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FROM CONSCIOUS EXPERIENCE TO MEMORY STORAGE AND RETRIEVAL: THE ROLE OF QUANTUM BRAIN DYNAMICS AND BOSON CONDENSATION OF EVANESCENT PHOTONS

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A quantum field theoretical formulation of an interaction between the radiation field and the electric dipole field of intracellular and extracellular water in perimembranous dendritic compartments is proposed. The intercellular spaces filled mostly with water are shown to be not just a filler but a proper substrate for dendritic processing composed of a boson condensation of evanescent photons. Macroscopic ordered dynamics of the electric dipoles of water in the perimembranous region immediately adjacent to dendritic membranes provides interactions with the radiation field to produce evanescent photons that ensure that the critical temperature of the boson condensation can be higher than the body temperature. Thus, superconducting phenomena can take place. Such a high-temperature boson condensate of evanescent photons can be understood as a physical substrate for distributed saltatory processing in dendritic arborizations. Memory storage can be understood in terms of processing involving the ionic coating of the dynamically ordered structure of water facilitated by the boson condensate of evanescent photons.

1. Introduction

Sir Arthur Eddington, the British astronomer, once remarked that "You cannot believe in astronomical observations before they are confirmed by theory." Much the same applies to the experiments we do in biology: we can begin to believe in results only if we have an adequate grasp of the theories that seek to explain the nature of the systems we study.

Gordon M. Shepherd, *Neurobiology*, 1988

One of the most intractable problems facing brain neurophysiologists has been to trace the passage of signals through the dendritic trees of neurons. The received

opinion is that such signals accumulate from their origins at synapses by simple summation of excitatory and inhibitory postsynaptic potentials to influence the cell body and its axon and thus the cell's output. This is not the case. Each synaptic site "is functionally bipolar — it both projects synapses onto and receives synapses from many other processes. — Hence input and output are each distributed over the entire dendritic arborization — where[ever] dendrodendritic interactions are important."¹ The anatomical complexity of the dendritic network has led to the opinion summarized by Szentagothai²: "The simple laws of histodynamically polarized neurons indicating the direction of flow of excitation — came to an end when unfamiliar types of synapses between dendrites, cell bodies and dendrites, serial synapses etc. were found in infinite variety."

The received opinion also focuses on the transmissive nature of synapses: Thus the term *neurotransmitters* is, more often than not, ubiquitously applied to the variety of molecular processes stimulated by the arrival of an axonic depolarization at the presynaptic site. This focus appears to us to be misplaced. In any signal processing device, the last thing one wants to do if unimpeded transmission is required, is to physically interrupt the carrier medium. Interruption is necessary, however, if the signal is to be processed in any fashion. Interruption allows switching, amplification, and storage to name a few purposes to which physical interruptions such as synapses could make possible.

What then might be the use to which synapses could be put when input and output are each distributed over an extent of dendritic arborization? One of us (KHP) suggested that any model we make of perceptual processes must take into account both the importance of imaging, a process that constitutes a portion of our subjective (conscious) experience, and the fact that there are influences on behavior of which we are not aware.³ Automatic behavior and awareness are often opposed — the more efficient a performance, the less aware we become. Sherrington noted this antagonism in a succinct statement: "Between reflex [automatic] action and mind there seems to be actual opposition. Reflex action and mind seem almost mutually exclusive — the more reflex the reflex the less mind accompanies it."

Evidence was then presented that indicates that automatic behavior is programmed by neural circuitry mediated by nerve impulses, whereas awareness is due to the synaptodendritic microprocess, the excitatory and inhibitory postsynaptic potentials and their effect on dendritic processing. The longer the delay between the initiation in the dendritic network of postsynaptic arrival patterns and the ultimate production of axonic departure patterns, the longer the duration of awareness.

Recent support for this proposal comes from the work of David Alkon and his colleagues who showed that as the result of Pavlovian conditioning there is an unequivocal reduction in the boundary volume of the dendritic arborizations of neurons.⁴ These neurons had previously been shown to increase their synthesis of mRNA and specific proteins under the same Pavlovian conditions. Although these experiments were carried out in molluscs, such conditioning induced structural

changes may be akin to the synapse elimination that accompanies development as the organism gains in experience, and therefore, automaticity in the appropriate sites in the cortex of rats exposed to enriched environments.

The hypothesis put forward thus states that as behavioral skills are attained, there is a progressive shortening of the duration of dendritic processing that occurs between the initiation of postsynaptic arrival patterns and the production of axonic departure patterns. This shortening is presumed due to structural changes in the dendritic network which facilitate transmission.

But, as we have seen, signal transmission in the dendritic network is far from straightforward. As Alkon points out in a *Scientific American* article⁵: Many of the molecular [and structural] transformations take place in — dendritic trees, which receive incoming signals. The trees are amazing for their complexity as well as for their enormous surface area. A single neuron can receive from 100,000 to 200,000 signals from separate input fibers ending on its dendritic tree. Any given sensory pattern probably stimulates a relatively small percentage of sites on a tree, and so an almost endless number of patterns can be stored without saturating the system's capacity."

