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A Quantum-Classical Model of Brain Dynamics

Alessandro Sergi

Dipartimento di Scienze Matematiche e Informatiche,
Scienze Fisiche e Scienze della Terra,
Università degli Studi di Messina,
Viale F. Stagno d'Alcontres 31,
98166 Messina, Italy
and
Institute of System Science, Durban University of Technology,
P. O. Box 1344, Durban, 4000, KwaZulu-Natal,
South Africa; correspondence: asergi@unime.it

Antonino Messina

Dipartimento di Matematica ed Informatica dell'Università di Palermo,via Archirafi 34,
Palermo, I-90123, Italy; antonino.messina@unipa.it, antonino.messina1949@gmail.com

Gabriel Hanna

Department of Chemistry, University of Alberta,
11227 Saskatchewan Drive Edmonton, Edmonton,
AB T6G 2G2, Canada; gabriel.hanna@ualberta.ca

Carmelo M. Vicario

Dipartimento di Scienze Cognitive, Psicologiche,
Pedagogiche e degli Studi Culturali, Università degli Studi di Messina,
Messina, Italy; carmelomario.vicario@unime.it

Gabriella Martino

Dipartimento di Medicina e Clinica Sperimentale,
Università degli Studi di Messina, Messina, Italy; gabriella.martino@unime.it

Abstract

In this article, we posit an approach to study brain processes by means of the quantum-classical dynamics of a Mixed Weyl symbol. The Mixed Weyl symbol is used to describe brain processes at the microscopic level and, when averaged over an appropriate ensemble, provides a link to the results of measurements made at the mesoscopic scale. The approach incorporates features of three well-known approaches (which are also reviewed in this paper), namely the electromagnetic field theory of the brain, orchestrated objective reduction theory, and the dissipative quantum model of the brain. Within this approach, quantum variables (such as nuclear and electron spins, dipolar particles, electron excited states, and tunnelling degrees of freedom) may be represented by spinors while while the electromagnetic fields and phonon modes involved in the processes are treated either classically or semiclassicaly, by also considering quantum zero-point fluctuations. In the proposed computation scheme, zero-point quantum effects can be incorporated into numerical simulations by controlling the temperature of each field mode *via* coupling to a dedicated Nosé-Hoover chain thermostat. The temperature of each thermostat is chosen in order to reproduce quantum statistics in the canonical ensemble. Viewing the brain in terms of QC processes has consequences on the theory of clinical psychology and potential implications for its practice.

I. INTRODUCTION

We would like to begin this paper with a quote by Judah Schwartz [1]: "the essence of mathematical creativity lies in the making and exploring of mathematical conjectures." The conjecture that it will be explored in this work is instead of a physical nature. Assuming that brain processes, spanning many scales of length and time, possess both quantum and classical elements, we propose a hybrid quantum-classical (QC) theoretical framework for describing the link between the microscopic and the mesoscopic levels of brain dynamics.

The human brain is perhaps the most complicated condensed matter system known. It is composed of about 10^2 billions of neurons and at least as many glia cells [2]. The brain is composed of 77 to 78 % water, 10 to 12 % lipids, 8 % proteins, 2 % soluble organic substances, and 1 % carbohydrates and inorganic salts [3]. It is also extremely fascinating that higher brain functions precisely define what it means to be human. Brain states and their dynamics have so far eluded a fundamental physical understanding. This means that it is most likely impossible to describe brain dynamics by brute force, *i.e.*, starting from the atomic level and reconstructing mesoscopic and macroscopic dynamics. Complex statistical systems invariably display emergent properties that cannot be reduced to the behavior of their microscopic constituents. Hence, a theoretical description of brain functions requires bridging many different time and length scales, going from molecules to clusters of brain cells, with the hope to achieve a better understanding of emergent properties of brain properties, such as, for example, cognition, emotions, and feelings.

Some of the most complex brain functions are delocalized over long distances and require synchronization processes that do not seem easy to explain through classical mechanics alone. In particular, the wholeness of perception requires to integrate the activity of an enormous number of brain cells. With respect to this, quantum features such as entanglement [4–6], nonlocality, contextuality, and coherence [7, 8] may hold the key to a possible microscopic understanding of brain functions. Over the years, several models supporting the importance of quantum mechanical effects in the brain have been put forth. In this paper, we present a review of three approaches to brain dynamics: The Electromagnetic Field (EMF) approach [9–17], Orchestrated Objective Reduction (Orch OR) theory [18–30], and the Dissipative Quantum Model of Brain (DQMB) [31–39]. These three approaches all view the brain from the perspective of condensed matter physics and matter-EMF interactions. We too adopt such a point of view and, borrowing various elements of these formalisms, propose a quantum-classical (QC) approach to brain dynamics. The expectation is that a QC formalism should simplify numerical calculations of averages and response functions, which could be compared with the pertinent experimental results of neuroscientists. At the same time, we believe that a QC description is more relevant than a purely quantum or classical one for describing brain processes because they involve multiple time and length scales.

There are several key differences between the EMF, Orch OR, and DQMB approaches. While DQMB [31–39] is mainly concerned with the explanation of memory storage and retrieval, long-range correlations between brain clusters of cells and brain correlates of perception, both the EMF [9–17] and Orch OR [18–30] approaches claim to describe aspects of consciousness. In this paper, we do not consider such models as possible candidates for the explanation of consciousness; rather, whenever we discuss the EMF or Orc OR approach, we reinterpret them as models for the study of brain dynamics.

