The Journal of Mind and Behavior
Spring and Summer 1997, Volume 18, Numbers 2 and 3
Pages 195 [93] – 204 [102]
ISSN 0271–0137
ISBN 0–930195–08–6

# Nonlinear Brain Systems With Nonlocal Degrees of Freedom

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Quantum degrees of freedom greatly enrich nonlinear systems, which can support nonlocal control and superposition of states. Basing my discussion on Yasue's quantum brain dynamics, I suggest that the Cartesian subject is a cybernetic process rather than a substance: I am nonlocal control and my meanings are cybernetic variables. Meanings as nonlocal attunements are not mechanically determined, thus is it concluded we have freedom to mean.

Over the last ten years connectionism has advanced to at least parity with the traditional notion of computation as logical processing of symbolic representations. In connectionist neural networks, "representations" are distributed rather than being local strings of atomic elements, and logic is replaced by an optimization principle (e.g., minimize the computational energy of the neural net [Hopfield and Tank, 1986]). (The much noted "self-organizing" property of neural nets is a consequence of optimization.) According to Smolensky (1988), logical computation can only approximate the neural network result (and not so gracefully either, it should be added, but by a brute mechanical force that intuitively seems alien to human existence). It remains unclear in the current debate whether processing by neural nets is going to supplement or replace conventional symbolic computation as a model of brain functioning.

Connectionist neural network theory arose in part out of nonlinear thinking by physicists (e.g., spin glass theory [Shaw, Silverman, and Pearson, 1985]). The attribution of chaos to neural nets (e.g., Skarda and Freeman, 1987) reinforced the nonlinear direction. The neural network is conceived

I thank Kunio Yasue for discussions on quantum brain dynamics and Chris King for his thoughtful comments on the manuscript. Requests for reprints should be sent to Gordon G. Globus, M.D., 360 San Miguel Drive, Suite 603, Newport Beach, California 92660.

along these lines to be a nonlinear dynamical system evolving under constraint. Here input is not information to be processed, but *a constraint on system dynamics*. This radical shift in the understanding of the role of input has not been widely appreciated however, given the hold that traditional thought maintains over our current conceptions. This conventional view is that input to the net has a distributed representation . . . that this information is processed while in distributed form . . . that the computational result is the attractor state into which the self-organizing system settles . . . from which system output is derived. What the net is supposed to achieve by computation, then, is mapping of an input vector to an output vector. The difference from symbolic computation is only that representations are distributed rather than local strings, and processing is self-organizing rather than logical.

But against the tradition, operations are not performed on the input information to get a result; instead the input *participates* in constraining the network evolution, one among many constraints, including memory and cognitive conditions of satisfaction; computation is just the wrong model (Globus, 1992). The system evolution is *steered* by the constraints, so cybernetics[1] is called for. This means a radical move away from information processing to optimal control theory for self-optimizing, autopoietic, autorhoetic systems (Globus, 1995a).[2]

So according to my version of history, connectionism is an incomplete nonlinear revolution with respect to computationalism. Old ideas about information processing have been dragged along, so that there is obscuration of the proper notion of a nonlinear system spontaneously evolving under both constraint and a principle of optimization. This history has been overtaken, however, by the revolutionary new ideas of quantum neurophysics (e.g., Hameroff, 1987, 1994; Penrose and Hameroff, 1995; Yasue, Jibu, and Pribram, 1991.) The lift-off article in the area of quantum neurophysics is that of Ricciardi and Umezawa (1967).

Suppose the nonlinear system just discussed has quantum nonlocal degrees of freedom. Such admission of highly peculiar quantum properties calls for a

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[1]Cybernetics is an interdisciplinary approach to the study of control and communication in both biological organisms and machines. The term is derived from the Greek *kybernetes*, which means "steersman."

[2]Optimization can be based on Hamilton's "least action" principle in classical dynamics [Yasue, Jibu, Misawa, and Zambrini, 1988], as elaborated below. Autopoiesis is the spontaneous self-forming and self-maintenance of system boundaries [Maturana and Varela, 1980], an upsurge of formative activity. The autopoietic system compensates for perturbations that may roil it. Autorhoesis is the spontaneous self-flowing characteristic of the system which arises from the self-tuning of constraints [Globus, 1995a]. If the constraints are adjusted through self-tuning, the system spontaneously changes state, due to the fundamental physical optimization principle of least neural action.

dynamics described by a nonlinear version of the Schrödinger wave equation, that is, a neural wave equation for nonlinear brain systems (Yasue, Jibu, Misawa, and Zambrini, 1988; Yasue, Jibu, and Pribram, 1991). Nonlinear quantum systems may also underlie neurodynamic chaos (King, 1991). Yasue formulates optimization here as minimization of the neural Lagrangian operator (which is a quantity of energy associated with the velocity and acceleration of ionic currents in the perimembranous region surrounding neural membranes). New capabilities are permitted when nonlinear brain systems have quantum degrees of freedom, such as nonlocal control and interpenetration (quantum "superposition") of states. Nonlocal degrees of freedom greatly enrich nonlinear systems.

## Quantum Brain Dynamics

Jibu and Yasue (1995) have recently provided an introduction to a version of quantum brain theory called quantum brain dynamics (QBD). QBD presents an alternative to the dominant conceptions in the brain and cognitive sciences, which consider neurons organized into networks to be the basic constituents of the brain. In QBD brain biosubstrates support quantum field phenomena, and the resulting strange quantum properties are used to explain consciousness. This change of perspective results in a radically new vision of how the brain functions.

I shall present an overview of QBD and extend it to cognition and perception here. Yasue and coworkers base quantum brain dynamics in the first physical principles of quantum field theory, as formulated by Umezawa (1993). This Umezawa/Yasue (U/Y) line of thought should be sharply distinguished from other approaches to quantum brain theory. Stapp (1993), for example, traces his lineage to Heisenberg's understanding of quantum mechanics in which the unobservable quantum mechanical wave function (whose evolution is given by the famous Schrödinger equation) collapses. I shall accordingly call this line of thought "H/S." In the contrasting U/Y view, there is no wave function collapse; instead all of reality has a quantum field description, whether "microscopic" objects like electrons and photons or "macroscopic" objects like measuring instruments. Umezawa (1993) was especially interested in macroscopic objects (which are obtained by a certain transformation of the quantized field, called the Bogoliubov transform). No "collapse" is involved here; instead the macroscopic object is a mean envelope structure of coherent quanta.

Now among the macroscopic objects at the level of quantum field reality, there are some that are brains-embedded-in-human-bodies. These brains (for short) have a variety of *biosubstrates that are quantum field supporting*. Thus the brain, like other macroscopic objects, has a quantum field description and on top of that, brain biosubstrates uphold quantum fields of great richness. A stone can't hoist quantum fields — and there goes its chance for consciousness. Recognition of the crucial role of quantum fields hoisted by brain biosubstrates steers between the extremes of panpsychism, in which everything is conscious, and an arbitrary demarcation of where consciousness begins in evolution. Quantum fields hoisted by brain biosubstrates are the *sine qua non* of consciousness.

One model of how the autopoietic (self-forming and self-maintaining) brain could hoist a quantum field is as follows. Imagine an ultra-thin layer of "soup" consisting of water molecules and charged particles (ions) immediately on either side of the neuronal membrane. This shallow soup is partitioned by the membrane, which is semipermeable, being riddled with channels that open and close under neurochemical and electropotential control. Ions flash back and forth through the membrane channels down electrical and chemical gradients, and ionic currents loop through the partitioned soup. The state of the ultra-shallow perimembranous soup is accordingly given by the ionic density distribution and its action by a function of the velocity and acceleration of looping ionic currents. A "plasma" forms in this perimembranous soup in which charged particles interact with the electromagnetic field. Quantum phenomena result (such as superconductivity within the perimembranous bioplasma and the formation of Josephson junctions at synapses on the membrane [Jibu, Pribram, and Yasue, in press]). So the thin bilayers of bioplasma in the perimembranous regions are of a quantum nature. Other candidate quantum field-supporting biosubstrates are ordered water molecules in the microtubules, which support super-transparency and super-radiance (Jibu, Hagen, Hameroff, Pribram, and Yasue, 1994), membrane lipoproteins, which support quantum coherence (Fröhlich condensation; see Fröhlich, 1968), and an immensely intricate nanolevel web of protein filaments which weaves inside and outside of neurons and neuroglia, and supports quantum coherence (Jibu and Yasue, 1995) and soliton formation (Davydov, 1978). (See also Hameroff [1987, 1994] and Penrose and Hameroff [1995] on microtubules.)