The picture becomes even more complicated when we consider the spines that extend perpendicularly from the dendritic fiber, hairlike structures (cilia) onto which axon branches terminate. Each spine consists of a bulbous synaptic head and a narrow stalk which connects the head to the dendritic fiber. Thus, synaptic depolarizations and hyperpolarizations become relatively isolated from the dendritic fiber because of the high resistance to the spread of polarization posed by the narrowness of the spine stalk. It appears, therefore, "that there is an isolation of the activity at a given site from the ongoing activity in the rest of the cell . . . Part of the strategy of the functional organization of a neuron is to restrict synaptic sites and action potential sites to different parts of the neuron and link them together with passive electronic spread."¹ Furthermore, "it has been shown that synaptic polarization in a spine head can spread passively with only modest decrement into a neighboring spine head."⁶ Thus, spine head polarizations passively spread to interact with each other via extra — as well as via the intracellular cable properties of dendrites. The interactions (dromic and antidromic) among spine originated dendritic potentials (that need to become effective at the cell's axon) thus depend on a process which is "discontinuous and resembles in this respect the saltatory conduction that takes place from node to node in myelinated nerve."⁶

The intracellular spread of dendritic polarizations can be accounted for by microtubular structures that act as wave guides and provide additional surface upon which the polarizations can act.^{7,8} The extracellular spread may be aided by a similar process taking place in the glia which show a tremendous increase in the metabolism of RNA when excited by the neurons which they envelope. But these mechanisms, by themselves, do not account for the initial relative isolation of the spine head polarizations, nor the related saltatory aspects of the process.

To account for these properties we turn to the dendritic membrane and its

immediate surround. Dendritic membranes are composed of two oppositely oriented phospholipid molecules. The interior of the membrane is hydrophobic as it is formed by "lipids which form a fluid matrix within which protein molecules are embedded — the lipids can move laterally at rates of ($2 \mu\text{m}/\text{sec}$); protein molecules move about 40 times more slowly ($50 \text{ nm}/\text{sec}$ or $3 \mu\text{m}/\text{min}$)."¹ Some of the intrinsic membrane proteins provide channels for ion movement across the membrane.

The outer layer of the membrane "fairly bristles with carbohydrate molecules attached to the membrane protein molecules: glycoproteins. The carbohydrate may constitute 95 percent of these molecules [which form a] long-branching structure [that resembles] a long test tube brush, or a centipede wiggling its way through the extracellular space. It attracts water, imparting a spongy turpor to the extracellular space."¹

On the basis of these considerations, we propose that a perimembranous process occurs within dendritic compartments during which boson condensation produces a dynamically ordered state in water. This proposal originates in the work of Umezawa and his collaborators Ricciardi, Takahashi and Stuart. First, Ricciardi and Umezawa pointed out the possibility of a domain structure that provides a long range order within each [dendritic field of a] neuron.⁹ Then, Stuart, Takahashi and Umezawa generalized this idea to a more extended region of brain tissue, assuming the existence of two quantum fields interacting with each other.^{10,11}

We have gone on to speculate that as each pattern of signals exciting the dendritic arborization produces a macroscopic, ionically produced change of the charge distribution in the dendritic network, it triggers a spontaneous symmetry breaking, altering the water molecular field in the immediately adjacent perimembranous region. A macroscopic domain of the dynamically ordered structure of water is created in which the electric dipole density is aligned in one and the same direction. It is this domain of dynamically ordered water that is postulated to provide the physical substrate of the interactions among polarizations occurring in dendritic spines.

2. Ordered Dynamics in Perimembranous Region of Dendritic Membranes

Our principal concern is to account for the existence of distributed patterns of activity in dendritic arborizations by proposing a role for the extracellular fluid outside dendrites. These distributed patterns serve as an ideal substrate for experienced perceptual awareness and subsequent storage of that experience. Especially, we focus on the dynamically ordered structure of water in the perimembranous region immediately adjacent to the dendritic membrane. Detailed analysis of the dynamically ordered structure, meaning here a certain systematic pattern of dynamics of water in the perimembranous region, requires a fundamental theoretical framework, because thermal fluctuation and dissipation of water molecules in the perimembranous region are 10^6 as small as that of bulk water. It is a quasi-two-dimensional

region far from thermal equilibrium, and the conventional theoretical framework of statistical physics can no longer be applied. We have to rely on a more fundamental theoretical framework of physics to investigate the dynamically ordered structure of perimembranous water.

Furthermore, the physical substrates taking part in the ordered dynamics would not be restricted to matter composed of atoms and molecules. It is most plausible that the radiation field (i.e. the field of photons; the electromagnetic field) plays an important role in realizing the dynamically ordered structure in the perimembranous region. Therefore, we will take into account not only the extracellular fluid but also the radiation field as physical substrates for the ordered dynamics. As the extracellular fluid is essentially water containing several kinds of ions, it is natural to regard the perimembranous region as a quasi-two-dimensional array of water molecules with "impurity" (i.e. ions) overlaying the outer surface of dendritic membranes. Then, the dynamically ordered structure of water may be easily illustrated as a systematic pattern of dynamics of water molecules. Indeed, several authors developed physical theories of water manifesting ordered dynamics¹²⁻¹⁷. However, the radiation field has been regarded to play only secondary roles. But, as will be shown below, it binds water molecules dynamically with each other as a gauge field, and coherent emission of photons (i.e. energy quanta of radiation field) follows the ordered dynamics of water molecules.

In our present investigation of the dynamically ordered structure in the perimembranous region, we will show that the radiation field plays not only secondary roles but a principal role as an ideal substrate accounting for the distributed saltatory aspects of dendritic processing. In other words, the radiation field manifests two distinct modes; a normal wave mode with real wave number and an evanescent wave mode with imaginary wave number. The former is essentially the well-known part of the radiation field binding water molecules dynamically with each other, making up the dynamically ordered structure of water. The latter is the damping part of the radiation field corresponding to a leak field which can be usually neglected in the case of bulk water but certainly not in the present case of a thin layer of water in the perimembranous region.

Let us start in the next section with a brief exposition of the dynamically ordered structure of water in the perimembranous region realized by the normal mode of the radiation field. Then, we will proceed in the section after next to investigating the dynamically ordered structure of condensed virtual photons associated with the evanescent mode.

3. The Normal Mode: The Dynamically Ordered Structure of Water

We denote the spatial region immediately adjacent to the dendritic membranes by V and call it a perimembranous region. Let us introduce a Cartesian system of coordinates O_{xyz} . Then, any point in the region V can be labelled by giving its coordinates $\mathbf{r} = (x, y, z)$.

