

The dissipative quantum model of brain and laboratory observations*

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We discuss the predictions of the dissipative quantum model of brain in connection with the formation of coherent domains of synchronized neuronal oscillatory activity and macroscopic functions of brain revealed by functional brain imaging.

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I. INTRODUCTION

The mesoscopic neural activity of neocortex appears consisting of the dynamical formation of spatially extended domains in which widespread cooperation supports brief epochs of patterned oscillations. These “packets of waves” have properties of location, size, duration and carrier frequencies in the beta-gamma range (12–80 *Hz*). They re-synchronize, through a sequence of repeated collective phase transitions in cortical dynamics, in frames at frame rates in the theta-alpha range (3 – 12 *Hz*). The formation of such patterns of amplitude modulated (AM) synchronized oscillations in neocortex has been demonstrated by imaging of scalp potentials (electroencephalograms, EEGs) and of cortical surface potentials (electrocorticograms, ECoGs) of animal and human from high-density electrode arrays [1]-[5]. The AM patterns appear often to extend over spatial domains covering much of the hemisphere in rabbits and cats [6, 7], and over the length of a 64×1 linear 19 *cm* array [1] in human cortex with near zero phase dispersion [8, 9]. Synchronized oscillation of large-scale neuronal assemblies in beta and gamma ranges have been detected also by magnetoencephalographic (MEG) imaging in the resting state and in motor task-related states of the human brain [10].

In this paper we compare the predictions of the dissipative quantum model of brain [11, 12] with these neurophysiological data [5, 13]. It turns out that the model explains two main features of the EEG data: the textured patterns of AM in distinct frequency bands correlated with categories of conditioned stimuli (CS), i.e. *coexistence* of physically distinct AM patterns, and the remarkably rapid onset of AM patterns into (irreversible) sequences that resemble cinematographic frames. Each spatial AM pattern is indeed described to be consequent

to spontaneous breakdown of symmetry (SBS) [14–16] triggered by external stimulus and is associated with one of the unitarily inequivalent ground states. Their sequencing is associated to the non-unitary time evolution in the dissipative model, as discussed below.

Cellular and molecular models of neuronal function have been formulated in the so-called K-set theory: a hierarchical set of models based in studies of single neurons embedded in populations of increasing size and complexity [17, 18]. The purpose of the present paper is to show that the dissipative quantum model may describe the entire forebrain dynamics as it selects, adapts, and elaborates generic intentional actions [5, 13].

In our presentation we closely follow Refs. [5, 13]. The question concerning the mass action in the observed cortical activity as originally pointed out by Lashley is considered in Section II. The dissipative many-body model of brain is summarized in Section III and it is there discussed in relation to the evidence of a multiplicity of ground states. The formation and recurrence of AM oscillatory patterns are further discussed in Section IV. Free energy and classicality of trajectories in brain space are discussed in Section V. Final remarks and conclusions are presented in Section VI.

II. LASHLEY DILEMMA

In the first half of the 20th century Lashley was led to the hypothesis of “mass action” in the storage and retrieval of memories in the brain and observed: “...Here is the dilemma. Nerve impulses are transmitted ...from cell to cell through definite intercellular connections. Yet, all behavior seems to be determined by masses of excitation...within general fields of activity, without regard to particular nerve cells... What sort of nervous organization might be capable of responding to a pattern of excitation without limited specialized path of conduction? The problem is almost universal in the activity of the nervous system” (pp. 302-306 of [19]). Many laboratory

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observations in the following years confirmed Lashley's finding. Pribram extended the concept of mass action by introducing the analogy between the fields of distributed neural activity in the brain and the wave patterns in holograms [20]. Observational access to real time imaging of "patterns of excitation" and dynamical formation of spatially extended domains of neuronal fields of activity has been provided by magnetoencephalogram (MEG), functional magnetic resonance imaging (fMRI), positron electron tomography (PET), blood-oxygen level deletion (BOLD) and single photon emission computed tomography (SPECT). As already mentioned in the Introduction, observations [7] show that cortex jumps abruptly from a receiving state to an active transmitting state. Spatial AM patterns with carrier frequencies in the beta and gamma ranges form during the active state and dissolve as the cortex return to its receiving state after transmission. These state transitions in cortex form frames of AM patterns in few *ms*, hold them for 80–120 *ms*, and repeat them at rates in alpha and theta ranges of EEG [1–8]. In such an activity neocortex appears to behave according to four interrelated properties [21, 22]: the exchangeability of its ports of sensory input; its ability to adapt rapidly and flexibly to short- and long-term changes; its reliance on large-scale organization of pattern of neural activity that mediate its perceptual functions; the incredibly small amounts of information entering each port in brief behavioral time frames that support effective and efficient intentional action and perception.