According to this view, not only do brain biosubstrates spontaneously generate and sustain quantum fields, but the brain also arranges for *quantum field interactions*. In quantum field interaction, the phase waves over the fields interfere with one another. Out of that interference, a real order is formed (as when a complex number is multiplied by its conjugate).

I have proposed that the quantum fields supported by different brain biosubstrates have different functional roles, namely, representation of the reality outside of the brain, memory and cognition (Globus, 1995b, in press). Out of the interaction between the quantum representative of reality and quantum cognition/memory, observables appear. (This is a quantum version of Neisser's [1976] dictum that perception is where cognition [schemata] and reality meet.) *Perception is the result of quantum field interactions autopoietically sustained by brain substrates.*

To summarize, brain biosubstrates sustain quantum fields serving reality, memory, and cognition (and other functions, e.g., emotional, which are neglected here). Perception is the product of these quantum field interactions. Input–output nonlinearity is due to the fluctuating intrinsic constraint (cognition/memory).

## A Vexing Problem Resolved?

A way of thinking about reality, cognition, memory and perception has been offered above within the QBD framework (see also Globus, 1995b, in press). This nonlinear way of thinking is alternative to the computational view (whether linear or nonlinear) in which the brain processes information (whether logically, by self-organizing, or some combination thereof). For the present way of thinking, reality, cognition and memory constrain the evolution of an autopoietic and autorhoetic, nonlinear dynamical system. The difference between these ways of thinking is radical enough that "scientific revolution" has been claimed (Globus, 1995a).

Having developed a quantum way of thinking about brain functioning and mental processes, we now want to see if anything has been gained. For example, is any outstanding problem resolved? Now, one of the most vexing problems that bedevils our thought is that "I"[3] has agency, yet no controller can be found by science (McGinn, 1995). (The controller is the notorious "ghost in the machine" [Ryle, 1949], spectator at the "Cartesian theater" [Dennett, 1991].) Despite enormous philosophical efforts over the years to explain "I" away — see, for example, Dennett's (1991) recent laborings — our strong intuition of "I" persists well beyond the conventions of language. "I" am "infinitely near," as Sartre (1957) puts it, yet despite this nearness, we cannot circle round "I" and specify "I's" location. "I" is tightly coupled to a particular location but doesn't seem to have the kind of properties that would make it locatable there.

The problem is that this intuitive conviction as to the existence of the subject conflicts with the completeness of science, since the subject is not captured within science's nomological net. It would be very nice if a scientific description of a full-fledged "I" could be given, while stifling the cry of

[3]When I use the quotes "I," I mean it to extend to subjectivity across individuals. So each person can read "I" for herself or himself, and should do so, to mitigate against *Seinsvergessenheit* (the forgetting of Being that characterizes modernity).

"category mistake!" Otherwise the subject must be denied, to save ontology. The key to accomplishing a scientific description of subjectivity, as we shall see, is to think of "I" as a nonlocal process.

It was noted above that in QBD there is a shift from the information processing framework to that of optimal control. Quantum fields entering into the interaction exercise control on the system's evolution. The control here is *nonlocal*, distributed over a region and exercised instantaneously (not confined to the speed of light). Control is in virtue of a phase wave over the field that is not real and so can't be localized — but can be mathematically described using complex numbers, or equivalently in the wave (rather than the geometric) formulation, using sines and cosines to represent phase. *Optimal control of nonlinear brain systems under quantum cybernetics is irreducibly global.*[4]

So the nonlinear brain systems with quantum degrees of freedom described above are under nonlocal control. We may also describe self-agency as nonlocalizable control, which has heretofore been physically so mysterious that we have been inclined to dualism. An explanation of self-agency by the nonlocal cybernetics of quantum brain systems is tempting, but this would still be a category mistake, mixing experiential and scientific descriptions. More carefully put (to avoid the category error), *being* a quantum brain system with nonlocal cybernetics is to *have* nonlocalizable control which is experienced as self-agency. Each person can properly say: *I am nonlocal control.* The categorical incompatibility between "I" and science thus moves toward resolution, since QBD makes room for a control that can't be located — which is just what we mean by "I's" agency.

*"I" am a cybernetic process*, then, not a Cartesian substance, and the proper scientific context is optimal control of a spontaneous, autopoietic and autorhoetic, nonlinear dynamical process, rather than computation. The cybernetic process varies, depending on the changing phase waves over the interacting quantum fields. The etymology of "cybernetic" (from the helmsman of a ship) is misleading in the quantum context, because the phase waves do not steer in the way that the helmsman at the wheel turns the ship. Instead the quantum fields of cognition and memory offer interpenetrated possibilities to the match with input, and perception results from the quantum field interference.

The suggestion that "I" am a nonlocal cybernetic process can be further elaborated. We might say that the "shape" of the control varies — but "shape" is a classical term, ill-suited for Schrödinger-like wave functions,

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[4]In terms of West's "Tutorial," quantum cybernetics violates the principle of "superposition." (This should not be confounded with the quantum sense of superposition.)

whose mathematical representation, as noted, requires the complex plane (i.e., there is an "imaginary" axis). As the phase wave varies, control varies. On the interpretation developed above, this means: as phase varies, possibilities (offered to the match with input) are tuned. Cognitive acts tune nonlocalizable phase waves. The quantum attunement is an interpenetration of likely possibilities, offered to the interaction with reality and memory.

The nonlocal cybernetic process tunes phase and thereby controls the possibilities. I have previously interpreted tuned possibilities as meanings (Globus, 1995a). In the intentional act, certain prescriptive conditions of satisfaction are included (Husserl's (1913/1960) "noemata"). Searle's (1983) conditions of satisfaction define a possibility which may or may not be matched; if matched by reality, the possibility is actualized. On the present interpretation, meanings are attunements of certain brain quantum fields whose interaction with other brain quantum fields results in perception. Thus the horizon of interpenetrated meanings within which we operate is a phase wave over a neural quantum field that participates in an interaction with other phase waves over other neural quantum fields, out of which perception takes place.

Meanings qua phase waves are "holistic" in a deep sense. Meaning holism goes back famously to Saussure (1966) for whom concepts are nodes in a network and are not properly considered in isolation, which of course well-fits connectionism. But on the quantum interpretation, concepts are not node-like but interpenetrated in the whole. The process is not one of local nodes interacting with nodes elsewhere located and coming to a pair-wise consensus under given constraints. Instead interpenetrated concepts are global over the attuned whole. On the present account, then, each person can properly say: *I am nonlocal control and my meanings are cybernetic variables*.

To summarize, I have presented some key ideas of Yasue and coworkers' quantum brain dynamics (QBD) and extended them to encompass "I," cognition and, to a lesser extent, perception. To be autopoietic and autorhoetic, nonlinear brain systems with quantum degrees of freedom is to have nonlocal control, i.e., self-agency. "I" am no longer problematic because consistent with science. Furthermore, new ways of thinking about meaning were developed, also consistent with science. To be such a brain with intrinsically generated phase waves over quantum fields is to have meanings which are interpenetrated conditions of satisfaction for the match with other phase waves (especially noteworthy, with the representative of external reality via sensory input). This offers a fresh way of thinking about meaning which is different from computationalism, whether symbolic or connectionistic.

## Are Meanings Free or Determined?

The Cartesian subject is newly justified when nonlinear brain systems have quantum degrees of freedom (justified, as we have seen, by identifying the subject with nonlocal control). One wonders how another deep persisting problem — freedom of the will — might fare in a quantum context. However, discussion of free will is so encumbered by an enormous literature — see Dennett's (1984) *Elbow Room* for a lucid analysis of the issues — that I think it better to consider a closely related question: Are we free to mean? Or are our meanings strictly determined?

In the quantum neurophysical account developed above, to mean this or that is to be attuned this or that way in the quantum field interactions. The issue is whether or not the attunement is determined. The answer has already been given: the attunement entails quantum nonlocality, hence indeterminacy (see also Penrose's [1989, 1994] arguments on the noncomputability of consciousness). Nonlocal attunement (described by a Schrödinger-like wave function) falls outside of mechanical causality; it's not conceivable within classical mechanism. Nonlocal attunement is noncomputable because it does not consist of interrelated pieces. So cognition is as free from mechanical necessity as either quotidian dualism or postmodernism might want. Cognition comes from nowhere — but that doesn't mean it's not physical; the cognitive is quantum physical. All along the problem has been that "I" and my mental acts aren't *classically* physical, but now we can see how they might be *quantum* physical, so the classical duality of the mental and the physical begins to dissolve. "I" am the quantum process of nonlocal control.