The perimembranous region V is not empty, but filled with water molecules. Of course, there may be other molecules and ions, but their numbers are relatively small, statistically comprising less than 1 percent of the total number. We consider an ideal case in which the existence of molecules other than those of water can be neglected. Effect of the presence of impurity will be discussed in the last section. It is most probable that the density of water in the perimembranous region V remains almost constant. Therefore, we fix the total number N of water molecules in the region V .

Let us take a look at a typical water molecule, say the j th water molecule. Here, j running from 1 to N denotes the fictitious number labelling the N water molecules in question. The molecule's position is given by coordinates $\mathbf{r}^j = (x^j, y^j, z^j)$. From a physical point of view, a water molecule has a constant electric dipole moment. The average moment of inertia and electric dipole moment of a water molecule are estimated to be $I = 2m_p d^2$ with $d \approx 0.82 \text{ \AA}$ and $\mu = 2e_p P$ with $P \approx 0.2 \text{ \AA}$, respectively. Here, m_p denotes the proton mass and e_p the proton charge.

Due to the electric dipole moment μ , the water molecule interacts strongly with the radiation field in the spatial region V . Although the water molecule has many energy eigenstates and so can exchange energy with the radiation field in many different values, we restrict our discussion to the case in which only the two principal energy eigenstates take part in the energy exchange.¹² These are taken to be low-lying states such that either the probability of transition between two other eigenstates is low relative to that between the two principal eigenstates or the equilibrium populations of the other levels become sufficiently small to allow them to be ignored. This coincides with the conventional two-level approximation in describing the energy exchange between atoms and the radiation field in laser theory.

Then, one sees immediately that the quantum dynamics of the j th water molecule can be described by a fictitious spin variable $\mathbf{s}^j = \frac{1}{2}\boldsymbol{\sigma}$ in energy spin space, where $\boldsymbol{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ and the σ_i 's are the Pauli spin matrices denoting the three components of the angular momentum for spin $\frac{1}{2}$. Let ϵ be the energy difference between the two principal energy eigenstates of the water molecule. Its actual value is $\epsilon \approx 200 \text{ cm}^{-1}$.¹⁸ Then the Hamiltonian governing the quantum dynamics of the j th water molecule is given by ϵs_z^j , and the total Hamiltonian for N water molecules becomes

$$H_{\text{WM}} = \epsilon \sum_{j=1}^N s_z^j. \quad (1)$$

The two energy eigenvalues of this Hamiltonian are $-\frac{1}{2}\epsilon$ and $\frac{1}{2}\epsilon$ reflecting the fact that only the two principal energy eigenstates with energy difference ϵ have been taken into account.

Now, let us consider the radiation field in the spatial region V from the point of view of quantum field theory. It is convenient to describe the radiation field in terms of its effect on an electric field operator $\mathbf{E} = \mathbf{E}(\mathbf{r}, t)$. Let us assume for simplicity that the electric field is linearly polarized, obtaining $\mathbf{E} = \mathbf{e}E$, where \mathbf{e}

is a constant vector of unit length pointing in the direction of linear polarization. Then, the radiation field in question comes to be described by a scalar electric field $E = E(\mathbf{r}, t)$ governed by the usual Hamiltonian

$$H_{EM} = \frac{1}{2} \int_V E^2 d^3r. \tag{2}$$

Next we introduce the interaction between the radiation field and the totality of water molecules by which they can exchange energy in terms of the creation and annihilation of photons, that is, energy quanta of the radiation field. Let us divide the electric field operator into positive and negative frequency parts

$$E = E^+ + E^-. \tag{3}$$

Then, the interaction Hamiltonian of the radiation field and the totality of water molecules becomes

$$H_I = -\mu \sum_{j=1}^N \{E^-(\mathbf{r}^j, t) s_-^j + s_+^j E^+(\mathbf{r}^j, t)\}, \tag{4}$$

where

$$s_{\pm}^j = s_x^j \pm i s_y^j, \tag{5}$$

are ladder operators in energy spin space. The total Hamiltonian governing the quantum dynamics of the radiation field, the electric dipoles of water molecules, and their interaction is given by

$$H = H_{EM} + H_{WM} + H_I. \tag{6}$$

Since the perimembranous region V may be considered as a cavity for the electromagnetic wave, it is convenient to introduce the normal mode expansion of the electric field operator $E = E^+ + E^-$, obtaining

$$E^{\pm}(\mathbf{r}, t) = \sum_{\mathbf{k}} E_{\mathbf{k}}^{\pm}(t) e^{\pm i(\mathbf{k} \cdot \mathbf{r} - \omega_{\mathbf{k}} t)}. \tag{7}$$

Here, $\omega_{\mathbf{k}}$ denotes the proper angular frequency of the normal mode with wave vector \mathbf{k} . We are mainly interested in the ordered collective behavior among the water molecules and the radiation field in the perimembranous region V . Let us introduce therefore collective dynamical variables $S_{\mathbf{k}}^{\pm}(t)$ and S for water molecules by

$$S_{\mathbf{k}}^{\pm}(t) \equiv \sum_{j=1}^N s_{\pm}^j(t) e^{\pm i(\mathbf{k} \cdot \mathbf{r}^j - \omega_{\mathbf{k}} t)} \tag{8}$$

and

$$S \equiv \sum_{j=1}^N s_z^j. \tag{9}$$

Then, the total Hamiltonian (6) becomes

$$H = H_{EM} + \epsilon S - \mu \sum_{\mathbf{k}} (E_{\mathbf{k}}^- S_{\mathbf{k}}^- + S_{\mathbf{k}}^+ E_{\mathbf{k}}^+). \tag{10}$$