Four material agencies have been then proposed to account for the processes involving large populations of neurons. None of them, however, appears to be able to explain the observed cortical activity [23]:

- Nonsynaptic neurotransmission [21] has been proposed as the mechanism for implementation of volume transmission to answer the question on how that broad and diffuse chemical gradients might induce phase locking of neural pulse trains at *ms* intervals. Although nonsynaptic transmission is essential for neuromodulation, diffusion of chemical fields of metabolites providing manifestations of widespread coordinated firing is, however, too slow to explain the highly textured patterns and their rapid changes [23]. The observed high rates of field modulation are not compatible with mediation of chemical diffusion such as those estimated in studies of spike timing among multiple pulse trains (e.g. [24–26]), of cerebral blood flow using fMRI or BOLD (e.g. [27, 28]), and of spatial patterns of the distributions of radio-labeled neurotransmitters and neuromodulators as measured with PET, SPECT and optical techniques.

- Weak extracellular electric currents have been postulated as the agency by which masses of neurons link together [29]. They have been shown to modulate the firing of neurons *in vitro*. However, the current densities required *in vivo* to modulate cortical firing exceed by nearly two orders of magnitude those currents that are sustained by extracellular dendritic currents across the resistance of brain tissue [17, 30]. The passive potential

differences are measured as the EEG.

- The intracellular current in palisades of dendritic shafts in cortical columns generates magnetic fields of such intensity that they can be measured 4–5 *cm* above the scalp with MEG. The earth's far stronger magnetic field can be detected by specialized receptors for navigation in birds and bees [31], leading to the search for magnetic receptors among cortical neurons (e.g. [32, 33]), so far without positive results.

- Radio waves propagating from the combined agency of electric and magnetic fields has also been postulated [34]. However, neuronal radio communication is unlikely, owing to the 80 : 1 disparity between electric permittivity and magnetic permeability of the brain tissue and to the low frequency (< 100 *Hz*) and kilometer wavelengths of e.m. radiation at EEG frequencies.

The conclusion is that Lashley dilemma remains still to be explained: neither the chemical diffusion, which is much too slow, nor the electric field of the extracellular dendritic current nor the magnetic fields inside the dendritic shafts, which are much too weak, are the agency of the collective neuronal activity. An alternative approach is therefore necessary. The dissipative quantum model of brain has been then proposed [5, 11–13] to account for the observed dynamical formation of spatially extended domains of neuronal synchronized oscillations and of their rapid sequencing.

III. THE DISSIPATIVE MANY-BODY MODEL AND THE EVIDENCE OF A MULTIPLICITY OF GROUND STATES

A. *The many-body model*

The dissipative quantum model of brain is the extension to the dissipative dynamics of the many-body model proposed in 1967 by Ricciardi and Umezawa [35, 36]. They suggested that the extended patterns of excitations observed in the neurophysiological research might be described by means of the SBS formalism in many-body physics. The fact that the brain is an open system in permanent interaction with the environment was not considered in the many-body model. It has been therefore extended in a way to include the intrinsically open dynamics of the brain. This led to the dissipative many-body model [11, 12]. Umezawa explains the motivation for using the quantum field theory (QFT) formalism of many-body physics [37]: "In any material in condensed matter physics any particular information is carried by certain ordered pattern maintained by certain long range correlation mediated by massless quanta. It looked to me that this is the only way to memorize some information; memory is a printed pattern of order supported by long range correlations..." In QFT long range correlations among the system constituents are indeed dynamically generated through the mechanism of SBS. These correlations manifest themselves as quanta, called the Nambu-Goldstone (NG) boson particles or modes, which have

zero mass and therefore able to span the whole system. At a mesoscopic/macrosopic scale, due to such correlations in this way established, the system appears in an ordered state. One expresses this fact by saying that the NG bosons are coherently condensed in the system lowest energy state (the system ground state) according to the Bose-Einstein condensation mechanism. The density of the condensed NG bosons provides a measure of the degree of ordering or coherence. One arrives thus to the definition of the *order parameter*, a classical field specifying the ordered patterns observed in the system ground state. This is the way the dynamical formation of extended ordered patterns is described in many-body physics. Laboratory observations allow to detect the NG quanta or particles by means of their scattering with observational probes; for example, one can use neutrons as probe to observe their scattering with phonons in a crystal. The phonons are the NG particle responsible for the crystalline ordering. They are the quanta associated to the elastic waves. Other examples of NG particles are the magnons in the ferromagnets, namely the quanta of the spin waves. In the case of the brain, the quantum variables are identified [11, 38, 39] with the electrical dipole vibrational field of the water molecules and of other biomolecules present in the brain structures. The associated NG quanta are named the dipole wave quanta (DWQ). These do not derive from Coulomb interaction. They are dynamically generated through the breakdown of the rotational symmetry of the electrical dipole vibrational field. Water is more than the 80% of brain mass and in the many-body model it is therefore expected to be a major facilitator or constraint on brain dynamics. The theoretically and experimentally well established knowledge of condensed matter physics thus suggested to Umezawa that memory storage might be described in terms of the coherent Bose condensation process in the system lowest energy state. It has to be remarked that the neuron and the glia cells and other physiological units are *not* quantum objects in the many-body model of brain.

