory, the total energy of the system of any field quantity plays an important role in specifying dynamics of the field, and it is usually called Hamiltonian. So, we call the total energy of the system of corticons as the Hamiltonian of the system of corticons or equivalently the Hamiltonian of QBD. Then, we obtain the following invariant or symmetry property:

The system of corticons in QBD manifests a symmetry under the rotation of the electric dipole field in a sense that the Hamiltonian of QBD is invariant.

At this point it seems easy to answer the question "What is QBD?" tentatively. QBD is nothing but QED of the electric dipole field with symmetry under the dipole rotation.

7. Collective Mode and Goldstone Mode

This section is devoted to an exposition of two basic concepts in quantum field theory, that is, the collective mode and the Goldstone mode which play the most important roles in understanding the fundamental physical process of QBD providing the brain tissue with the highly systematized functioning.

Let us consider the system of corticons in QBD. Recall that it is nothing else but the totality of as many atomic ingredients with electric dipole moments as Avogadro's number. Then, a naive question may arise naturally:

We may have certainly a non-living matter made of as many atomic ingredients with electric dipole moments as Avogadro's number. It is essentially living and thinking about the beginning of our universe?

The answer is, of course, negative. It is neither living nor thinking about. As we have emphasized in the preceding section 2, the living matteruch as the brain tissue is the totality of atomic ingredients with strong mutual correlation, whereas the non-living matter is that with vanishing mutual correlation. In other words, the non-living matter made of as many atomic ingredients with electric dipole moments as Avogadro's number has a typical physical aspect that it manifests disordered dynamics well described by quantum statistical mechanics. There, each atomic ingredient with electric dipole moment manifests a time evolution irrespective to the precise time evolutions of neighboring ones but only respective to the energy transfer between them. Thus, the neighboring electric dipole moments cancel out mutually, obtaining no net electric dipole field any more. Conversely, the living matter made of as many atomic ingredients with electric dipole moments as Avogadro's number has a different typical physical aspect that it manifests ordered dynamics well described by quantum field theory. There, each atomic ingredient with electric dipole moment manifests a time evolution strongly correlated to the precise time evolutions of neighboring ones. In such a peculiar situation, the neighboring electric dipole moments no longer cancel out, but accumulate to their collective value. Such a collective value of strongly correlated neighboring electric dipole moments given in each position provides us with the electric dipole field which is nothing but the principal degree of freedom of the system of corticons in QBD. This is the very reason why we should rely on quantum field theory to understand the fundamental physical process taking part in the fundamental system of living matteruch as the system of corticons.

Let us investigate the fundamental physical process of the system of corticons by means of the electric dipole field arising from the ordered collective dynamics of atomic ingredients with electric dipole moments within the general framework of quantum field theory. We refer to Stuart et al. (1979) and Del Giudice et al. (1985), though the essential framework had been originally developed by Ricciardi and Umezawa (1967).

In quantum field theory, the simplest way to describe the electric dipole field is given by a spinor field. It is a two-component complex field usually described by a two by one matrix form. The spinor field itself does not correspond directly to the collective value of electric dipole moments. In the spinor representation, dynamical variables providing us with the electric dipole moment are the Pauli spin matrices. The electric dipole moment of the electric dipole field is then given by first multiplying the spinor field by the Pauli spin matrices and then multiplying the result by the conjugate spinor field. Thus the spinor field does not stand for the electric dipole moment, but it represents physically the field of molecular vibrations of protein filaments and water molecules in the brain tissue from which the electric dipole field arises. (Del Giudice et al. 1985) Therefore, the spinor field of molecular vibrational field is more essential than the electric dipole moment itself.