It seems worthwhile to note here that this total Hamiltonian for the system of N water molecules and the radiation field in the perimembranous region V is essentially of the same form as Dicke's Hamiltonian for the laser system.¹⁹ Therefore, it might be expected that water in the perimembranous region should manifest a laser-like coherent optical activity, that is, act as a water laser. Recently, we have developed a new quantum theoretical framework in which water in the vicinity of cytoskeletal microtubules is shown to bear rich, ordered and systematic dynamics allowing two typical cooperative quantum phenomena called superradiance and self-induced transparency to be realized.^{15,17}

Let us consider the total Hamiltonian (10) governing the quantum dynamics of the radiation field and the electric dipoles of water molecules interacting with each other. We want to see the dynamical symmetry inherent in the quantum dynamics governed by the total Hamiltonian (10). Towards this aim, it is convenient to introduce the canonical variables for the radiation field through the relation.

$$P_{\mathbf{k}}(t) = \sqrt{\frac{\hbar\omega_{\mathbf{k}}}{2}} i(E_{\mathbf{k}}^- - E_{\mathbf{k}}^+), \tag{11}$$

$$Q_{\mathbf{k}}(t) = \sqrt{\frac{\hbar}{2\omega_{\mathbf{k}}}} (E_{\mathbf{k}}^- + E_{\mathbf{k}}^+). \tag{12}$$

These canonical variables satisfy the canonical commutation relations:

$$[P_{\mathbf{k}}(t), Q_{\mathbf{h}}(t)] = -i\hbar\delta_{\mathbf{k}\mathbf{h}}, \tag{13}$$

$$[P_{\mathbf{k}}(t), P_{\mathbf{h}}(t)] = [Q_{\mathbf{k}}(t), Q_{\mathbf{h}}(t)] = 0, \tag{14}$$

$$P_{\mathbf{k}}^*(t) = P_{-\mathbf{k}}(t), \tag{15}$$

$$Q_{\mathbf{k}}^*(t) = Q_{-\mathbf{k}}(t). \tag{16}$$

Here, A^* denotes the adjoint operator of A .

In terms of the canonical variables, the total Hamiltonian (10) becomes

$$H = \frac{1}{2} \sum_{\mathbf{k}} \{P_{\mathbf{k}}^*(t)P_{\mathbf{k}}(t) + \omega_{\mathbf{k}}^2 Q_{\mathbf{k}}^*(t)Q_{\mathbf{k}}(t)\} + \epsilon \sum_{j=1}^N s_z^j - \sqrt{\frac{2}{\hbar}} \mu \sum_{j=1}^N \sum_{\mathbf{k}} \left\{ \sqrt{\omega_{\mathbf{k}}} Q_{\mathbf{k}}(t) s_x^j - \frac{1}{\sqrt{\omega_{\mathbf{k}}}} P_{\mathbf{k}}(t) s_y^j \right\}. \tag{17}$$

This Hamiltonian is of the same form as Takahashi's Hamiltonian for the quantum system of "corticons" and "Stuartons" in the brain.¹¹ It is an immediate conse-

quence that this total Hamiltonian, governing the quantum dynamics of the radiation field and the electric dipoles of water molecules interacting with each other, remains invariant under the transformatin of canonical variables given by

$$Q'_{\mathbf{k}}(t) = Q_{\mathbf{k}}(t) \cos \theta - \frac{1}{\omega_{\mathbf{k}}} P_{\mathbf{k}}(t) \sin \theta, \tag{18}$$

$$P'_{-\mathbf{k}}(t) = \omega_{\mathbf{k}} Q_{\mathbf{k}}(t) \sin \theta + P_{-\mathbf{k}}(t) \cos \theta, \tag{19}$$

$$s_x^{j'}(t) = s_x^j(t) \cos \theta + s_y^j(t) \sin \theta, \tag{20}$$

$$s_y^{j'}(t) = -s_x^j(t) \sin \theta + s_y^j(t) \cos \theta, \tag{21}$$

$$s_z^{j'}(t) = s_z^j(t), \tag{22}$$

for a continuous parameter θ . 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 of rotations in two dimensions.

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 radiation field and water molecules in the perimembranous region V . The Heisenberg equations are given by

$$\frac{dQ_{\mathbf{k}}(t)}{dt} = \frac{1}{i\hbar} [Q_{\mathbf{k}}(t), H], \tag{23}$$

$$\frac{dP_{\mathbf{k}}(t)}{dt} = \frac{1}{i\hbar} [P_{\mathbf{k}}(t), H], \tag{24}$$

$$\frac{ds_x^j(t)}{dt} = \frac{1}{i\hbar} [s_x^j(t), H], \tag{25}$$

$$\frac{ds_y^j(t)}{dt} = \frac{1}{i\hbar} [s_y^j(t), H], \tag{26}$$

$$\frac{ds_z^j(t)}{dt} = \frac{1}{i\hbar} [s_z^j(t), H], \tag{27}$$

and the time-independent solution is obtained as follows:

$$P_{\mathbf{k}}(t) \equiv 0, \tag{28}$$

$$Q_{\mathbf{k}}(t) \equiv Q_{\mathbf{k}}^0, \tag{29}$$

$$s_x^j(t) \equiv u, \tag{30}$$

$$s_y^j(t) \equiv 0, \tag{31}$$

$$s_z^j(t) \equiv w. \tag{32}$$

Here, $Q_{\mathbf{k}}^0$ is a constant taking different values for each different value of the wave number \mathbf{k} , and u and w are also constants. Each energy spin variable

$s^j = (s_x^j, s_y^j, s_z^j)$ describing the quantum dynamics of the j th water molecule is found to be aligned in one and the same direction given by a constant vector $(u, 0, w)$. Such a long-range alignment of spin variables is a manifestation of a dynamical order of the system of the radiation field and water molecules. Namely, there exists a long-range order so that the energy spin variable is systematized globally in the perimembranous region V to realize a uniform configuration. It is the dynamically ordered structure of water in the perimembranous region realized by the normal mode of the radiation field.