In the many-body model the external input or stimulus acts on the brain as a trigger for the spontaneous breakdown of the symmetry with the consequent long range correlation established by the coherent condensation of NG bosons. In the dissipative model it becomes clear that the stimulus action may trigger the symmetry breakdown only provided the cortex is at or near a singularity (see below), predicting indeed the laboratory observations [40]. The density value of the condensation of DWQ in the ground state acts as a *label* classifying the memory there created. The memory thus stored is not a representation of the stimulus. This reflects a general feature of the *spontaneous* breakdown of symmetry in QFT: the specific ordered pattern generated through SBS by an external input does not depend on the stimulus features. It depends on the system internal dynamics. The model thus accounts for the laboratory observation of lack of invariance of the AM neuronal oscillation patterns with

invariant stimuli.

The recall of the recorded information occurs under the input of a stimulus able to excite DWQ out of the corresponding ground state. In the many-body model such a stimulus is called “similar” to the one responsible for the memory recording [36]. In the model similarity between stimuli thus refers not to their intrinsic features, but to the reaction of the brain to them; in other words, to the possibility that under their action DWQ are condensed into or excited from the ground state carrying the same label.

The many-body model, however, fails in explaining the observed coexistence of AM patterns and also their irreversible time evolution. Indeed, one shortcoming of the model is that any subsequent stimulus would cancel the previously recorded memory by renewing the SBS process with the consequent DWQ condensation, thus overprinting the ‘new’ memory over the previous one (‘memory capacity problem’). In order to solve these problems, considering that the brain is an open system, the original many-body model has been extended [11] to the dissipative dynamics.

B. The dissipative many-body model

The mathematical structure of QFT provides the possibility of having different vacua with different symmetry properties. Indeed, infinitely many representations of the canonical commutation relations (CCR’s) exist in QFT. They are, with respect to each other, unitarily inequivalent (i.e there is no unitary operator transforming one representation into another one of them) [41]. Thus they are physically inequivalent: they describe different physical phases of the system (it is not so in Quantum Mechanics where all the representations are unitarily (and therefore physically) equivalent) [15, 42, 43]. The existence of infinitely many representations of the CCR’s is fully exploited in the dissipative quantum model of brain, which is therefore not a quantum mechanical model but a QFT model [43].

In the dissipative model the environmental influence on the brain is taken into account by performing a suitable *choice* of the brain vacuum state (the brain ground state) among the infinitely many of them, each other unitarily inequivalent. The choice of the *effective* vacuum is done in the process of SBS triggered by the external stimulus. As explained above, the specificity of such a “choice” is fully controlled by the internal dynamics of the brain system; “making” the choice signals that the brain-environment interaction is “active”. A change in the brain-environment reciprocal influence then corresponds to a change in the choice of the brain vacuum: the brain evolution through the vacuum states thus reflects the evolution of the coupling of the brain with the surrounding world. The vacuum condensate of DWQ, consequent to SBS induced by the external stimulus, is assumed to be the quantum substrate of the AM pattern observed at a phenomenological level. In agreement with observations, the dissipative dynamics

allows (quasi-)non-interfering degenerate vacua with different condensates, i.e. different values for the order parameter (AM pattern textures), and (phase) transitions among them (AM patterns sequencing). These features could not be described in the frame of the original many-body model. By exploiting the existence of the infinitely many representations of the CCR's in QFT, the dissipative model allows a huge memory capacity.

In the QFT formalism for dissipative systems [44] the environment is described as the time-reversal image of the system. This is realized by "doubling" the system degrees of freedom. In the dissipative model, the brain dynamics is indeed described in terms of an infinite collection of damped harmonic oscillators a_κ (a simple prototype of a dissipative system) representing the boson DWQ modes [11] and by the \tilde{a}_κ modes which are the "time-reversed mirror image" (the "mirror or doubled modes") of the a_κ modes. \tilde{a}_κ represent the environment modes. The label κ generically denotes degrees of freedom such as, e.g., spatial momentum, etc. [11, 44].