The corticon in QBD described by the electric dipole field of both dipolar solitons and water dipole moments is thus found to be essentially described by the spinor field of molecular vibrations of both protein filaments and water molecules spanning the spatial volume of the brain tissue. Therefore, we may be allowed to call the spinor field the corticon field. Recall that any physical quantity such as the electric dipole moment is given by an expectation of certain function of field variables over possible field configurations characterized by a ceratin proper value of the Hamiltonian (i.e., the total energy function) in quantum field theory. In the present case of the corticon field, the electric dipole moment is the expectation of a quantity given by first multiplying the spinor field by the Pauli spin matrices and then multiplying the result by the conjugate spinor field. Then, the invariant or symmetry property of the system of corticons in QBD under the rotation of the electric dipole field may be translated into that of the corticon field. For this aim, we present in what follows the quantum field theoretical framework of the system of corticons in terms of the corticon field.

The system of corticons in QBD is represented by the corticon field. The Hamiltonian, that is, the total energy of the system of corticons is then given by a certain functional of the corticon field, possibly depending on its both spatial and temporal derivative. The symmetry property of the system of corticons in QBD implies that the Hamiltonian is invariant under the group of dipole rotation. In terms of the corticon field, such a rotation group can be well represented by the SU(2) group of complex two by two unitary matrices with determinants equal to unity. Since we are mainly interested in the symmetry structure of the system of corticons in QBD, we will not specify the explicit form of the Hamiltonian as a functional of the corticon field, but concentrate on its invariant property under the SU(2) group. In other words, the present investigation of QBD remains general and independent of the details of the dynamics.

Those who are interested in the explicit form of the Hamiltonian are invited to see the appendices of Stuart et al. (1979).

Let us see the typical physical aspect of the system of corticons in QBD which may explain the highly systematized functioning of the brain tissue. For this aim, we focus on the dynamics of corticons corresponding to the minimum proper value of the Hamiltonian. Dynamics of corticons with larger proper value of the Hamiltonian will be easily investigated on the basis of that with the minimum one. In quantum field theory, such a dynamical state of the system is said to be the lowest energy state or the vacuum state. The vacuum state of the system of corticons (i.e., the corticon field) in QBD violates its original dynamical symmetry structure under the SU(2) group of dipole rotations. Such a vacuum state is said to be of spontaneous symmetry breaking type. There, corticons are all fallen into a uniform configuration of their electric dipole moments up to the quantum fluctuation, and so the original dynamical symmetry under dipole rotations is broken.

The vacuum state of the corticon field may be well characterized by the presence of nonvanishing uniform electric dipole moment. We call this uniform electric dipole moment characteristic to the vacuum state of the corticon field the vacuum polarization. It represents the mean value of the uniform electric dipole moment of every dipolar soliton and water molecule aligned along one and the same direction. In this sense, the system of corticons in the vacuum state of spontaneous symmetry breaking type manifests a typical physical aspect that it creates a long-range (i.e., large-scale) order in its dynamics. Namely, there exists a long-range order so that the corticon field is systematized globally to realize the uniform configuration of electric dipole moment. Umezawa and coworkers used the expression "macroscopic ordered state" to refer to large-scale phenomena of order creation whose occurrence cannot be explained without recourse to the action of specific quantum field theoretical mechanisms responsible for the spontaneous rearrangement of the symmetry attributes of the system. Thus, the vacuum state of the corticon field in QBD is a typical macroscopic ordered state.

It is known from the Goldstone theorem in quantum field theory that in any macroscopic ordered state, cooperative excitations of the symmetry attributes appear as long-range correlation waves and behave as bosons (i.e., quanta obeying the Bose-Einstein statistics) whose minimum energy is zero. They are called Goldstone bosons or Goldstone modes. Since the Goldstone boson manifests a continuous energy spectrum above zero, it is also called a gapless mode because there exists no energy gap in the spectrum. It is nothing else but the action of the corticon field in the vacuum state accounting for the rearrangement of symmetry attributes leading to the creation of a macroscopic order with long-term stability and nonlocal presence.