A long-range alignment of energy spin variables cannot be extended to the whole perimembranous region, but restricted to a domain with linear dimension smaller than a characteristic length. This characteristic length of the long-range order of energy spin variables is called a coherence length of the dynamically ordered structure of water in the perimembranous region. The coherence length, denoted by l_c , is estimated to be inversely proportional to the energy difference ϵ between the two principal energy eigenstates of the water molecule, obtaining $l_c \approx 50 \mu\text{m}$. Thus, we have a macroscopic distributed spatial structure of the perimembranous region composed of the non-overlapping domains of dynamically ordered states of water smaller than the coherence length. This domain structure can be understood as basic to the distributed saltatory patterns of activity in the large extent of the extracellular fluid in which spine heads of dendrites are embedded.

It is interesting to note that the time-independent solution, representing a dynamically ordered state of the system of the radiation field and water molecules in the region V , is no longer invariant under the continuous transformation of canonical variables (18)–(22). 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, governing 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.²⁰ Perhaps the most interesting one is the emergence of evanescent wave modes of the radiation field with imaginary wave vectors in which photons have nonvanishing effective mass as it will be seen in the next section.

4. Evanescent Mode: Boson Condensation of Evanescent Photons

The concept of spontaneous symmetry breaking is one of the most powerful theoretical tool in quantum field theory for investigating various fundamental physical phenomena. Indeed, superconducting phenomena can be well understood as order creating phenomena emerging from certain spontaneous symmetry breaking mechanism without recourse to the detailed microscopic mechanism of superconductivity. Spontaneous symmetry breaking was first incorporated into the theoretical

investigation of cerebral cortical processing by Ricciardi and Umezawa.⁹ Then, two different branches were born; say, the Canadian and Italian schools both founded by Umezawa. The former has pursued further the distributed processing mechanism in relation to the origin of brain waves (EEG; electroencephalogram) and developed a new theoretical framework called “quantum brain dynamics”,^{10,11} and the latter has developed a quantum field theoretical framework for describing electromagnetic interactions in general biological systems which may be called “quantum biodynamics”.^{12-14,21} The Canadian and Italian schools seem to be unified recently by the elegant contribution of Vitiello.²²

Let us describe the spontaneous symmetry breaking phenomena in the perimembranous region within the quantum field theoretical framework of the Italian school. In spite of introducing a finite number of water molecules explicitly, a molecular field represented by a two component spinor field

$$\psi(\mathbf{r}, t) = \begin{pmatrix} \psi^+(\mathbf{r}, t) \\ \psi^-(\mathbf{r}, t) \end{pmatrix}, \tag{33}$$

is introduced to prescribe the quantum dynamics of water in the perimembranous region V . Here, $\psi^+(\mathbf{r}, t)$ and $\psi^-(\mathbf{r}, t)$ are upper and lower spinor components corresponding to the probability amplitudes of water molecules in the first excited state and the lowest energy state of rotation, respectively. This molecular field will be called the water molecular field. Density of the electric dipole of water molecules can be given by

$$\mathbf{D}(\mathbf{r}, t) \equiv \tilde{\psi}(\mathbf{r}, t) \frac{\hbar}{2} \sigma \psi(\mathbf{r}, t), \tag{34}$$

where

$$\tilde{\psi}(\mathbf{r}, t) = (\psi^+(\mathbf{r}, t)^* \quad \psi^-(\mathbf{r}, t)^*), \tag{35}$$

is the adjoint spinor field. Explicit form of the Pauli spin matrixes $\sigma = (\sigma_1, \sigma_2, \sigma_3)$ is given by

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \tag{36}$$

Clearly, we have

$$\mathbf{D}(\mathbf{r}^j, t) = \hbar s^j = \frac{\hbar}{2} \sigma, \tag{37}$$

when the water molecular field $\psi(\mathbf{r}, t)$ manifests localization in a sense that $\psi(\mathbf{r}, t) \neq 0$ only in each position $\mathbf{r} = \mathbf{r}^j$ of the j th water molecule. This is the case we treated in the preceding section in which spontaneous symmetry breaking was investigated by means of Heisenberg equations (23)–(27) with respect to Takahashi’s Hamiltonian (17). There, the dynamically ordered state of the system of the radiation field and water molecules in the perimembranous region was represented by the time-independent solution (28)–(32). Let us denote the corresponding quantum state by $|0\rangle$ in the quantum field theoretical Hilbert space. As each energy spin variables s^j

is aligned in one and the same direction given by a constant vector $(u, 0, w)$ in the dynamically ordered state, the expectation value of the electric dipole density does not vanish, obtaining

$$\langle 0 | \mathbf{D}(\mathbf{r}, t) | 0 \rangle = (u, 0, w) \neq 0. \quad (38)$$

The rotational transformation of energy spin variables (20)–(22) around the third axis is represented by the $U(1)$ subgroup of $SU(2)$ rotations for the water molecular field $\psi(\mathbf{r}, t)$;

$$\psi(\mathbf{r}, t) \rightarrow \psi'(\mathbf{r}, t) = e^{i\theta\sigma_z/2} \psi(\mathbf{r}, t). \quad (39)$$

The dynamically ordered state $|0\rangle$ of the system of the radiation field and the water molecular field in the perimembranous region cannot be $U(1)$ invariant, since it has to carry the nonvanishing electric dipole density (38). Namely, the $U(1)$ rotational symmetry around the third axis is spontaneously broken in the dynamically ordered state $|0\rangle$.

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.²⁰ 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 radiation field and the water molecular field, the energy spin variables related to the electric dipole moment of the water molecules are aligned uniformly in a dynamically ordered state of spontaneous symmetry breaking type. Goldstone bosons created with near vanishing energy requirement are quanta of long-range correlation waves of the aligned electric dipoles.