This opening for freedom should not lull us into *Seinsvergessenheit* (Heidegger, 1982), that is, a forgetting of Being, for the present case, forgetting what it is to be a nonlinear brain system with quantum degrees of freedom embedded in the human body. To exist thus is to have nonlocal control and to have meanings which are not mechanically determined. It is a mistake to identify "I" and cognition with brain systems under quantum description: it is *being* those systems that is so identified, which is to have nonlocal control denoted by "I" and nonlocal control variables denoted by "my meanings." The mental is no longer categorically incompatible with the physical, once quantum degrees of freedom are admitted to nonlinear brain systems whose biosubstrates hoist interacting quantum fields.

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The Journal of Mind and Behavior
Spring and Summer 1997, Volume 18, Numbers 2 and 3
Pages 205 [103] – 228 [126]
ISSN 0271–0137
ISBN 0–930195–08–6

# Magic Without Magic: Meaning of Quantum Brain Dynamics

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A theoretical framework called "Quantum Brain Dynamics" to describe long range ordered dynamics of the quantum system of electromagnetic field and water dipole field in the brain is proposed as a revival of the original idea developed by Umezawa in the early 1960s. Based on Umezawa's world view of quantum field theory, the manifestation of long range ordered dynamics is a macroscopic object of quantum origin, and so it reveals the existence of specific macroscopic objects in the brain called "tunneling photon water." Tunneling photon water is shown to manifest several interesting quantum phenomena involving coherent photon emission and transmission, and is suggested to play an important role in quantum brain dynamics. The ordered quantum dynamics of such a macroscopic condensate of tunneling photons with nonvanishing effective charge and mass as tunneling photon water is governed by the macroscopic Schrödinger equation, and ensures superconducting phenomena in the brain at body temperature. The meaning of quantum brain dynamics is clearly explained for brain and cognitive scientists who have been confused by either (a) the overstatement with misplaced quantum concepts usually given by those not appropriately schooled in physics or (b) the understatement with textbook quantum concepts given by technical physicists.

The recent increase of discussions concerning the incorporation of quantum physics into the fundamental researches of brain and cognitive sciences seems to result in a somewhat unfortunate situation: good brain and cognitive scientists begin to question the quantum theoretical approach to consciousness research due to either overstatement of misplaced quantum concepts usually given by those not appropriately schooled in physics (i.e.,

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so-called "physicians") or understatement utilizing textbook quantum concepts given by technical physicists who are only "users" of quantum physics. Consequently, many brain and cognitive scientists begin to believe "they use quantum approaches to consciousness because quantum theory is mysterious and consciousness is mysterious." Unfortunately, it is easy and natural to believe this statement if one sees the intensive activity of those not appropriately schooled in physics in popular publications. Quantum physics begins to look like astrology. Therefore, for the purpose of making the present bad situation a little better it is necessary to make a brief but solid exposition of the true quantum theoretical approach to consciousness research given by a few fundamental physicists who are "deep explorers" of quantum physics. We wish to contribute this paper toward that aim.

## Modern World View of Quantum Field Theory

Matter is revealed to be constituted of energy quanta of certain matter fields spreading over the whole of space and changing in time within the realm of quantum field theory. Light was already known to be constituted of energy quanta of the electromagnetic field also spreading over the whole of space and changing in time. Today, it is agreed that quantum field theory provides the first principles of physics from which all the natural phenomena in this universe are derived and explained theoretically (Umezawa, 1993).

It is astonishing that even the very presence of macroscopic objects (see Appendix) common in our daily experience cannot be well understood without recourse to quantum field theory (Umezawa, 1993), although this has been dismissed by many scientists. Even among physicists it is misunderstood that the basic laws of quantum mechanics and quantum field theory reduce to those of Newtonian mechanics and Maxwellian electromagnetism as the Planck constant simply goes to zero: as classical physics describes matter and light in the macroscopic scale of our daily lives. There, it has been misunderstood that classical physics suffices to investigate the various properties of matter and light in the macroscopic scale, and quantum mechanics and quantum field theory have no role to play. Hence, it may be natural that people may not believe the necessity of incorporating quantum theory into the research of brain functioning, simply because the brain is a macroscopic object.

The most fundamental theory of modern physics is provided by quantum field theory. Starting from the basic principles of quantum field theory, indeed, the whole framework of quantum mechanics can be derived by an approximation scheme valid in a restricted case of finite-number of quanta. Furthermore, classical field theory and classical mechanics can be also derived from the basic principles of quantum field theory by another approximation scheme valid in the different case of condensations of quanta in macroscopic ordered states (Umezawa, 1993). In other words, the very existence of macroscopic objects can be understood only within the realm of quantum field theory. A naive point of view, that macroscopic objects are all governed by the basic principles of classical mechanics and classical field theory, is nothing more than a phenomenological hypothesis given by our direct perception of natural phenomena involving such objects. All the natural phenomena involving both microscopic and macroscopic objects must be described starting from the first principles of theoretical physics, that is, the fundamental principles of quantum field theory (Umezawa, 1993).

From the fundamental point of view of quantum field theory, macroscopic objects familiar to our direct perceptions are all manifestations of certain kinds of order: such as the crystal order, magnetic order, superconducting order, life order and so on. Of course, "order" (which means here a certain systematic pattern of dynamics of quanta of certain fields) might not be a complete order, and there are many macroscopic defects in any macroscopic object (Umezawa, 1993). Among macroscopic objects, seen as manifestations of certain kinds of order in the macroscopic scale, a macroscopic domain structure of defects or disorder would appear depending on the specific interactions between the quanta. Thus, macroscopic objects manifest a trade-off between order and disorder, and result in the large variety of forms or "phases" perceptible by our consciousness.

The brain is indeed a typical macroscopic object extraordinary in its functioning as it gives rise to highly advanced mental "objects" such as consciousness (plus unconscious), mind, memory and will. It is the custom in brain and cognitive sciences to regard the brain as a tissue made of a huge number of brain cells, and many phenomenological theories of brain functioning based on the macroscopic picture of electric and chemical circuits of brain cells take into account various mesoscopic aspects of the brain cell revealed by molecular biological studies (Alberts et al., 1994).

Molecular biology is a branch of biophysics developed phenomenologically by gathering the fragmentary knowledge of molecule-based organic chemistry, quantum chemistry and quantum statistical mechanics. Patching those fragments into a single system of knowledge is made by the long standing and excellent intuitions of biologists. Nevertheless, molecular biology does not succeed in explaining the essential aspects of the brain functioning directly related to the highly advanced mental "objects." Considering the fact that the brain is the highest example of living matter, it might be obvious that we should investigate the brain by considering it as a macroscopic object in ordered phases (see Appendix) [Ricciardi and Umezawa, 1967; Stuart, Takahashi, and Umezawa, 1978, 1979; Umezawa, 1993]. Thus the shortcoming of brain and cognitive sciences is clarified: one must depend on the new biophysics derived from the basic principles of quantum field theory so that the essential features of the brain as a macroscopic object in ordered phases can be better understood.

## Macroscopic Objects in Brain: Water and Electromagnetic Field

Quantum brain dynamics, a new biophysics of brain derived from the basic principles of quantum field theory, is a unified theoretical framework of macroscopic objects of quantum origin applied to the brain (Umezawa, 1993). Here, the term macroscopic objects means not only macroscopic matter, such as a stone, but also macroscopic field, such as the electromagnetic field carrying electromagnetic waves. Our first task is to find the key macroscopic objects of quantum origin that play important roles in quantum brain dynamics.