Dynamics of the corticon field in the vacuum state of spontaneous symmetry breaking type is a typical example of peculiar physical aspect called the collective mode in quantum field theory. Namely, the corticon field manifests highly ordered dynamics as aligning all the electric dipole moments of corticons along one and the same direction up to the quantum fluctuation. It is a static collective mode of the corticon field which does not change in time. In general, the collective mode of a certain field stands for a cooperative dynamics of the field variable which is highly systematized and synchronized. The collective mode provides us with an appropriate approximative framework to describe the typical physical aspect of a complex system of atomic ingredients with strong mutual correlation such as living matter. Thus, the collective mode of the corticon field is a typical dynamical aspect of the system of corticons with strong mutual correlation in which every corticon manifests one and the same dynamical configuration. If we translate by analogy this quantum field theoretical concept of the collective mode into our familiar concept, it may be compared with the synchronized swimming. Just as you find a collective movement of a team of synchronized swimmers as a single large-scale ordered state of the team, the collective mode of the corticon field behaves as a distinct physical entity and the precise dynamical factors of the atomic ingredients on which its existence depends can be neglected.

More adequate analogy to understand the typical aspect of the vacuum state of spontaneous symmetry breaking type in QBD may be found in physics of magnetized matter as well as superconducting matter. For example, spontaneously magnetized matter is a complex system of as many atomic ingredients as Avogadro's number in which magnetic dipole moment of each atomic ingredient is aligned spontaneously along one and the same direction.

In QBD the vacuum state of the corticon field violating the original SU(2) symmetry of the dipole rotation appears as a macroscopic ordered state and behaves itself as a distinct physical entity. It may be seen as a macroscopic spatial domain of the brain tissue in which nonvanishing electric dipole moment distributes uniformly up to the quantum fluctuation. Such a domain of the vacuum state cannot be arbitrary small because a considerable number of atomic ingredients must take part in forming the macroscopic ordered state. Any collective mode requires the strong mutual correlation of a large number of atomic ingredients, and it cannot appear when the domain of organization is too small. The minimum linear dimension (i.e., size) of the domain for realizing the macroscopic ordered state such as the vacuum state is called the coherence length. It seems worthwhile to notice that consequently the vacuum state of QBD can only appear in a spatial domain with linear dimension larger than the coherence length. Umezawa emphasized this fact as saying that the order is intrinsically diffused. In other words, the fundamental system of the brain tissue manifests a macroscopic dynamical structure made of nonoverlapping large-scale spatial domains in which the nonvanishing vacuum polarizations exist. Therefore, the fundamental physical process of the fundamental system of the brain tissue may be well investigated by taking the dynamical action of the vacuum state of the corticon field against the energy supply into account. This is the very reason why the concept of Goldstone mode becomes so important in QBD. The Goldstone mode is nothing but a wave of defects of the corticon field from the vacuum polarization created by any amount of the energy supply from the metabolizing system of the brain tissue. It appears as a new degree of freedom carrying the original symmetry property of the corticon field with respect to the SU(2) group of dipolar rotations. Thus, taking the symmetry property of Goldstone modes, the system of corticons in QBD ensures again the original symmetry even though its vacuum state remains of spontaneous symmetry breaking type. The broken symmetry is now restored by the creation of Goldstone bosons.

8. Memory as Vacuum State of the Corticon System

Having seen the two basic concepts in quantum field theory, that is, the collective mode and the Goldstone mode, we proceed to investigating the fundamental physical process of QBD which provides the brain tissue with the highly systematized functioning. More precisely, we introduce an interesting scheme of the information processing of the brain in terms of the phase transition from a disordered state to an ordered one of the system of corticons in QBD.

Let us start by recalling the essential framework of QBD explained in the preceding sections:

The brain tissue is a mixed physical system composed of the fundamental system and the metabolizing system interacting with each other. The latter is the molecular biologically well-known structure maintaining the completely thermalized dynamics of the brain tissue which plays the role of input and output interface between the fundamental system and the external world of the human body. It is the neuronal network associated with the disordered electrochemical processes such as transmembrane ionic diffusions, and represents the communication mode in which stimuli from and responses to the external world are transmitted in a macroscopically organized fashion. The fundamental system manifests a quantum interaction among corticons from which macroscopic ordered states are realized as collective modes in quantum field theory accounting for the creation of memory with long-term stability and nonlocal presence. Those macroscopic ordered states are vacuum states of spontaneous symmetry breaking type maintained by the Goldstone boson. There, dynamics of macroscopic ordered states arising from the cooperative quantum interaction among corticons is directly responsible for the fundamental physical process from which emerge the highly systematized functioning of the brain.