The breakdown of the dipole rotational symmetry is induced by the external stimulus and this leads to the dynamical generation of DWQ a_κ . Their condensation in the ground state is then constrained by inclusion of the mirror modes \tilde{a}_κ in order to account for the system dissipation. The system ground state is indeed not invariant under time translation and this reveals the irreversible time evolution of the system, namely dissipation.

Although the brain holds itself far from equilibrium, the balance of the energy fluxes at the system-environment interface, including heat exchanges, holds in a sequence of states through which the brain evolves. This is manifested in the regulation of mammalian brain temperature. At some arbitrary initial time $t_0 = 0$, we denote the zero energy state (the vacuum) of the system by $|0\rangle_{\mathcal{N}}$. This prescribes [11] that $E_0 = \sum_\kappa \hbar\Omega_\kappa(\mathcal{N}_{a_\kappa} - \mathcal{N}_{\tilde{a}_\kappa}) = 0$. Here, Ω_κ is the common frequency of a_κ and \tilde{a}_κ , and \mathcal{N}_{a_κ} and $\mathcal{N}_{\tilde{a}_\kappa}$ are the (non-negative integer) numbers of a_κ and \tilde{a}_κ which are condensed in $|0\rangle_{\mathcal{N}}$.

This implies that the "memory state" $|0\rangle_{\mathcal{N}}$ is a condensate of *equal number* of modes a_κ and mirror modes \tilde{a}_κ for any κ : $\mathcal{N}_{a_\kappa} - \mathcal{N}_{\tilde{a}_\kappa} = 0$. \mathcal{N} denotes the set of integers defining the "initial value" of the condensate, $\mathcal{N} \equiv \{\mathcal{N}_{a_\kappa} = \mathcal{N}_{\tilde{a}_\kappa}, \forall \kappa, \text{ at } t_0 = 0\}$, namely the label, or *order parameter* associated to the information recorded at time $t_0 = 0$. Clearly, balancing $\mathcal{N}_{a_\kappa} - \mathcal{N}_{\tilde{a}_\kappa}$ to be zero for any κ , does not fix the value of either \mathcal{N}_{a_κ} or $\mathcal{N}_{\tilde{a}_\kappa}$ for any κ . It only fixes, for any κ , their difference. Therefore, at t_0 we may have infinitely many perceptual states, each one in one-to-one correspondence to a given \mathcal{N} set.

The dynamics ensures that the number $(\mathcal{N}_{a_\kappa} - \mathcal{N}_{\tilde{a}_\kappa})$ is a constant of motion for any κ (see [11]). The system of \tilde{a}_κ mirror modes represents the system's *Double*.

It can be shown that a_κ and \tilde{a}_κ modes satisfy the Bose-Einstein distribution. $|0\rangle_{\mathcal{N}}$ is thus recognized to be a finite temperature state and it can be shown to be a squeezed coherent state [11, 15, 45, 46].

The important point is that the spaces $\{|0\rangle_{\mathcal{N}}\}$ and

$\{|0\rangle_{\mathcal{N}'}\}$ are each other unitarily inequivalent for different labels $\mathcal{N} \neq \mathcal{N}'$ in the infinite volume limit:

$$\lim_{V \rightarrow \infty} \langle 0|0\rangle_{\mathcal{N}\mathcal{N}'} \longrightarrow 0 \quad \forall \mathcal{N}, \mathcal{N}', \quad \mathcal{N} \neq \mathcal{N}' . \quad (1)$$

The whole space of states thus includes infinitely many unitarily inequivalent representations $\{|0\rangle_{\mathcal{N}}\}$, for all \mathcal{N} 's, of the CCR's. A huge number of sequentially recorded memories may *coexist* without destructive interference since infinitely many vacua $|0\rangle_{\mathcal{N}}, \forall \mathcal{N}$, are independently accessible. In contrast with the non-dissipative model, recording the memory \mathcal{N}' does not necessarily produce destruction of previously printed memory $\mathcal{N} \neq \mathcal{N}'$, which is the meaning of the non-overlapping in the infinite volume limit expressed by Eq. (1). Dissipation allows the possibility of a huge memory capacity by introducing the \mathcal{N} -labeled "replicas" of the ground state. The model thus predicts the existence of textures of AM patterns, as indeed observed in the laboratory.