Matter and light have been revealed to be constituted by energy quanta of certain fields spreading over the whole of our universe (Lawrie, 1989). As long as we investigate low-energy physical phenomena such as life phenomena of living matter, we can think of only three fields; electromagnetic field, electron field, and nucleon field. Waves of the electromagnetic field described by the fundamental principles of quantum field theory are called energy quanta of electromagnetic field or simply photons. Those of the electron field are called energy quanta of electron field or simply electrons. Those of the nucleon field are energy quanta of nucleon field or simply nucleons (i.e., protons and neutrons). These three fields are coupled with each other, and there thus exist many kinds of coupled waves which are nothing but the microscopic constituents of matter called atoms and molecules. Among the many kinds of coupled waves, a specific kind of coupled wave, called water, constitutes 70–80% of living matter. Those constituting the remaining 20–30% are the large variety of coupled wave called biomolecules, which have been and continue to be the principal subjects of conventional biophysics. The brain, as a macroscopic object, is thus made of three different parts; water, biomolecules, and electromagnetic field.

It is important to emphasize again the following: (a) there exists an incorrect perception that the quantum system has only microscopic manifestations: as has been shown by Umezawa (1993), the manifestation of macroscopic ordered states is of quantum origin; (b) when we recall that almost all of the macroscopic ordered states are the result of quantum field theory, it seems natural to assume that macroscopic ordered states in biological systems are also created by a similar mechanism.

Water is well known in everyday practice but unknown from the fundamental point of view of theoretical physics. Indeed, the conventional molecular dynamics approach from quantum statistical mechanics fails to reveal the essential aspect of water as a macroscopic group of water molecules, though the quantum mechanical analysis of the so-called water molecule,

$H_2O$, can explain the electron states, molecular vibrational states and molecular rotational states of each $H_2O$ molecule. Thus, water might be more than a mere group of water molecules. Water might be a macroscopic object in ordered phases, because macroscopic objects in ordered phases manifest in general the specific feature of not simply being an aggregation of elements.

To see that water is a macroscopic object in ordered phases, we need to investigate quantum dynamics of water starting from the first principles of physics, that is, basic principles of quantum field theory. Fortunately, such an investigation was intensively conducted by Del Giudice, Doglia, and Milani (1982) and Del Giudice, Preparata, and Vitiello (1988). In these studies the interaction between water and electromagnetic field is described within the realm of quantum field theory. Water is nothing but a macroscopic bound state of many electrons and nucleons interacting with electromagnetic field. What is peculiar to water is the fact that this macroscopic bound state of electrons and nucleons creates a quantum electric dipole in each point of a macroscopic spatial region occupied by this bound state, that is, water. In other words, the macroscopic bound state of electrons and nucleons constituting water can be seen as a quantum electric dipole field. Therefore, the dynamics of water can be well described by investigating the interaction between the quantum electric dipole field and quantized electromagnetic field, and this description certainly falls into the accepted conceptions of quantum field theory.

## Quantum Electrodynamics of Ordered Water

Taking into account the nature of matter that constitutes the brain, we arrive at a simple physical picture of brain as an interacting quantum dynamic of two fields: that is, the quantum electric dipole field of water, hereafter called the water dipole field, and the electromagnetic field. This physical picture may be the first approximation of quantum brain dynamics, since all other microscopic ingredients of the brain are treated as simply an external system playing a role of giving boundary conditions to the system of the water dipole field and the electromagnetic field. It is a familiar and powerful strategy in quantum field theory to investigate first the major part of the system in question, then to proceed to the next major part of the remaining system, and so on. A theoretic metaphor which might help the reader understand the development of the parts or dynamics of the quantum consciousness story is that of holonomic brain theory. In holonomic brain theory perceptual phenomena are erected in the brain by means of complex frequency, amplitude, and phase patterns of interference among microdendritic networks (Pribram, 1991; Vandervert, 1993; Vandervert, this issue). In this paper we hope to develop the necessary quantum theoretical dynamics of consciousness by first developing the major part of quantum brain dynamics (Del Giudice, Doglia, and Milani, 1982; Del Giudice, Preparata, and Vitiello, 1988; Jibu and Yasue, 1992, 1993a, 1993b, 1995; Ricciardi and Umezawa, 1967; Stuart, Takahashi, and Umezawa, 1978, 1979).

In the following equations we will develop the basis for describing the water dipole field in quantum field theory. Like any other quantum electric dipole field, the water dipole field can be represented by a two-component spinor field (see Appendix).

$$\psi(\mathbf{x},t)=\begin{pmatrix} \psi^{+}(\mathbf{x},t) \\ \psi^{-}(\mathbf{x},t) \end{pmatrix},$$

where $\psi^{+}(\mathbf{x},t)$ and $\psi^{-}(\mathbf{x},t)$ are spinor components. The electric dipole moment of the water dipole field is then given by

$$\tilde{\psi}(\mathbf{x},t)\frac{\hbar}{2}\sigma\psi(\mathbf{x},t),$$

where $\psi(\mathbf{x},t)=(\psi^{+}(\mathbf{x},t)^{*}\ \psi^{-}(\mathbf{x},t)^{*})$ is the adjoint spinor field, $\sigma=(\sigma_1,\sigma_2,\sigma_3)$ is a vector with three components equal to Pauli spin matrices (see Appendix), and $\hbar$ denotes the Planck constant divided by $2\pi$.

The water dipole field manifests localization of electric dipole moment in a sense that $\psi(\mathbf{x},t)\neq 0$ only in each position $\mathbf{x}=\mathbf{x}_m$ of the $m^{\text{th}}$ manifestation of localization. Such a localization of the water dipole field has been regarded as a molecule of water, that is, an $H_2O$ molecule, though a naive picture of water as a mere group of $H_2O$ molecules more than Avogadro's number (see Appendix) fails to completely describe quantum dynamics of water. What is needed is a correct description of water in terms of the water dipole field manifesting more localizations than Avogadro's number. The water dipole field with M localizations can be described by M quantum dynamical variables

$$\tau^{m}=\tilde{\psi}(\mathbf{x}_m,t)\sigma\psi(\mathbf{x}_m,t), \qquad m=1,2,3,\cdots,M$$

These quantum dynamical variables $\tau^{m}$'s are not Pauli spin matrices but still subject to the same commutation relations as those satisfied by Pauli spin matrices:

$$\left[\tau_1^{m}(t),\tau_2^{j}(t)\right]=2i\tau_3^{m}(t)\delta_{mj}$$
$$\left[\tau_2^{m}(t),\tau_3^{j}(t)\right]=2i\tau_1^{m}(t)\delta_{mj}$$
$$\left[\tau_3^{m}(t),\tau_1^{j}(t)\right]=2i\tau_2^{m}(t)\delta_{mj}$$

where $[A,B] \equiv AB - BA$, $\tau^m(t)=(\tau_1^m(t),\tau_2^m(t),\tau_3^m(t))$, $i^2=-1$ and $\delta_{mj}$ is Klonecker's delta symbol meaning

$$\delta_{mj} = \begin{cases} 1 & \text{if } m=j \\ 0 & \text{if } m \neq j \end{cases}$$

In the following equations we will develop the bàsis for describing the electromagnetic field in quantum field theory. Let us consider the electromagnetic field confined in a spatial region of volume V containing water. The quantum dynamics of the electromagnetic field is usually described in terms of a vector field called vector potential of the electromagnetic field. The electric and magnetic fields can be derived from the vector potential. Let

$$\mathbf{A}(\mathbf{x},t)=(A_1(\mathbf{x},t),A_2(\mathbf{x},t),A_3(\mathbf{x},t))$$

be the vector potential of the electromagnetic field. According to the canonical quantization procedure in quantum field theory, we introduce an eigenmode expansion of the vector potential

$$\mathbf{A}(\mathbf{x},t)= \sum_{\lambda=1}^{\infty} a_\lambda(t)\mathbf{u}_\lambda(\mathbf{x}).$$

Here, $\{\mathbf{u}_\lambda(\mathbf{x})\}_{\lambda=1}^{\infty}$ denotes a complete normalized orthogonal system of vector-valued functions defined on the spatial region V subject to the eigenvalue equation

$$\left(\Delta+\frac{\omega_\lambda^2}{c^2}\right)\mathbf{u}_\lambda(\mathbf{x})=0$$

together with a subsidiary condition

$$\nabla \cdot \mathbf{u}_\lambda(\mathbf{x}) =0$$

and appropriate boundary conditions. Here, $\omega_\lambda$ is a positive constant standing for the eigenvalue of the eigenmode of the electromagnetic field represented by the eigenfunction $\mathbf{u}_\lambda(\mathbf{x})$, and c denotes the speed of light. We assume for simplicity that the vector potential is linearly polarized, obtaining $\mathbf{u}_\lambda(\mathbf{x}) = \mathbf{e}u_\lambda(\mathbf{x})$, where $\mathbf{e}$ is a constant vector of unit length pointing in the direction of linear polarization.