A new mechanism for memory has been presented by Umezawa and coworkers in which the two systems are necessarily coupled in order to achieve memory printing and recall. (Ricciardi and Umezawa 1967; Stuart et al. 1978; 1979) The coupling is given in QBD by the creation of dipolar solitons in the microscopic protein filaments triggered by the energy supply from the ATP cyclic process which protect memory in stable form against excitations with the communication mode.

We consider in what follows how the mechanism proposed by Umezawa can account for the highly systematized functioning of the brain associated with memory:

Let us start with the fundamental system of the brain, that is, the system of corticons where memory of a specific stimulus from the external world is yet to be printed. The brain tissue is here exposed to stray signals including unattached perception of external events as well as activity associated with general physiological events such as motor activity and the like. Those stray signals are organized and transmitted to the system of corticons through the metabolizing system (i.e., the neuronal network). Namely, they can create corticons indirectly in the fundamental system, and various spatial domains of the macroscopic ordered states are formed provided that the created corticons manifest a long-range correlation whose spatial extent is larger than the coherence length. Thus, there exist apparent thresholds for the incoming energy from the metabolizing system to the fundamental one to create ordered domains. The stray signals to the brain tissue transmitted with energy slightly exceeding the threshold value are all tacitly coded in the dynamical domain structure of macroscopic ordered states in the small domains. Notice that in such a dynamical structure the direction of electric dipole moments of the corticon field can randomly vary from domain to domain and there exists no hierarchy among the coded signals.

The learning process can be identified with the phase transition of the system of corticons from the less ordered state of many but small ordered domains to the more ordered state of a few but large ordered domains. Such a phase transition is induced by an external stimulus which supplies the system of corticons with enough energy to break domain boundaries of many small ordered domains, thus aligning the electric dipole moments of the corticon field in much larger domains. Of course, the notion of external stimulus denotes an energy flow organized and transmitted through the metabolizing system. We obtained quite an interesting point of view of the fundamental physical process of QBD that may be understood as the learning process of a typical signal from the external world. It seems worthwhile to notice here that the phase transition requires the onset of the aligning process of the electric dipole moments which goes through an interaction between the external stimulus and the Goldstone boson. This implies a fact that the external stimulus can induce the phase transition from the less ordered state to the more ordered one only when it can interact with the Goldstone bosons and the interaction energy is sufficiently large to break the domain boundaries. In other words, there exists a filter such as the selection rule for the coupling of transmitted signals to the system of corticons in which stray signals have been coded in the domain structure. Stuart et al. (1978) saw there inherent limitations on learnability for the brain tissue.

By such a learning process, a typical external stimulus can be printed in the system of corticons of the fundamental system as a stable macroscopic ordered state. There, the external stimulus is coded into the vacuum state of the corticon field manifesting a large-scale uniform alignment of the electric dipole moments along one and the same direction. The stability of printed memory comes from the very fact that it is coded into the vacuum state of the corticon field the stability of which is a consequence of quantum field theory. Apparently, printed memory manifests nonlocal (i.e., diffused) existence.

Once memory of a typical external stimulus is printed in the macroscopic ordered state of the system of corticons, it can be recalled quite easily thanks to the Goldstone bosons. Namely, when the system of corticons receive even a weak signal of a nature similar to that used in the learning process, it can excite the gapless Goldstone mode of the vacuum state corresponding to printed memory. The recalling process is nothing but a creation process of Goldstone bosons (i.e., long-range correlation waves) with almost no energy requirement. They play the role of a replication signal of the original external signal. In this way, the existence of printed memory can be taken into account by consciousness. Consciousness in QBD means the quantum field theoretical dynamics of the system of corticons itself. Thus, any weak external signal can recall printed memory, and it take part in consciousness. It is implicit to this view that recall involves the stimulation of those parts of the metabolizing system of the brain that were once excited to organize and transmit external signals during the original learning process. It seems also worthwhile to point out that a weak external stimulus might interact with two or more kinds of Goldstone bosons, the recalling more than one stored code. This may explain the association in the recall process.