The stability of the order parameter against quantum fluctuations is a manifestation of the *coherence* of the DWQ boson condensation. The memory \mathcal{N} is thus not affected by quantum fluctuations and in this sense it is a macroscopic observable. The "change of scale" (from microscopic to macroscopic scale) is dynamically achieved through the boson condensation mechanism. The state $|0\rangle_{\mathcal{N}}$ provides an example of "macroscopic quantum state".

In "the space of the representations of the CCR's", each representation $\{|0\rangle_{\mathcal{N}}\}$ denotes a physical phase of the system and may be thought as a "point" identified by a specific \mathcal{N} -set. In the infinite volume limit, points corresponding to different \mathcal{N} sets are distinct points (do not overlap, cf. Eq. (1)). We also refer to the space of the representations of the CCR's as to the "memory space" or the *brain state space*. The brain in relation with the environment may occupy any one of the multiplicity of ground states, depending on how the $E_0 = 0$ balance or equilibrium is approached. Or else, it may sit in any state that is a collection or superposition of these brain-environment equilibrium ground states. The system may shift, under the influence of one or more stimuli acting as a control parameter, from ground state to ground state in this collection (from phase to phase) namely it may undergo an extremely rich sequence of phase transitions, leading to the actualization of a sequence of dissipative structures formed by AM patterns, as indeed experimentally observed.

Denote by $|0(t)\rangle_{\mathcal{N}}$ the state $|0\rangle_{\mathcal{N}}$ at time t specified by the initial value \mathcal{N} , at $t_0 = 0$. Time evolution of the state $|0(t)\rangle_{\mathcal{N}}$ is represented as the trajectory of "initial condition" specified by the \mathcal{N} -set in the space of the representations $\{|0(t)\rangle_{\mathcal{N}}\}$. The state $|0(t)\rangle_{\mathcal{N}}$ provides the 'instantaneous picture' of the system at each instant of time t , or the 'photogram' at t in a cinematographic sequence.

When the DWQ frequency is time-dependent, κ -components of the \mathcal{N} -set with higher momentum have been found to possess longer life-time. Since the mo-

mentum is proportional to the reciprocal of the distance over which the mode can propagate, this means that modes with shorter range of propagation (more “localized” modes) survive longer. On the contrary, modes with longer range of propagation decay sooner. Correspondingly, condensation domains of different finite sizes with different degree of stability are allowed in the model [51].

Finally, let us observe that coherent domains of finite size are obtained by non-homogeneous boson condensation described by the condensation function $f(x)$ which acts as a “form factor” specific for the considered domain [15, 47, 48]. The important point is that such a condensation function $f(x)$ has to carry some topological singularity in order for the condensation process to be physically detectable. A regular function $f(x)$ would produce a condensation which could be easily “washed” away by a convenient field transformation (“gauged” away by a gauge transformation). In a similar way, the phase transition from one space to another (inequivalent) one can be only induced by use of a singular condensation function $f(x)$. One can show that this is the reason why topologically non trivial extended objects, such as vortices, appear in the processes of phase transitions [15, 47, 48]. Stated in different words, this means that phase transitions driven by boson condensation are always associated with some singularities in the field phase (indeterminacy of the phase at the phase transition point). The observational counterpart in the brain dynamics is the decrease in power that in the perceptual phase transition precedes the formation of a new AM pattern which reflects the reduction in the amplitude of the spontaneous background activity [40]. The event that initiates a phase transition is thus an abrupt decrease in the analytic power of the background activity to near zero, depicted as a null spike. This reduction induces a brief state of indeterminacy in which the amplitude of ECoG is near to zero and phase of ECoG is undefined, as indeed should be as said above according to the dissipative model.

If a stimulus arrives at or just before this state, then the cortex can be driven by the input across the phase transition process to a new AM pattern. The response amplitude depends not on the input amplitude, as the dissipative model also predicts, but on the intrinsic state of the cortex, specifically the degree of reduction in the power and order of the background brown noise. The null spike in the band pass filtered brown noise activity is conceived as a *shutter* that blanks the intrinsic background. At very low analytic amplitude when the analytic phase is undefined, the system, under the incoming weak sensory input, may re-set the background activity in a new AM frame, if any, formed by reorganizing the existing activity, not by the driving of the cortical activity by input (except for the small energy provided by the stimulus that is required to select an attractor and force the phase transition). The decrease (*shutter*) repeats in the theta or alpha range, independently of the repetitive sampling of the environment by limbic input. In conclu-

sion, the reduction in activity constitutes a singularity in the dynamics at which the phase is undefined (in agreement with the dissipative model requiring the singularity of the boson condensation function). The aperiodic shutter allows opportunities for phase transitions. The power is not provided by the input, exactly as the dissipative model predicts, but by the pyramidal cells, which explains the lack of invariance of AM patterns with invariant stimuli [40].