Recall that the domain structure of distributed systematic patterns in the perimembranous region has been revealed to be an ideal physical substrate for the distributed saltatory dendritic process in which each domain of dynamically ordered structure of water stands for each processing node. Each stimulus flowing into the dendritic arborization in terms of neural impulses produces a macroscopic change of the charge distribution in the membranes of the dendritic spines. Then, this change of the charge distribution triggers the spontaneous symmetry breaking of the system of the radiation field and the water molecular field in the perimembranous region immediately adjacent to the dendritic membrane in question. A macroscopic domain of the dynamically ordered structure of water with the size smaller than the coherence length l_c is created in which the electric dipole density is aligned in one and the same direction. It is this domain of the dynamically ordered structure of water that is postulated to be a basic part of the physical substrate coordinate with perceptual awareness of the external stimulus in question.

In quantum field theory, the emergence of Goldstone bosons in the dynamically ordered state can be understood formally from the point of view of local $U(1)$

rotational symmetry. As it is not possible to rotate the electric dipole density simultaneously in every place by the same amount, the dynamically ordered state $|0\rangle$ has no $U(1)$ rotational symmetry. However, the dynamically ordered state $|0\rangle$ can still have local $U(1)$ rotational symmetry under the transformation

$$\psi(\mathbf{r}, t) \rightarrow \psi'(\mathbf{r}, t) = e^{i\theta(\mathbf{r}, t)\sigma_z/2}\psi(\mathbf{r}, t) \quad (40)$$

with a space-time dependent parameter $\theta = \theta(\mathbf{r}, t)$. This is a local gauge transformation for the water molecular field $\psi(\mathbf{r}, t)$, and it is immediate to see that such a local $U(1)$ rotational symmetry can be ensured by the corresponding gauge transformation of the radiation field

$$\mathbf{A}(\mathbf{r}, t) \rightarrow \mathbf{A}'(\mathbf{r}, t) = \mathbf{A}(\mathbf{r}, t) - \nabla\theta(\mathbf{r}, t). \quad (41)$$

Here, $\mathbf{A}(\mathbf{r}, t)$ is the vector potential of the radiation field such that the electric field $\mathbf{E}(\mathbf{r}, t)$ is given by $\mathbf{E} = -\partial\mathbf{A}/\partial t$. The space-time dependent parameter $\theta(\mathbf{r}, t)$ thus restores the broken $U(1)$ rotational symmetry and can be regarded as the Goldstone field whose energy quanta are Goldstone bosons.

The dynamically ordered state of the system of the radiation field and the water molecular field in the perimembranous region thus create a longitudinal mode of the radiation field, that is, the Goldstone field, so that the broken symmetry is restored. In other words, the additional longitudinal mode must be superposed to the vector potential in the perimembranous region, and consequently energy quanta of the radiation field (i.e. photons) become to have nonvanishing (effective) mass due to the Higgs mechanism in gauge theory.²⁰ The interactions between the ordered water and the radiation field make photons massive. This means that the gauge transformed vector potential $\mathbf{A}'(\mathbf{r}, t)$ is subject to the modified Maxwell equation with mass term;

$$\left(\square + \frac{M^2 c^2}{\hbar^2}\right) \mathbf{A}'(\mathbf{r}, t) = 0, \quad (42)$$

where

$$\square \equiv \left(\frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2\right)$$

denotes the d'Alembertian operator, and M stands for the effective mass of a photon. The electric field $\mathbf{E}(\mathbf{r}, t)$ is also given by $\mathbf{E} = -\partial\mathbf{A}'/\partial t$ in this gauge and so subject to the same modified Maxwell equation with mass term

$$\left(\square + \frac{M^2 c^2}{\hbar^2}\right) \mathbf{E}(\mathbf{r}, t) = 0 \quad (43)$$

in the perimembranous region.

Recall that the normal mode of the radiation field subject to the Maxwell equation (without mass term) took part in realizing the dynamically ordered state of water molecules in the perimembranous region. Once such an ordered state is created, then a longitudinal mode of the radiation field carrying photons interacting

with ordered water to display a nonvanishing effective mass emerges by means of the Higgs mechanism which claims that the emergence of Goldstone bosons restoring the spontaneously broken symmetry can be shielded by making gauge bosons, that is, photons, massive. We call this mode of the radiation field an evanescent mode. Energy quanta of the evanescent mode of the radiation field with nonvanishing mass will be called evanescent photons or virtual photons. The modified Maxwell equation (43) yields that the evanescent mode is characterized by imaginary wave vectors. They are also called tunneling photons designating the fact that they are moving "evanescently" in the dynamically ordered structure of water in the perimembranous region.

Since the effective mass of the evanescent photon is essentially a spatial damping factor for the evanescent mode of the radiation field in the macroscopic domain of the dynamically ordered structure of water, it is of the order inversely proportional to the penetration depth δ of the evanescent mode,^{12-14,21} obtaining

$$M \approx \frac{\hbar}{c\delta} \approx 13.6 \text{ eV}, \quad (44)$$

and

$$\delta \approx 150 \text{ \AA}. \quad (45)$$

The penetration depth δ is of the same order as the actual "depth" of the outer perimembranous region immediately adjacent to the dendritic membranes, that is, the extracellular space between the brain cells. In other words, the extracellular space between the brain cells is filled up with not only the ordered domains of water but also the evanescent mode in which evanescent photons with effective mass M manifest the boson condensation. This boson condensate of evanescent photons overlaps the domain structure of the dynamically ordered states of the system of the radiation field and the water molecular field, in both the external and the inner perimembranous region.