9. Quantum Decay Process of Memory

The most important concept in QBD is the vacuum state of spontaneous symmetry breaking type as we have seen in the preceding section. In quantum field theory, a system with the Hamiltonian which is invariant under some continuous transformation group like the system of corticons is known to have infinitely many vacuum states. Furthermore, those vacuum states are not the true vacuum state which must be the unique proper state of the Hamiltonian with the lowest proper value of energy. Each of them is an approximative vacuum state of the system in which the field variable manifests the smallest deviation from a classical minimum energy solution. In the terminology of quantum field theory, they are coherent states around classical field configurations corresponding to different energy minima. Each vacuum state can be transformed into another by the symmetry transformation. Therefore, those vacuum states are in general not invariant under the original symmetry transformation of the Hamiltonian. They are of spontaneous symmetry breaking type.

As Umezawa and coworkers have shown, each vacuum state of the system of corticons plays the role of memory storage in QBD. It is important to see the fact that the vacuum state of spontaneous symmetry breaking type is capable of creating Goldstone bosons with zero energy requirement. This means that the stored memory code can be easily excited during the recall process and it contributes to other fundamental physical processes of the fundamental system of the brain tissue by means of Goldstone bosons. In this way the existence of a memory can be "consciously" taken into account in the information processing of the brain. The fact that the system of corticons in QBD has infinitely many vacuum states of spontaneous symmetry breaking type implies an infinite capacity of memory coded and stored in the brain. The whole fundamental system of the brain tissue is divided into extremely many ordered domains of vacuum states, and Goldstone bosons corresponding to those vacuum sates take part in the quantum field theoretical dynamics of the corticon field, that is, consciousness. Thus memory coded in the vacuum state affects always the further development of consciousness because of its long-term stability. It may be concluded, therefore, that the memory codes stored in the vacuum sates of the system of corticons will never be lost, which seems not the case in the actual functioning of the brain. However, the symmetry property of the system of corticons in QBD does provide us with a more realistic feature of the memory codes as being rendered unstable due to the quantum tunnel effect. The memory code is no longer stable completely if we take the vacuum tunneling phenomena of the corticon field into account. Let us see this by restricting our discussion to a typical spatial domain of the vacuum state.

Suppose that after a ceratin learning process the system of corticons in this domain has fallen into a vacuum state, say vacuum state A, that breaks the original symmetry of the system spontaneously. It is a memory code which can be easily recalled by the creation process of Goldstone bosons. As we have mentioned before, it is not a true vacuum state of the corticon field from the strict point of view of quantum field theory, but an approximative one standing for a classical field configuration with minimum energy. This means that the vacuum state A is no longer invariant under the time evolution of the system of corticons driven by the Hamiltonian. As the time passes, the vacuum state A is put into another state, say state B, which differs from the vacuum state A. Only the exact vacuum state remains always the same vacuum state as the time passes. Then, the probability that the actual state B of the system of corticons is found to be in another vacuum state, say vacuum state C, is given by the absolute square of the inner product of the state B and the vacuum state C in quantum field theory. Since the actual state B is not the vacuum state, the inner product in question does not vanish. Namely, the system of corticons in this domain may happen to be in another vacuum state C with nonvanishing probability. This is the quantum tunnel effect. It is also a decay process of a vacuum state storing a memory code into another which stores a meaningless code having nothing to do common with the original memory code. In quantum field theory, such a quantum decay process of vacuum state due to the quantum tunnel effect can be thought of as the onset of a new quantum field theoretical mode called instanton. We may conclude in QBD that the memory codes stored in the ordered domain structure of vacuum states of the system of corticons are rendered unstable due to the tunnel effect and the decay process of printed memory is described by the creation process of instantons just as the recall process is by that of Goldstone bosons.