IV. EMERGENCE AND RECURRENCE OF AMPLITUDE PATTERNS

High-density electrode arrays (typically 8×8 in a $2D$ square) fixed on the scalp or the epidural surface of cortical areas and fast Fourier transform (FFT) have been used in order to measure AM pattern textures for which high spatial resolution is required [1, 49].

The set of n amplitudes squared from an array of n electrodes (typically 64) defines a feature vector, $\mathbf{A}^2(t)$, of the spatial pattern of power at each time step. The vector specifies a point on a dynamic trajectory in *brain state space*, conceived as the collection of all possible brain states, essentially infinite. Measurement of n EEG signals defined a finite n -dimensional subspace, so the point specified by $\mathbf{A}^2(t)$ is unique to a spatial AM pattern of the aperiodic carrier wave. Similar AM patterns form a cluster in n -space, and multiple patterns form either multiple clusters or trajectories with large Euclidean distances between digitizing steps through n -space. A cluster with a verified behavioral correlate denotes an *ordered AM pattern*. The vector $\mathbf{A}^2(t)$ is taken to be the best available numeric estimator of our order parameter, because when the trajectory of a sequence of points enters into a cluster, that location in state space signifies increased order from the perspective of an intentional state of the brain, owing to the correlation with a conditioned stimulus. We use the reciprocal of the absolute value of the step size between successive values of $D_e(t) = |\mathbf{A}^2(t) - \mathbf{A}^2(t-1)|$ as a scalar index of our order parameter.

Pattern amplitude stability was proved by small steps in Euclidean distances, $D_e(t)$, between consecutive points (higher spikes in Fig. 1). Pattern phase stability was proved by calculating the ratio, $R_e(t)$, of the temporal standard deviation of the mean filtered EEG to the mean temporal standard deviation of the n EEGs [3, 4] (lower curve in Fig. 1). By these measures AM/phase-modulated patterns stabilized just after the phase transitions and before reaching the maximum in the spatial AM pattern amplitude. $R_e(t) = 1$ when the oscillations were entirely synchronized. When n EEGs were totally desynchronized, $R_e(t)$ approached one over the square root of the number of digitizing steps in the moving window. Experimentally $R_e(t)$ rose rapidly within a few *ms* after a phase discontinuity and several *ms* before the onset of a marked increase in mean analytic amplitude, $\underline{A}(t)$.

The succession of the high and low values of $R_e(t)$ revealed episodic emergence and dissolution of synchrony; therefore $R_e(t)$ was adopted as an index of cortical *efficiency* [50], on the premise that cortical transmission of spatial patterns was most energy-efficient when the dendritic currents were most synchronized.

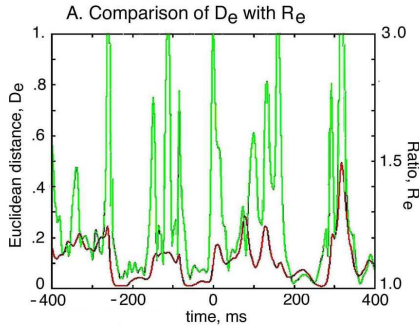


FIG. 1. Spikes: D_e stability measure. Curve: R_e boson density. [3]

Re-synchronized oscillations in the beta range near zero lag commonly recurred at rates in the theta range and covered substantial portions of the left cerebral hemisphere under observation [2] (exceeding the length of the recording array (19 cm) in human brain).

We conclude that a specific value of the phenomenological order parameter $\mathbf{A}^2(t)$ may be assumed to correspond to a specific value of \mathcal{N} of the order parameter predicted by the dissipative model: the observation of the AM pattern textures and of their sequencing finds thus a description in the dissipative model. The time evolution in the brain space described by the space of the representations of the CCR's gives the image of quantum origin of the trajectories described by the time dependent vector $\mathbf{A}^2(t)$ in the brain state space as phenomenologically described above .

A further agreement of the dissipative model with observed features is recognized by considering the common frequency $\Omega_\kappa(t)$ for the a_κ and \tilde{a}_κ modes (cf. Eq. (8) in [51]): the duration, size and power of AM patterns are predicted to be decreasing functions of the carrier wave number κ , as indeed confirmed in the observations. Carrier waves in the gamma range (30 – 80 Hz): durations seldom exceeding 100 ms, diameters seldom exceeding 15 mm; low power in the $1/f^a$ relation. Carrier frequencies in the beta range (12 – 30 Hz): durations often exceeding 100 ms; estimated diameters large enough to include multiple primary sensory areas and the limbic system; greater power by $1/f^a$.