In the following equations we will show that the quantum dynamics of the electromagnetic field is properly described by the Hamiltonian operator. In quantum field theory, $a_\lambda(t)$ and its complex conjugate $a_\lambda{}^*(t)$ are identified with the annihilation and creation operators up to the multiplicative factor, and it is convenient to introduce the canonical operators $P_\lambda(t)$ and $Q_\lambda(t)$ satisfying the following relations:

$$a_\lambda(t) = \frac{1}{\sqrt{2\hbar}}\left\{\sqrt{\omega_\lambda}\, Q_\lambda(t) + \frac{i}{\sqrt{\omega_\lambda}} P_\lambda(t)\right\}$$

$$a_\lambda{*}(t) = \frac{1}{\sqrt{2\hbar}}\left\{\sqrt{\omega_\lambda}\, Q_\lambda(t) - \frac{i}{\sqrt{\omega_\lambda}} P_\lambda(t)\right\}$$

As long as those dynamical variables $P_\lambda(t)$ and $Q_\lambda(t)$ are regarded as canonical operators, quantum field theory assumes the canonical commutation relations:

$$P_\lambda(t)Q_\nu(t) - Q_\nu(t)P_\lambda(t) \equiv [P_\lambda(t), Q_\nu(t)] = -i\hbar\,\delta_{\lambda\nu} \tag{1}$$

$$P_\lambda(t)P_\nu(t) - P_\nu(t)P_\lambda(t) \equiv [P_\lambda(t), P_\nu(t)] = 0 \tag{2}$$

$$Q_\lambda(t)Q_\nu(t) - Q_\nu(t)Q_\lambda(t) \equiv [Q_\lambda(t), Q_\nu(t)] = 0 \tag{3}$$

Starting from the canonical operators subject to the canonical commutation relations, quantum dynamics of the electromagnetic field can be properly described by the Hamiltonian operator; that is, the total energy of the electromagnetic field expressed in terms of the canonical operators,

$$H_{\mathrm{EM}} = \frac{1}{2}\sum_{\lambda=1}^{\infty}\left\{P_\lambda(t)^2 + \omega_\lambda^2 Q_\lambda(t)^2\right\}. \tag{4}$$

This Hamiltonian operator describes the quantum dynamics of only the electromagnetic field. Therefore, the first approximation of quantum brain dynamics, that is, the quantum dynamics of the water dipole field and electromagnetic field interacting with each other, will be completed after obtaining the Hamiltonian operators describing the quantum dynamics of the water dipole field and its interaction with the electromagnetic field.

In the following equations we will establish the total Hamiltonian operator which describes the first approximation of quantum brain dynamics. As for the water dipole field, the Hamiltonian operator can be approximated to be

$$H_{\mathrm{W}} = \varepsilon \sum_{m=1}^{M} \tau_3^m(t) \tag{5}$$

as long as higher energy excitations are irrelevant to macroscopic objects in ordered phases. Here, $\varepsilon \approx 200\text{cm}^{-1}$ is a positive constant standing for the minimum amount of excitation energy of each localization of the water dipole field. The interaction between the water dipole field and the electromagnetic field can be described by the Hamiltonian

$$\begin{aligned} H_I &= -f\sum_{m=1}^{M}\sum_{\lambda=1}^{\infty}\left\{a_\lambda^*(t)\tau_-^m + \tau_+^m(t)a_\lambda(t)\right\} \\ &= -f\sum_{m=1}^{M}\sum_{\lambda=1}^{\infty}\sqrt{\frac{2}{\hbar}}\left\{\sqrt{\omega_\lambda}\,\tau_1^m(t)Q_\lambda(t) - \frac{1}{\sqrt{\omega_\lambda}}\tau_2^m(t)P_\lambda(t)\right\} \end{aligned} \tag{6}$$

where $\tau_\pm^m \equiv \tau_1^m \pm i\tau_2^m$ are ladder operators in energy spin space of water dipole field, and $f$ denotes the coupling constant between the water dipole field and the electromagnetic field which is nothing but the electric dipole moment of water. Then the total Hamiltonian operator describing the first approximation of quantum brain dynamics is given by the sum,

$$H = H_{EM} + H_W + H_I \tag{7}$$

denoting the total energy of the system of water dipole field and electromagnetic field interacting with each other.

In the following equations we will show that this total Hamiltonian operator, which governs the quantum dynamics of the electromagnetic field and the water dipole field interacting with each other, remains invariant under the transformation of canonical variables given by

$$\begin{aligned} Q_\lambda'(t) &= Q_\lambda(t)\cos\theta - \frac{1}{\omega_\lambda}P_\lambda(t)\sin\theta \\ P_\lambda'(t) &= \omega_\lambda Q_\lambda(t)\sin\theta + P_\lambda(t)\cos\theta \\ \tau_1^{m\prime}(t) &= \tau_1^m(t)\cos\theta + \tau_2^m(t)\sin\theta \\ \tau_2^{m\prime}(t) &= -\tau_1^m(t)\sin\theta + \tau_2^m(t)\cos\theta \\ \tau_3^{m\prime}(t) &= \tau_3^m(t) \end{aligned} \tag{8}$$

for a continuous parameter $\theta$. This transformation corresponds to a continuous rotation around the third axis in energy spin space and can be regarded as belonging to the continuous group *SO(2)* of rotations in two dimensions. In the first approximation of quantum brain dynamics as the system of water dipole field and electromagnetic field, it is shown that the system manifests a dynamical symmetry property represented by a compact Lie group of rotation. It is this dynamical symmetry property that makes the system of water dipole field and electromagnetic field rich in macroscopic structure of order.

Let us look for a time-independent solution to the Heisenberg equations for the canonical variables in order to investigate the dynamically ordered state of the system of the electromagnetic field and the water dipole field in the region V. The Heisenberg equations are given by

$$\begin{aligned} \frac{dQ_\lambda(t)}{dt} &= \frac{1}{i\hbar}[Q_\lambda(t), H] \\ \frac{dP_\lambda(t)}{dt} &= \frac{1}{i\hbar}[P_\lambda(t), H] \\ \frac{d\tau_1^m(t)}{dt} &= \frac{1}{i\hbar}[\tau_1^m(t), H] \\ \frac{d\tau_2^m(t)}{dt} &= \frac{1}{i\hbar}[\tau_2^m(t), H] \\ \frac{d\tau_3^m(t)}{dt} &= \frac{1}{i\hbar}[\tau_3^m(t), H] \end{aligned} \tag{9}$$

and the time-independent solution is obtained as follows up to quantum fluctuations:

$$\begin{aligned} P_\lambda(t) &\equiv 0 \\ Q_\lambda(t) &\equiv Q_\lambda^0 \\ \\ \tau_1^m(t) &\equiv v \\ \tau_2^m(t) &\equiv 0 \\ \tau_3^m(t) &\equiv w \end{aligned} \tag{10}$$

Here, $Q_\lambda^0$ is a constant taking different values for each different eigenmode $\lambda$, and $v$ and $w$ are also constants. Each spin variable $\tau^m=(\tau_1^m,\tau_2^m,\tau_3^m)$ describing the m$^{th}$ localization of the water dipole field is found to be aligned in one and the same direction given by a constant vector $(v,0,w)$. Such a long range alignment of spin variables is nothing but a manifestation of a dynamical order of the system of quantized electromagnetic field and water dipole field. Namely, there exists a long range order so that the spin variable is systematized globally in the region V to realize a uniform configuration.

It is interesting to note that this time-independent solution, representing a dynamically ordered state of the system of quantized electromagnetic field and water dipole field in the region V, is no longer invariant under the continuous transformation of canonical variables (8). The direction of alignment is transformed into another direction under such a continuous rotation around the third axis. Thus, a strange situation is realized in which the total Hamiltonian operator, which governs the quantum dynamics of canonical variables, is invariant under a certain compact continuous transformation, whereas it admits a stable time-independent solution which is not invariant under the same transformation. In quantum field theory, such a situation is known as spontaneous symmetry breaking, and several interesting quantum phenomena are known to emerge (Umezawa, 1993). Namely, the Nambu–Goldstone theorem in quantum field theory asserts that in such a situation of spontaneous symmetry breaking, 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 (Umezawa, 1993). 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 or massless boson because there exists no energy gap in the spectrum.