Because the system of the radiation field and the water molecular field in the perimembranous region is kept far from equilibrium and thermal fluctuation and dissipation do not take place, we can no longer define temperature there. However, the evanescent mode can be regarded to be in thermal equilibrium, as it manifests no spontaneous symmetry breaking, and we can define the temperature of each ordered domain of the perimembranous region. As the evanescent photons do not interact with each other, the boson condensate of evanescent photons can be treated as an ideal Bose gas confined in each ordered domain of the perimembranous region with linear dimension of the order of the coherence length l_c . Then, a standard calculation gives a rough estimate $T \approx 300 \text{ K}$,^{13,14,21} which goes well along with the actual body temperature. Furthermore, the critical temperature of the boson condensate of evanescent photons with effective mass $M \approx 13.6 \text{ eV}$ can be estimated to be much higher than the body temperature, since it is inversely proportional to the boson mass.

5. Superconductive Properties

We have shown that the high-temperature boson condensates of evanescent photons in the perimembranous region immediately adjacent to the dendritic membranes can be understood as a description of distributed saltatory processing in dendritic arborizations manifesting nonlocality. The dynamically ordered structure of water in the perimembranous region realized by the spontaneous symmetry breaking mechanism ensures the existence of such boson condensates. As those boson condensates of evanescent photons are directly related to the quantum dynamics of the radiation field, certain superconducting phenomena could take place there. Indeed, the longitudinal mode of the radiation field plays the role of the order parameter characterizing the macroscopic dynamics of superconducting media, because it is locked to the phase of any matter field with electric charge through the gauge transformation.

Recall that the dendritic membrane is composed of two oppositely oriented phospholipid molecules. Thus, not only does the outer layer provide for hydrophilic extracellular processing, but the inner layer also makes possible an ordered water medium within the dendrites (and their spines).

Consequently, we can expect that, within the patch (or compartment) of dendrite (including its spine) that falls within the coherence length of the ordered water, a couple of outer and inner perimembranous regions separated by a thin layer of cell membrane form a Josephson junction, that is, a sandwich-structured junction of two superconducting regions weakly coupled with each other through the membrane by means of quantum tunneling mechanism. The Josephson junction is a well-investigated superconducting device which is revealed to maintain specific superconducting phenomena called Josephson effects. The existence of Josephson effects in general biological cells had been suggested theoretically and several positive experimental evidence were reported.^{23,24} There, however, emphasis is put mainly on the extraordinary sensitivity of the superconducting current across the Josephson junction (i.e. Josephson current) to the imposed magnetic field. Such a magnetic Josephson effect can be an important clue as not only an indirect evidence of the existence of the high-temperature boson condensate but also a possible mechanism explaining the high sensitivity of the brain to the weak magnetic field.^{23,24} Besides the magnetic Josephson effect we have another one typical for the Josephson junction; that is, an electric Josephson effect. The latter will play an important role in realizing the nonlinear network of superconducting current among the brain cells as can be seen as follows:

Let us focus on a domain of the dendritic membrane smaller than the coherence length l_c in which the sandwich-structured Josephson junction is realized in terms of the boson condensates of evanescent photons in the perimembranous regions outside and inside the membrane. The electric potential difference $U = U(t)$ between the outer and inner surfaces of the membrane can be thought of as the voltage across the Josephson junction. Then, the standard quantum field theoretical treatment of the electric Josephson effect yields that the Josephson current induced by the voltage $U(t)$ is given by

$$J(t) = J_0 \sin \left(\theta_0 + \frac{q}{\hbar} \int_0^t U(s) ds \right), \quad (46)$$

where J_0 , θ_0 and q are certain constants.²⁵ The circuit equation for the Josephson junction is therefore given by

$$C \frac{dU(t)}{dt} = -J(t), \quad (47)$$

where C stands for the capacitance parameter of the membrane. Introducing a new variable

$$W(t) \equiv \theta_0 + \frac{q}{\hbar} \int_0^t U(s) ds, \quad (48)$$

we can rewrite the above equation as follows:

$$\frac{d^2 W(t)}{dt^2} = -\frac{J_0 q}{C \hbar} \sin W(t). \quad (49)$$

This is a nonlinear differential equation of the same form as the classical equation of motion for the physical pendulum, and has an oscillatory solution $W = W(t)$ represented implicitly by the elliptic function. Correspondingly, the membrane electric potential difference $U(t)$ manifests a self-excited oscillation $U(t) = \frac{\hbar}{q} \frac{dW(t)}{dt}$ characteristic to the Josephson junction. This is called the Josephson oscillation.

As there are extremely many Josephson junctions in the totality of perimembranous regions among the brain cells, we can think of a huge nonlinear network of superconducting currents across the Josephson junctions among the brain cells. Dynamics of this huge network could be seen by investigating all the Josephson oscillations coupled with each other. Although the detailed investigation seems difficult in practice, we can expect that a considerable number of synchronized Josephson oscillations would result in realizing the macroscopic electric potential oscillations measured by microelectrode recordings of sensory activated dendritic fields or by recordings made from scalp. In other words, the totality of synchronized Josephson oscillations in the perimembranous region of the dendritic membranes can be supposed to generate at least a portion of the scalp-recorded electroencephalogram (EEG). The fact that the Josephson oscillation is extraordinarily sensitive to the magnetic field imposed on the Josephson junction might explain the experimental finding that the human brain can be influenced by small variations of the Earth's magnetic field.

6. Memory

Before closing our speculations on boson condensate of evanescent photons in the perimembranous region immediately adjacent to the dendritic membranes, it may be worthwhile to mention the transformation of the distributed saltatory dendritic process into storage. The crucial point is the existence of "impurity", that is, ions in the dynamically ordered structure of water in the perimembranous region. Among

several kinds of ions typical for the extracellular and intracellular fluid are Na^+ , K^+ , Ca^{2+} , Cl^- , etc. The effect of the presence of such ions in the dynamically ordered structure of water is clear: There are three types of ions, that is, M-ions, C-ions and B-ions. This classification is made upon the effect of the ion on the dynamically ordered structure of water. However, the effect of an ion on water molecules is essentially due to the electromagnetic interaction of Coulomb type, and so its strength depends highly on the distance between each water molecule and the ion in question.