V. FREE ENERGY AND CLASSICALITY

In the frame of the dissipative model one can show that, provided changes in the inverse temperature β are slow, the changes in the energy $E_a \equiv \sum_k E_k \mathcal{N}_{a_k}$ and in

the entropy \mathcal{S}_a are related by

$$dE_a = \sum_k E_k \dot{\mathcal{N}}_{a_k} dt = \frac{1}{\beta} d\mathcal{S}_a \quad , \quad (2)$$

i.e. the minimization of the free energy \mathcal{F}_a holds at any t :

$$d\mathcal{F}_a = dE_a - \frac{1}{\beta} d\mathcal{S}_a = 0 \quad . \quad (3)$$

As usual heat is defined as $dQ = \frac{1}{\beta} d\mathcal{S}_a$. Moreover, the time-evolution of the state $|0(t)\rangle_{\mathcal{N}}$ at finite volume V is controlled by the entropy variations, which reflects the irreversibility of time evolution (breakdown of time-reversal symmetry) characteristic of dissipative systems, namely the choice of a privileged direction in time evolution (*arrow of time*) [11, 44].

Eq. (2) shows that the change in time of the condensate, i.e. of the order parameter, turns into heat dissipation dQ . Therefore the ratio between the rate of free energy dissipation to the rate of change in the order parameter is a good measure of the ordering stability. This is in agreement with observations. Indeed, in terms of the laboratory observables the rate of change of the order parameter is specified by the Euclidean distance $D_e(t)$ between successive points in the n -space. Typically $D_e(t)$ takes large steps between clusters, decreases to a low value when the trajectory enters a cluster, and remains low for tens of ms within a frame. Therefore $D_e(t)$ serves as a measure of the spatial AM pattern stability. Empirically [6, 7] it was found that the best predictor of the onset times of ordered AM patterns was, as suggested by the dissipative model, the ratio $H_e(t)$ of the rate of free energy dissipation to the rate of change in the order parameter because $D_e(t)$ falls and $\mathbf{A}^2(t)$ rises with wave packet evolution:

$$H_e(t) = \frac{\dot{\mathbf{A}}^2(t)}{D_e(t)} .$$

This index is named the *pragmatic information* index after Atmanspacher and Scheingraber [52].

Our measurements showed that typically the rate of change in the instantaneous frequency $\omega(t)$ was low in frames that coincided with low $D_e(t)$ indicating stabilization of frequency as well as AM pattern. Between frames $\omega(t)$ increased often several fold or decreased even below zero in interframe breaks that repeated at rates in the theta or alpha range of the EEG [2] (*phase slip* [53]).

In the dissipative model as well as in the laboratory observations the time evolution of the brain state is represented as a trajectory in the brain state space. The possibility of deriving from the microscopic dynamics the classicality of such trajectories is one of the merits of the dissipative many-body field model [11, 12, 51, 54]. These trajectories are found to be deterministic chaotic trajectories [54, 55], and thus the observed changes in the order parameter become susceptible to be described in terms

of trajectories on attractor landscapes. One can show indeed that in the brain space the trajectories are *classical* and that

i) they are bounded and each trajectory does not intersect itself (trajectories are not periodic).

ii) there are no intersections between trajectories specified by different initial conditions.

iii) trajectories of different initial conditions are diverging trajectories.

The property *ii*) implies that no *confusion* or interference arises among different memories, even as time evolves. In realistic situations of finite volume, states with different \mathcal{N} labels may have non-zero overlap (non-vanishing inner products). This means that some *association* of memories becomes possible. In such a case, at a “crossing” point between two, or more than two, trajectories, one can “switch” from one of these trajectories to another one which there crosses. This reminds us of the “mental switch” occurring, in the perception of ambiguous figures, or in general, while performing some perceptual and motor tasks [56, 57] as well as while resorting to free associations in memory tasks [58].

From the property *iii*) one can derive [54] that the difference between κ -components of the sets \mathcal{N} and \mathcal{N}' may become zero at a given time t_κ . However, the difference between the sets \mathcal{N} and \mathcal{N}' does not necessarily become zero. The \mathcal{N} -sets are made up by a large number (infinite in the continuum limit) of $\mathcal{N}_{a_\kappa}(\theta, t)$ components, and they are different even if a finite number (of zero measure) of their components are equal (here θ is a convenient parameter, see [54, 55]). On the contrary, for very small $\delta\theta_\kappa$, suppose that $\Delta t \equiv \tau_{max} - \tau_{min}$, with τ_{min} and τ_{max} the minimum and the maximum, respectively, of t_κ , for all κ 's, be “very small”. Then the \mathcal{N} -sets are “recognized” to be “almost” equal in such a Δt . Thus we see how in the “recognition” (or recall) process it is possible that “slightly different” \mathcal{N}_{a_κ} -patterns are “identified” (recognized to be the “same pattern” even if corresponding to slightly different inputs). Roughly, Δt provides a measure of the “recognition time”.