In the actual case of the system of the quantized electromagnetic field and the water dipole field, the spin variables related to the electric dipole moment of the water dipole field are aligned uniformly in a dynamically ordered state of a spontaneous symmetry breaking type. Goldstone bosons created with near vanishing energy requirements are nothing but quanta of long range correlation waves of aligned electric dipoles. Such Goldstone bosons can be created by even very weak perturbations and can propagate over distances up to the coherence length of about $50\mu m$. It is found in quantum brain dynamics that the Nambu–Goldstone theorem assures the existence of specific macroscopic objects in the brain realized by ordered states of quantized electromagnetic field and water dipole field interacting strongly with each other. If the emphasis is put on matter, such a macroscopic object may be understood as an ordered water in the brain. If the emphasis is put on light, on the other hand, such a macroscopic object can be seen as being made of virtual photons enveloping the water dipole field. In terms of Goldstone bosons, furthermore, we can see such a macroscopic object as a macroscopic condensate of Goldstone bosons.

## Fast Phenomena (see Appendix): Superradiance

In the following equations it is argued that the collective dynamics of the water dipole field can give rise to cooperative emission of coherent photons given energy by structured biomolecules. We are mainly interested in the ordered collective behavior of quantum dynamics of electromagnetic field and water dipole field in the region V. Let us introduce therefore collective dynamical variables $S_\lambda^\pm(t)$ and $S(t)$ for water dipole field by

$$S_\lambda^\pm(t) \equiv \sum_{m=1}^{M} \tau_\pm^m(t) u_\lambda(\mathbf{x}_m) \text{ and } S(t) \equiv \sum_{m=1}^{M} \tau_3^m(t).$$

Then, the total Hamiltonian (7) becomes

$$H = H_{EM} + \varepsilon S(t) - f \sum_{\lambda=1}^{\infty} \{a_\lambda{}^*(t) S_\lambda^-(t) + S_\lambda^+(t) a_\lambda(t)\} \tag{11}$$

It seems worthwhile to note that the total Hamiltonian operator for the system of M localizations of water dipole field and electromagnetic field in the region V is essentially of the same form as Dicke's (1954) Hamiltonian for the laser system. Therefore, it might be expected that water in the region V should manifest a laser-like coherent optical activity. Inspection of the form of the total Hamiltonian (11) reveals that it manifests a dynamical symmetry property not evident in the ground state, so that the resulting quantum dynamics is known to involve certain long range order creating phenomena due to spontaneous symmetry breaking (Ricciardi and Umezawa, 1967; Stuart, Takahashi, and Umezawa, 1978, 1979). The spatial dimension of this long range order, that is, the coherence length $\ell_c$, is estimated to be inversely proportional to the energy difference $\varepsilon$, or $\ell_c \approx 50\mu m$. Among the long range order-creating phenomena we may find a specific one in which the collective dynamics of the water dipole field in the spatial region of linear dimension up to $50\mu m$ can give rise to cooperative emission of coherent photons given energy by certain systems external to the quantum system of electromagnetic field and water dipole field.

Let us consider the system of structured biomolecules in brain cells that can provide the quantum system of electromagnetic field and water dipole field with energy. About 20–30% of the brain is made of a variety of structured biomolecules, especially proteins forming the cytoskeletal structure plus lipids forming the membrane structure. There exist typical protein molecules which manifest relatively large electric dipole moments due to their own intrinsic electron states. The more geometrically structured such protein molecules are, the larger the total electric dipole moment becomes. Therefore, it seems reasonable to take into account only the highly structured protein molecules in the cytoskeletal structure of brain cells as the external system of the quantum system of electromagnetic field and water dipole field in the brain. Microtubules (see Appendix) are such protein molecules which manifest a common highly geometrical structure of hollow cylinder about 25 *nm* in diameter whose wall is a polymerized array of protein subunits called tubulins having a dynamical degree of freedom of electric dipole. The length of a microtubule may range from tens of nanometers to micrometers.

For simplicity, we consider the microtubule as a hollow cylinder with radius $r_{MT} \approx 12nm$ and length $\ell_{MT} \approx 10^2$–$10^3 nm$. The spatial region V of the quantum system of electromagnetic field and water dipole field is either the hollow core of the microtubule or exterior region adjacent to the wall of the microtubule.

Let us investigate the collective dynamics of electromagnetic field and water dipole field in the region V starting from the total Hamiltonian (11). We assume for simplicity that only one eigenmode with a specific eigenvalue, say $\omega_{\lambda_0}$, resonates with the energy difference $\varepsilon$ between the two principal energy eigenstates. Namely we have

$$\varepsilon=\hbar\omega_{\lambda_0} \tag{12}$$

and all the other eigenmodes are neglected. In the conventional laser theory, this is known as a single mode laser.

Since we have only one eigenmode with eigenvalue $\omega_{\lambda_0}$, we may omit all the eigenvector indices of the dynamical variables. Then, the total Hamiltonian (11) becomes

$$H=\hbar\omega\left(a^*a+\frac{1}{2}\right)+\varepsilon S-f(a^*S^-+S^+a). \tag{13}$$

The corresponding Heisenberg equations of motion for the three collective dynamical variables, S, and $S^{\pm}$, for water dipole field and the two variables, a* and a, for electromagnetic field are given by:

$$\frac{dS}{dt}=-i\frac{f}{\hbar}(a^*S^--S^+a) \tag{14}$$

$$\frac{dS^+}{dt}=i\frac{2f}{\hbar}Sa^*+i\frac{\varepsilon}{\hbar}S^+ \tag{15}$$

$$\frac{dS^-}{dt}=-i\frac{2f}{\hbar}Sa-i\frac{\varepsilon}{\hbar}S^- \tag{16}$$

$$\frac{da^*}{dt}=-i\frac{2\pi\varepsilon f}{\hbar V}S^+ \tag{17}$$

$$\frac{da}{dt}=i\frac{2\pi\varepsilon f}{\hbar V}S^-. \tag{18}$$

Let us investigate the most interesting case in which the eigenmode with eigenvalue ω represents a pulse mode of electromagnetic field. Because of the short length of the microtubule cylinder, the pulse mode propagating along the microtubule cylinder stays in the region V only for a short transit time $t_{MT}\approx\ell_{MT}/c$. As this transit time of the pulse mode is much shorter than the characteristic time of thermal interaction due to disordered environment of the body temperature T, the collective dynamics of the system of electromagnetic field and water dipole field is free from thermal dissipation and fluctuation, and can be considered as a closed system well-described by the above Heisenberg equations of motion. Furthermore, the time derivative of the dynamical variables $a^*$ and $a$ of the quantized electromagnetic field can be approximated by $a^*/\ell_{MT}$ and $a/\ell_{MT}$ in the case of a pulse mode propagating along the longitudinal axis of the microtubule cylinder. Then, equations (17) and (18) yield

$$a^* = -i\,\frac{2\pi\varepsilon f \ell_{MT}}{\hbar V} S^+ \tag{19}$$

$$a = i\,\frac{2\pi\varepsilon f \ell_{MT}}{\hbar V} S^- \tag{20}$$

This means that a pulse mode of the quantized electromagnetic field in the region V follows the collective dynamics of water dipole field. In other words, once a collective mode with long range order is created in quantum dynamics of water dipole field due to the spontaneous symmetry breaking, coherent emission of pulse modes of the quantized electromagnetic field follows. This phenomenon is called superradiance (see Appendix) or photon echo.

The important question is whether such a collective mode can be realized in the quantum dynamics of water dipole field starting from any incoherent and disordered initial and boundary conditions. Notice that such incoherent and disordered initial and boundary conditions of water dipole field are due to the interaction between water dipole field and thermally disordered states of electric dipoles of tubulins. The onset of this collective mode can be seen by rewriting the three Heisenberg equations (14), (15) and (16) for the collective variables of water dipole field by substituting equations (19) and (20), obtaining

$$\frac{dS^\pm}{dt} = \beta S S^\pm \pm i\varepsilon S^\pm \tag{21}$$

$$\frac{dS}{dt} = -\beta S^+ S^- \tag{22}$$

where $\beta$ is a positive constant given by

$$\beta = \frac{4\pi\varepsilon f^2 \ell_{MT}}{\hbar^2 V}.$$

These are coupled nonlinear differential equations for non-commuting operators $S$, and $S^\pm$, and have semi-classical solutions specifying a collective mode realized in the quantum dynamics of water dipole field starting from any incoherent and disordered initial and boundary conditions. Then, coherent emission of pulse modes of the quantized electromagnetic field follows, and the phenomenon of superradiance is shown to take place in the spatial region V inside or in the vicinity of the microtubule.