It may be of certain interest, though speculative at this moment, to interpret the virtual dynamics of instantons as the fundamental physical process corresponding to the dream. A dream is a virtual action of consciousness based on the actual memory codes but resulting in irrelevant memory codes which cannot be reached by the normal action of consciousness. The dream is not a causal event at all. This empirical fact on the typical aspect of the dream may be compared with that of virtual dynamics of instantons. Namely, dynamics of instantons is a virtual physical process starting from the actual vacuum state but ending with an irrelevant vacuum state by the quantum tunnel effect which cannot be transformed by the normal and causal physical process of QBD. In this sense, the quantum decay process of the vacuum state is said to be a virtual physical process. The virtual dynamics of instantons triggered by the quantum tunnel effect is not a causal event at all.

10. Beyond QBD

So far we have restricted our discussion mainly to the fundamental physical process of QBD which provides the brain tissue with a highly systematized functioning. However, the concept of macroscopic ordered state of the atomic ingredients can be equally taken into serious consideration in investigating the typical physical aspect of the fundametal system of living matter other than the brain tissue. Indeed, the original idea of Umezawa was aimed to incorporate the quantum field theoretical framework to the investigation of living matter emphasizing the fact that they are systems of as many atomic ingredients as Avogadro's number with strong and long-range mutual correlation. Ordered collective dynamics of such systems cannot be well described by the framework of conventioanl quantum statistical mechanics but only by that of quantum field theory. It was pointed out also by Froehlich that collective mode or long-range coherent dynamics of atomic ingredients in macroscopic scale may play an essentail role in energy storage of biological systems. (Froehlich 1968) There, emphasis has been put on certain macroscopic physical characteristics of living matter arising from the interaction between the collective mode of the fundamental system of living matter and that of the external electromagnetic field. As such a collective mode appears as a domain structure of macroscopic ordered states it can be coupled only with a long-range coherent wave mode of the external electromagnetic field. Incoherent and disordered excitations of the electromagnetic field cannot interact with the collective mode of the fundamental system of living matter. In other words, they are stray electromagnetic waves which cannot penetrate into the domain of a macroscopic ordered state. This is an effect similar to the Meissner effect of the superconducting matter in which the stray electromagnetic field cannot penetrate into the superconducting matter.

The non-living matter can manifest the collective coherent dynamics only when the disordered and incoherent dynamics of atomic ingredients disappear by annihilating the thermalized (i.e., disordered) energy as lowering the temperature to the absolute zero degree. Superconducting matter is a typical example. However, living matter is capable of maintaining the collective coherent dynamics of the atomic ingredients even in the higher temperature environment. Living matter has a two-fold structure of as many atomic ingredients as Avogadro's number, that is, the fundamental and metabolizing systems. The latter manifests the disordered and incoherent dynamics, while the former the ordered coherent one. The stray electromagnetic waves can interact only with the metabolizing system, thus providing the living matter with the thermalized energy. The fundamental system of living matter couples with only collective and long-range coherent modes of the electromagnetic field which are nothing but coherent photons like those emitted from the LASER device. This implies that the living matter may interact with each other by emitting and absorbing coherent photons even though they are separated by a macroscopic spatial distance. Such phenomena are nowadays known as biophotons or ultraweak photon emissions. More interestingly, the meridian flow of Qi (vital energy /pneuma), which is the central dogma of the Chinese and Japanese traditional medicine, is reported to emit a weak but coherent electromagnetic wave in the infrared frequency region and affect other person's meridian flow of Qi at a distance. Such a photon emission by the meridian flow of Qi is considered as a physical basis of the yunqi therapy in the Chinese and Japanese traditional medicine:

The yunqi therapy is the curing of disorders through the passing of Qi from a person of much oder (doctor) to another of disorder (patient) without bodily contact.

Although some remarkable experimental results on the phenomena caused by the meridian flow of Qi have been obtained and reported, most of researchers in medical and biological sciences are still in doubt about the existence of meridian flow of Qi in human body or any other biological systems. The reason is clear:

There seems to be no room for the Qi flow in our modern scientific languages from the molecular biological point of view. The reported experimental results are of phenomenological and macroscopic nature and do not give any impact to the conventional realm of modern medical and biological sciences fully based on nowadays physical knowledge about the microscopic molecular picture of biochemical processes of metabolism.