The relevant point, at the present stage of our research, is that the dissipative model predicts that the system trajectories through its physical phases may be chaotic [54] and itinerant through a chain of ‘attractor ruins’ [59], embedded in a set of attractor landscapes [60] accessed serially or merely approached in the coordinated dynamics of a metastable state [61–64]. The manifold on which the attractor landscapes sit covers as a “classical blanket” the quantum dynamics going on in each of the representations of the CCR’s (the AM patterns recurring at rates in the theta range (3 – 8 Hz)). The picture which emerges is that a CS *selects* a basin of attraction in the primary sensory cortex to which it converges, often with very little information as in weak scents, faint clicks, and weak flashes. The convergence constitutes the process of *abstraction*. The astonishingly low requirements for information in high-level perception have been amply demonstrated by recent accomplishments in sensory sub-

stitution [22, 65, 66]. There is an indefinite number of such basins in each sensory cortical area forming a pliable and adaptive attractor landscape. Each attractor can be selected by a stimulus that is an instance of the category (*generalization*) that the attractor implements by its AM pattern. In this view the waking state consists of a collection of potential states, any one of which but only one at a time can be realized through a phase transition.

VI. FINAL REMARKS AND CONCLUSIONS

In this paper we have compared the predictions of the dissipative quantum model of brain with the dynamical formation of spatially extended domains in which widespread cooperation supports brief epochs of patterned oscillations. The model seems to explain two main features of the neurophysiological data: the coexistence of physically distinct AM patterns correlated with categories of conditioned stimuli and the remarkably rapid onset of AM patterns into irreversible sequences that resemble cinematographic frames. A relevant rôle is played by the main ingredients of the model, namely spontaneous breakdown of symmetry and dissipation: each spatial AM pattern is indeed described to be consequent to spontaneous breakdown of symmetry triggered by external stimulus and is associated with one of the QFT unitarily inequivalent ground states. Their sequencing is associated to the non-unitary time evolution implied by dissipation. Many other features predicted by the model have been found in agreement with laboratory observations.

We finally observe that another possible way to break the symmetry in QFT is to modify the dynamical equations by adding one or more terms that are explicitly not consistent with the symmetry transformations (are not symmetric terms). In QFT this is called *explicit* breakdown of symmetry. The system is forced by the external action into a specific non-symmetric state that is determined by the imposed breaking term. Again this fits well with our observation in the response of cortex to perturbation by an impulse, such as an electric shock, sensory click, flash, or touch: the evoked or *event-related potential* (ERP). The explicit breakdown in cortical dynamics is observed by resort to stimulus-locked averaging across multiple presentations in order to remove or attenuate the background activity, so as to demonstrate that the location, intensity and detailed configuration of the ERP is predominantly determined by the stimulus, so the ERP can be used as evidence for processing by the cortex of exogenous information. Contrastingly, in SBS the AM pattern configurations are determined from information that is endogenous from the memory store.

The variety of these highly textured AM patterns, their exceedingly large diameters in comparison to the small sizes of the component neurons, the long ranges of correlation despite the conduction delays among them, and the extraordinarily rapid temporal sequence in the neocorti-

cal phase transitions by which they are selected, provide the principal justification for exploring the interpretation of nonlinear brain dynamics in terms of dissipative many-body theory and multiple ground states to complement basin-attractor theory.

In conclusion, much work remains to be done in many research directions, such as the analysis of the interaction between the boson condensate and the details of the electrochemical neural activity, or the problems of extending the dissipative many-body model to account for higher cognitive functions of the brain. At the present status of our research, the study of the dissipative many-body

dynamics underlying the richness of the laboratory observations seems to be promising. John von Neumann noted that "...the mathematical or logical language truly used by the central nervous system is characterized by less logical and arithmetical depth than what we are normally used to. ...We require exquisite numerical precision over many logical steps to achieve what brains accomplish in very few short steps" (pp.80-81 of [67]). The dissipative quantum model describing the textured AM patterns and the sequential phase transitions observed in brain functioning perhaps opens a window on such a view.

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