The intensity of coherent photon emission due to the superradiance can be given in this semi-classical approximation by

$$I = \frac{\hbar^2}{(4t_R f)^2}\,\mathrm{sech}^2\left(\frac{t-t_0}{2t_R}\right),$$

where

$$t_R = \frac{c\hbar^2 V}{4\pi f^2 \varepsilon M \ell_{MT}}$$

and $t_0 = t_R \ln 2M$ denote life time and delay of the superradiance, respectively.

We have found that the quantum collective dynamics of the water dipole field and the electromagnetic field inside or in the vicinity of the microtubule cylinder manifests the long range cooperative phenomenon of superradiance in which collective excitation of the water dipole field can be induced by incoherent and disordered perturbations due to the macroscopic thermal dynamics of protein molecules that form the wall of the microtubule cylinder. This fact ensures that each microtubule in the cytoskeletal structure of brain cells, that is, neurons, astrocytes and glia cells, may play an important role in the optical information processing regime of brain functioning as a superradiant device which converts the macroscopic disordered dynamics of protein molecules into the long range ordered dynamics of water dipole field and electromagnetic field involving a pulse mode emission of coherent photons. In other words, each microtubule is a coherent optical encoder in a dense microscopic optical computing network in the cytoplasm of each brain cell.

We have shown the possibility of a completely new mechanism of fundamental brain functioning in terms of coherent photon emission by superradiance in and around microtubules. Unlike a laser, superradiance is a specific quantum theoretical ordering process with a characteristic time much shorter than that of thermal interaction. Therefore, microtubules may be thought of as ideal optical encoders providing a physical interface between the following two systems: the conventional macroscopic system of classical, disordered and incoherent neural dynamics in terms of transmembrane ionic diffusions and thermally perturbed molecular vibrations, as well as the yet unknown microscopic optical computing network system of ordered and coherent quantum dynamics free from thermal fluctuation (noise) and dissipation (loss).

## Slow Phenomena: Water Laser and Thermal Fluctuation

We have focused on the collective dynamics of the quantum system of electromagnetic field and water dipole field in the vicinity of a microtubule whose characteristic time is much shorter than that of thermal fluctuation and dissipation due to the interaction with thermally disordered dynamics of electric dipoles of protein molecules. We consider now the case in which the collective dynamics has characteristic time comparable to that of thermally disordered dynamics and thus suffers from thermal fluctuation and dissipation.

It will be shown that the laser-like emission of coherent photons can be realized even in such a case with thermal noise and loss provided that the electric dipoles of protein molecules of the microtubule manifest a certain collective dynamics sufficient to "pump up" the water dipole field. Recall the Heisenberg equations of motion for the three collective dynamical variables, $S$ and $S^{\pm}$, for water dipole field and the two variables, $a^*$ and $a$, for the quantized electromagnetic field (14) — (18). Taking the thermal interaction with the disordered external systems at body temperature $T$, the Heisenberg equations of motion must be replaced by either the Heisenberg–Langevin equation or the Schrödinger–Langevin equation (Yasue, 1976, 1977, 1978a, 1978b, 1979a, 1979b). In the present analysis we use the Heisenberg–Langevin equations:

$$\begin{aligned}
\frac{dS}{dt} &= -\gamma(S-S_\infty)-i\frac{f}{\hbar}(a^*S^- - S^+a)+\eta \\
\frac{dS^+}{dt} &= i\frac{2f}{\hbar}Sa^* - \gamma_0 S^+ + i\frac{\varepsilon}{\hbar}S^+ + \eta^+ \\
\frac{dS^-}{dt} &= -i\frac{2f}{\hbar}Sa - \gamma_0 S^- - i\frac{\varepsilon}{\hbar}S^- + \eta^- \\
\frac{da^*}{dt} &= -\gamma_{EM}a^* - i\frac{2\pi\varepsilon f}{\hbar V}S^+ + \eta_{EM}^* \\
\frac{da}{dt} &= -\gamma_{EM}a + i\frac{2\pi\varepsilon f}{\hbar V}S^- + \eta_{EM}
\end{aligned} \tag{23}$$

Here, $\gamma$ and $\gamma_0$ are damping coefficients for the water dipole field, $\gamma_{EM}$ is a damping coefficient for the electromagnetic field, $\eta$, $\eta^+$, and $\eta^-$ are thermal fluctuations for the electromagnetic field, and $S_\infty$ is a parameter designating the rate of pumping due to the interaction with a certain collective dynamics of the electric dipoles of protein molecules of the microtubule.

In this case, the collective dynamical variables of water dipole field can be deleted in the adiabatic approximation, and the Heisenberg–Langevin equations (23) can be reduced approximately to the Heisenberg–Langevin equations for the quantized electromagnetic field, that is,

$$\frac{da^*}{dt} = \alpha a^* - \beta a a^* a^* + \xi^* \tag{24}$$

$$\frac{da}{dt} = \alpha a - \beta a^* a a + \xi . \tag{25}$$

Here, $\alpha$ and $\beta$ are constants given by

$$\alpha = -\gamma_{EM} + \frac{4\pi\varepsilon f^2 S_\infty}{\hbar^2 V \gamma_0}$$

$$\beta = \frac{16\pi\varepsilon f^4 S_\infty}{\hbar^4 V \gamma_0^2 \gamma}$$

and $\xi^*$ and $\xi$ are effective thermal fluctuations for the quantized electromagnetic field.

The Heisenberg–Langevin equations (24) and (25) governing the collective dynamics of the quantized electromagnetic field in the region V can be reduced to the Langevin equation if Glauber's coherent state representation is adopted (Klauder and Sudarshan, 1968):

$$\frac{dZ}{dt} = \alpha Z - \beta \bar{Z} Z^2 + B \tag{26}$$

Here, $Z=Z(t)$ is a Markov process in the complex plane denoting the complex eigenvalue of the electromagnetic field operator $a$; $B=B(t)$ is a complex Gaussian white noise representing the thermal fluctuation of the quantized electromagnetic field; and $\bar{z}$ denotes the complex conjugate of a complex number $z$. The mean and variance of the complex Gaussian white noise are given by

$$\langle B(t) \rangle = 0$$

and

$$\langle \bar{B}(t) B(s) \rangle = 2D\delta(t-s)$$

respectively, where $\langle \quad \rangle$ indicates the expectation value, $\delta(t)$ is the Dirac delta function and D is a diffusion constant given by

$$D = \frac{M\pi^2\varepsilon^2 f^2 \gamma_0}{2\gamma_{EM}^2 \hbar^2 V^2} + \frac{2\pi\gamma_{EM}\varepsilon}{V}\left(\frac{1}{e^{\varepsilon/k_B T}-1} + \frac{1}{2}\right)$$

with $k_B$ the Boltzmann constant.

The Langevin equation (26) is equivalent to the Fokker–Planck equation

$$\frac{\partial}{\partial t} f = -\frac{\partial}{\partial z}\left[(\alpha z - \beta \bar{z} z^2) f\right] + D\,\frac{\partial^2}{\partial z \partial \bar{z}} f \tag{27}$$

for the probability distribution function $f=f(z,\bar{z},t)$ of the complex Markov process $Z=Z(t)$. The stationary solution of the Fokker–Planck equation (27) can be obtained immediately:

$$f = C\exp\left[\frac{2\alpha\bar{z}z - \beta(\bar{z}z)^2}{2D}\right] \tag{28}$$

where C is a normalization constant such that

$$\iint f(z,\bar{z},t)\,dz\,d\bar{z} = 1 \tag{29}$$

holds.