The above classification, therefore, can be regarded also as a classification upon the size of the ion: Ions whose radius is smaller than that of the water molecule are M-ions, and they do not disturb the dynamically ordered structure of water. Na^+ and Ca^{2+} ions are M-ions. Those whose radius is approximately the same as that of the water molecule are C-ions, and they play the role of water molecules in realizing the dynamically ordered structure of water. In other words, C-ions can be mixed with water molecules in the dynamically ordered state. K^+ ion is a C-ion. Those whose radius is larger than that of the water molecule are B-ions, and they disturb the dynamically ordered structure of water considerably. If there are B-ions in the perimembranous region, then the system of the radiation field and water molecules will suffer from dynamical disorder and so the dynamically ordered structure of water manifests defects. Cl^- ion is a B-ion.

Recalling the fact that K^+ ions and Na^+ ions show higher populations inside and outside the brain cell, respectively, the normal ionic environment of the cytoplasm and extracellular fluid might not disturb the dynamically ordered structure of water in the perimembranous region immediately adjacent to the cell membrane. However, Cl^- ions disintegrated from the anesthetic molecules can be thought to make many defects in the dynamically ordered structure of water, and consequently the patient loses consciousness during general anesthesia.

We consider the normal environment in which we have only M-ions and C-ions in the perimembranous region. There, the dynamically ordered structure of water is maintained by the spontaneous symmetry breaking mechanism. Both the "apparent" dynamically ordered structure of water and the "evanescent" one of the boson condensate of evanescent photons play a role in the distributed saltatory processing occurring in dendritic arbors. However, it seems evident that the brain can stabilize the process over iterations that associate current input signals with the residuals remaining from prior inputs.²⁶ For completing our quantum field theoretical approach we have to describe the possible mechanism of stabilizing the dynamically ordered structure of water and the boson condensate of evanescent photons in the perimembranous region immediately adjacent to the membrane.

It has been shown theoretically that the boson condensate of evanescent photons can be coated selectively by specific molecules and ions.^{13,14,21} Such a molecular coating makes the dynamically ordered structure much more stable, and as a result the physical substrate for memory can be created. Namely, the more the dynamically ordered structure of water and the boson condensate of evanescent photons

is molecular coated, the more it is made stable. The transformation mechanism of processing an input of signals into memory can be thus aided by the molecular coating of the dynamically ordered structure of water and the boson condensate of evanescent photons. Actually it has been reported that the distributed pattern of such a molecular coating has been observed in the cerebellum of rats.²⁷

Evidence that, indeed, patches of dendritic membrane become the site of memory storage comes from the work of Daniel Alkon and his associates.⁴ Alkon has shown that local interactions among neighboring spines are responsible for the learning induced changes that give rise to classical conditional responses. The interaction between adjacent spine heads, as noted by Shepherd,¹ must proceed to a considerable extent extracellularly because of the high internal electric resistance of the narrow spine necks. According to Alkon, the interaction is communicated intracellularly (dromically) to the cell body which, in turn, generates factors that return (antidromically) to the site of the interaction and "hard wire" it.

The dromic and antidromic intracellular processes are triggered by a reduction in K^+ ion flow (which results only when the conditional and unconditional stimuli are paired). This reduction lasts for many days. "The ion flow changes seem to result from the movement of the calcium-sensitive enzyme [Protein Kinase C] PKC. In response to the changes in calcium-ion concentration and in another second messenger, diacyl glycerol, that accompany the association of temporally related sensory stimuli, PKC moves from the cell cytoplasm to the cell membrane, where it reduces K^+ ion flow."⁵

The protein target of the PKC enzyme is the GAP-binding protein that appears to be involved in regulating ion channels. "This 20 kilodalton protein may serve functions in the context of learning that are analogous to the functions [that] so-called G proteins assume in developmental and oncogenetic contexts."⁵

A second enzyme, another calcium activated kinase known as CAM Kinase II also phosphorylates the 20 kilodalton protein target. This enzyme is concentrated at postsynaptic sites (including those on spine heads) throughout cortical dendritic trees.

The induction by these enzymes of changes in the cellular quantity of 20 kilodalton proteins is accompanied by increases in the synthesis of a number of species of mRNA. One of these species actually corresponds to the 20 kilodalton protein.

Both the extracellular and the dromic and antidromic intracellular processes need a physical substrate, a medium, within which to accomplish the molecular transformations that lead to reduction of K^+ ion flow that accompanies conditioning. The extracellular spongy turpor produced by glycoproteins provides the necessary structure for holding perimembranous ordered water to which ions can adhere.

Internally, the dynamically ordered water can provide the substrate for dromic and antidromic superconductivity in the dendritic compartment activated by the temporal association of a conditional with an unconditional input signal.

Dynamically ordered water can also aid memory retrieval. Once a physical

substrate is formed in the perimembranous region as a macroscopic domain of the dynamically ordered structure of water, we can make use of the emergence of Goldstone bosons as a physical process involved in conscious memory retrieval, as originally proposed by Ricciardi and Umezawa²⁰ and Stuart, Takahashi and Umezawa.^{10,11} Namely, when the system of the radiation field and the water molecular field suffers from even a weak perturbation due to a change of the charge distribution in the dendritic membranes induced by an external stimulus of a nature similar to that used in the perceptual process, the Goldstone bosons characteristic to the domain of the dynamically ordered state corresponding to the physical substrate for the delayed input-output processing that makes awareness possible. The physical process of conscious memory retrieval is postulated to be mediated by the Goldstone bosons (i.e. long-range correlation waves) with almost no energy requirement. The Goldstone bosons play a role in the replication of the original external stimulus. In this way, the existence of memory in terms of the domain structure of the dynamically ordered states of the system of the radiation field and the water molecular field can give rise, as in the initial processing of the stimulus, to the delay in processing that is coordinate with conscious experience.

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