It is our opinion that the quantum field theoretical investigation of collective modes of the fundamental system of living matter introduced in the present article focussing mainly on the brain may well provide us with a reliable and concrete physical foundation of the meridian flow of Qi. It will open a new field of research in medical and biological sciences from which we could derive a better understanding of the question. "What is life?" This field, though yet to be developed, deserves to be called "Quantum Biodynamics" and abbreviated again as "QBD."

11. Outlook

It seems of much importance now to let the neuro- and cognitive scientists know the truth: it is needed to rely on quantum theory even if physical phenomena of matter and light in the macroscopic scale are concerned. Of course, the brain is not the exception, and intensive researches from the very fundamental point of view of quantum theory will be respectable. (Pribram 1991; Jibu and Yasue 1995; Jibu et al. 1996; 1997) It has been widely believed in neuro- and cognitive sciences that the brain can be understood as a macroscopic object governed not by quantum physics but by classical physics or at most by molecular and chemical biologies.

Recently, several ambitious theories are proposed which aim at explaining such basic features of consciousness as "unity (binding problem)," "qualia," "non-algorithmic processing," "synchrony" and "free will" in terms of quantum theoretical concepts. (Penrose 1989; 1994; Hameroff 1987; Eccles 1986) In most cases, quantum theoretical concepts are quoted from quantum mechanics, and the famous conceptual difficulties of quantum mechanics such as "nonlocality," "superposition of states," "uncertainty principle," "reduction or collapse of wave function (state)," "EPR-paradox," "non-separability," "Bell's theorem" and "measurement by abstract ego" are put into heavy use.

However, it must be warned strongly that quantum mechanical concepts are necessarily restricted to the highly idealistic cases of microscopic objects imperceptible directly by our consciousness. As most of neuro- and cognitive scientists believe, the brain is a macroscopic object open to its noisy thermal surroundings, and a naive application of those quantum mechanical concepts to the brain might be hardly accepted. Neverthless, in the present paper, it is emphasized that incorporation of quantum theory into the investigation of brain functioning is an inevitable turning point of the consciousness research. Here, unlike those recent ambitious theories, quantum theory means not quantum mechanics but quantum field theory that provides us with the first principle of modern physics. (Umezawa 1993; Jibu and Yasue 1995; Vitiello 2001)

It may be true that consciousness would not fall yet into the competition of modern scientific activity because of difficulty to elucidate any defining aspects. Among a few defining aspects of consciousness frequently focused on in neuro- and cognitive sciences, we may restrict our discussion to "unity" or "binding problem." This is because unity is the most consistently identified defining aspect of consciousness capable of approaching from the fundamental scientific framework of theoretical physics. The long-standing difficulty of understanding the origin and mechanism of unity of consciousness (as a unified self) has been called the binding problem in neurophysiology: What is it that controls and unifies all the physico-chemical processes taking part in the stratified society of brain cells?

We may suppose in QBD that quantum electromagnetic phenomena play essential roles in realizing unity of the stratified society of brain cells spanning hierarchically from molecular biology of neural networks to chemical biology of cytoskeletal networks and extracellular matrices. The binding problem must be solved not by introducing the idealistic quantum mechanical nonlocality but by investigating the usually neglected quantum electromagnetic phenomena taking place in the dynamically ordered regions (i.e., perimembranous regions) of intracellular and extracellular water. There, each brain cell is enfolded within a common field of macroscopic condensation of evanescent photons and all the physico-chemical processes taking part in the stratified society of brain cells are subject to the control and unification by quantum electrodynamics. Unity of consciousness thus arises from the existence of the global field of condensed evanescent photons overlapping the whole brain tissue in the cranium. The origin and mechanism of EEG (i.e., electroencephalogram, brain wave) may be explained within the same quantum electrodynamical framework of QBD. (Jibu et al. 1997)

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