This stationary solution (28) of the Fokker–Planck equation (27) is nothing but the unique equilibrium probability distribution function of the Markov process $Z(t)$. By the explicit form given by equation (28), it is immediately clear that the characteristics of the equilibrium probability distribution of the Markov process $Z(t)$, denoting the dynamics of the quantized electromagnetic field in the region V, depend sensitively on the rate of pumping $S_\infty$ provided by the collected dynamics of electric dipoles of the microtubule proteins. Namely for smaller values of $S_\infty$ such that $\alpha<0$, the most probable value for the intensity of the electromagnetic field $I = \sqrt{Z\bar{Z}}$ vanishes, while it becomes nonvanishing for larger values of $S_\infty$ such that $\alpha>0$, obtaining

$$I = \sqrt{\frac{\alpha}{\beta}}$$

We have found that the collective dynamics of the quantum system of electromagnetic field and water dipole field in the region V manifests a long range cooperative phenomenon of photon emission even if the thermal fluctuation and dissipation are taken into account. Excitation of the quantized electromagnetic field, that is, emission of photons in the region V is induced by the interaction with the thermally disordered dynamics of electric dipoles of tubulins if the pumping rate $S_\infty$ exceeds a threshold value,

$$S_\infty > \frac{\hbar^2 V \gamma_0 \gamma_{EM}}{4\pi\varepsilon f^2}$$

## Superconducting Phenomena in Tunneling Photon Water

We have revealed that the quantum system of electromagnetic field and water dipole field manifests long range ordered dynamics due to the spontaneous symmetry breaking in quantum field theory even though it suffers from interaction with thermally disordered dynamics of the external systems of biomolecules. For the time scale much shorter than the characteristic time of thermal fluctuation at body temperature, manifestation of such a collective mode as long range ordered dynamics was found to result in nonlinear quantum optical phenomena such as superradiance, realized in macroscopic regions adjacent to the highly structured biomolecules as cytoskeletal microtubules. For the longer time scale, the collective mode was shown to be realized as the water laser emitting coherent photons. In both cases, the most important role was played by the collective mode of the quantum system of electromagnetic field and water dipole field interacting strongly with each other.

As was clarified systematically by Umezawa (1993), collective modes of long range ordered dynamics are nothing but macroscopic objects of quantum origin. Crystals, magnetic media and superconducting media are familiar examples of such macroscopic objects, but it seems difficult to get a correct image of the "macroscopic object" realized by a collective mode of the quantum system of electromagnetic field and water dipole field. Of course, the collective mode in question was shown to induce coherent photon emission phenomena. However, it must be emphasized that those photons are not ordinary ones but specific ones which cannot go away from the spatial region occupied by the "macroscopic object." In other words, those photons are associated not to the usual advancing plane wave mode but to the evanescent wave mode of the quantized electromagnetic field wrapping the localizations of water dipole field, and they can exist only in conjunction with water. We call such photons "tunneling photons" in water.

Since the tunneling photons in water are not associated to the advancing plane wave, we cannot see them from the outside as light. Therefore, we need to put the finest optical fiber or metallic fiber into the region of the "macroscopic object" made of tunneling photons in water, so that energy quanta of the trapped evanescent wave mode are scattered into the advancing plane wave mode and finally detected as light. As the evanescent wave mode of the quantized electromagnetic field is maintained by the ordered dynamics of water dipole field strongly coupled to it, the tunneling photons accompany the coupled wave of water dipole field and can be seen as charged quanta. Namely, unlike the usual concept of photons, the tunneling photons in water have effective electric charge $e^*$ and effective mass $m^*$, and behave as Bose quanta with the transmission speed smaller than the speed of light c.

It may be of certain help for giving a correct image of the "macroscopic object" of a collective mode of the quantum system of electromagnetic field and water dipole field if we call it "tunneling photon water" (see Appendix). Namely, tunneling photon water is a typical macroscopic object in brain cells which can be regarded as a macroscopic condensate of tunneling photons with certain effective charge and mass. The physical situation is similar to that of superconducting media in which a macroscopic (Bose–Einstein) condensate of pseudo-particles (Cooper pairs) with certain effective charge and mass is realized. The macroscopic condensate of Cooper pairs is realized only at lower temperature close to absolute zero, and so superconducting phenomena of Cooper pairs can hardly be realized in macroscopic objects at body temperature. This fact had been referred to as a common negative claim against the possibility of superconducting phenomena in living matter. However, because the macroscopic condensate of tunneling photons has been shown to be realized even at body temperature in the vicinity of structured biomolecules as cytoskeletal microtubules, we can expect the possibility of superconducting phenomena of tunneling photons in living matter, especially in the brain. Simply put, as the tunneling photon has mass nonvanishing but much smaller than that of the Cooper pair of electrons, the macroscopic condensate of tunneling photons has the critical temperature higher than the body temperature, and we still have superconducting phenomena in tunneling photon water in the brain at body temperature (Jibu, Pribram, and Yasue, 1996). Therefore, it seems highly plausible that it is not the microscopic quantum mechanical system of electrons in biomolecules but the macroscopic quantum ordered dynamical system of tunneling photons in water which plays the essential role in realizing the biological order in living matter.

As the tunneling photon in evanescent wave mode can be described as a pseudo-particle with small but nonvanishing effective charge $e^*$ and mass $m^*$ subject to the usual Schrödinger equation, the macroscopic condensate of tunneling photons in the region V of the quantum ordered dynamics of electromagnetic field and water dipole field may be well described by the macroscopic Schrödinger equation for the macroscopic wavefunction, just as it was so in the case of macroscopic condensates of Cooper pairs (Feynman, Leighton, and Sands, 1968). Namely, macroscopic ordered dynamics of the most important "macroscopic object" in the brain — tunneling photon water — is governed by the macroscopic wavefunction $\Psi=\Psi(\mathbf{x},t)$ subject to the macroscopic Schrödinger equation

$$i\hbar\frac{\partial\Psi}{\partial t}=-\frac{\hbar^2}{2m^*}\Delta\Psi+e^*U\Psi \qquad (30)$$

where $U = U(\mathbf{x},t)$ denotes the mean electric potential given by the external systems. It is interesting to notice here that this macroscopic Schrödinger equation applies not only to tunneling photon water in the vicinity of cytoskeletal microtubules but also to tunneling photon water immediately adjacent to dendritic membranes of brain cells.

## Conclusion

We developed the holonomic brain theory starting from the macroscopic Schrödinger equation for the dynamical system of bioplasma of perimembranous regions immediately adjacent to the cell membrane (Pribram, 1991). There, we derived a Schrödinger-like wave equation of the same form as the macroscopic Schrödinger equation only in a phenomenological manner. The present macroscopic Schrödinger equation for the tunneling photon water immediately adjacent to dendritic membranes of brain cells might deserve to be the fully quantum theoretical foundation of the mathematical formulation in Pribram's holonomic brain theory. With expectations that the further theoretical investigation of various physical aspects of tunneling photon water not only in brain cells but also in general biological cells will be fruitful, we conclude our exposition by quoting Umezawa (1993, p. 133): "Through this structure (of macroscopic ordered states in quantum field theory), the entire body as a whole may form a system of intensive correlations."

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## Appendix

*Avogadro's number.*

A number 6.02252 times 10 to the power of 23. Macroscopic matter contains approximately the Avogadro's number of atoms or molecules.

*fast phenomena.*

Physical phenomena with a life time shorter than the relaxation time of thermal phenomena (i.e., the life time of thermally fluctuating phenomena).

*macroscopic object.*

In physics, an object whose spatial extension is larger than the wavelength of visible light.

*microtubule.*

A hollow cylinder of proteins called tublins with a diameter of about 10 nanometers and a length of about 100 nanometers. They form pipe-lines in cytoplasm and play important roles in forming the cytoskeletal structures in biological cells.

*ordered phases.*

The internal dynamics of matter manifests order, that is, a certain dynamical pattern.

*Pauli spin matrices.*

2 X 2 matrices introduced by W. Pauli for mathematically describing the magnetic moment of an electron, called spin, in quantum mechanics. Pauli spin matrices also can be used to describe electric dipole moment in quantum mechanics as well as two level atoms.

*slow phenomena.*

Physical phenomena with a life time longer than the relaxation time of thermal phenomena (i.e., the life time of thermally fluctuating phenomena).

*spinor field.*

A field entity describing matter made of spinning quanta such as electrons and quarks. Both electric and magnetic dipole fields can be thought of as spinor fields.

*Superradiance.*

Superradiance is a typical fast phenomenon of matter interacting with an electromagnetic field in which random and incoherent dynamics of matter becomes ordered and coherent, and then induces a collective emission of photon.

*tunneling photon water.*

Water in ordered phase in which evanescent photons or tunneling photons are realized.

*water laser.*

Superradiance realized by water and an electromagnetic field.

*thermal fluctuation.*

A random component of internal dynamics of matter typical for matter in thermal equilibrium.