In many QC theories, the nature of the interaction between the classical and quantum subsystem is somewhat unclear and the quantum and classical degrees of freedom (DOF) are not treated on the same footing. However, there is a formulation of QC dynamics based on Mixed Weyl symbols [40–60] that is conceptually free from this drawbacks. Hence, we believe that it can be very useful to address brain dynamics within this framework [40–60]. Having in mind the construction of efficient numerical simulation algorithms, although possible, we do not adopt a quantum field approach. Our idea is to eventually use QC spin-boson models [61–64] with the dissipation represented in terms of equilibrium or non-equilibrium thermostats and/or non-Hermitian Hamiltonians. In such models, the Mixed Weyl symbol of the statistical operator is a convenient tool to describe the

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dissipative dynamics of the quantum subsystem of interest. We note that the QC approach to brain dynamics proposed herein is still in its early stages. However, our goal in this paper is to first lay down a stepping stone toward a consistent description of the open quantum system brain dynamics in a classical environments [40–60].

One hopes that quantum approaches to biological processes might revolutionize medical research [65]. Similarly, pursuing either a quantum or a QC explanation of brain dynamics may lead to improvements in mental health care, a deeper knowledge of the quantum roots of neuroscience [66–68], and novel tools for clinical psychology [69–80]. To this end, we discuss General Semantics (GS) [69–71], Syncronicity [72–76], and Bi-logic [77–80] and illustrate their link to a QC perspective on psychological processes.

The paper is structured as follows. In Sec. II to IV, we review the EMF, Orch OR, and DQMB approaches, respectively. Our QC approach is presented in Sec. V. A discussion of the conceptual links between QC view on the brain and both theoretical and clinical psychology is given in Sec. VI. In particular, Subsec. VI A discusses GS, Subsec. VI B treats Synchronicity, and Subsec. VI C examines Bi-logic. Finally, our conclusions are given in Sec. VII.

II. ELECTROMAGNETIC FIELDS IN THE BRAIN

The role of EMFs in bridging space and time scales is undeniable [9–17]. Brain states are routinely studied *via* computer simulation [81] and various noninvasive stimulation techniques such as alternating current stimulation (ACS) [82–85] and transcranial direct-current stimulation (TDCS) [87, 88]. In particular, TDCS is one of the most investigated methods in the field of non-invasive brain stimulation. It modulates the excitability of the cerebral cortex with direct electrical currents ($1 \approx 2$ mA) delivered *via* two or more electrodes of opposite polarities (*i.e.*, anode and cathode) placed on the scalp. TDCS modulates resting neuronal membrane potentials at sub-threshold levels [87], with anodal and cathodal stimulation increasing and decreasing cortical excitability, respectively [88]. Although the TDCS-induced physiological mechanisms are not yet fully understood, it is assumed that its effects are based on long-term potentiation (LTP) and long-term depression-like (LTD) mechanisms [88, 89]. Although the EMF approach was not originally related to QM when it was first formulated [9–17], a deeper quantum optical reformulation [90–94] cannot be excluded in principle.

In the history of brain research, it was assumed that higher brain functions, such as learning and memory, arise from electrical impulses passing through neurons. The physical explanation of permanent information storing was assigned to multiple reflections of impulses through neuron circuits [95, 96]. This idea is basically exemplified by the Hodgkin-Huxley model [97]. This model runs into problems since also glia cells take part in brain functions [98, 99]. Of course, more complicated models, based on intricate networks including glia and other molecules, have been proposed (see Ref. citeagnati, for example). However, even assuming that, by means of Darwinian evolution, the most efficient hyper-network can emerge, given enough time, there still would be the problem of explaining the origin of *software* running on the hyper-network. One has to also consider that the classical theories of self-assembling of hyper-networks are based on statistical fluctuations, *e.g.*, on the mechanism that Schrödinger called "order from disorder" [101]. This kind of order is associated with diffusive motion and entropy increase in the system. As discussed by Schrödinger [101], an order-from-disorder mechanism cannot explain the synchronization of molecular processes, which is required by brain functions and living matter in general. In order to explain living matter, Schrödinger proposed the mechanism of "order from order" [101], which is fundamentally based on quantum mechanics. In his book [101], first published in 1944, Schrödinger speculated that an "aperiodic solid" was key to implement the quantum mechanism of order from order. This idea led to the discovery of DNA.

The idea that other physical agents, rather that the sole dynamics of neural networks, must be invoked to describe highly coordinated brain activity is not new [102–105]. Electric charges (*e.g.*, electrons, protons, ions), together with their associated currents, are the sources of EMFs [9–12, 15, 16]. In turn, these EMFs interact with water dipoles and also influence van der Waals and Casimir interactions among brain macromolecules. ACS has shown the importance of EMFs in the brain [82–85], TDCS of human subjects [87, 88] has shown the importance how both cognition processes and psychological state changes can be modulated. For instance, Anodal (excitatory) TDCS of the prefrontal cortex boosts affective memory such as fear extinction learning [106–108]. Moreover, the cathodal (*i.e.*, inhibitory) stimulation of the tongue motor neurons of the primary motor cortex reduces appetite [109].

The working of TDCS might be understood through a mechanical analogy. The complex dynamics of brain EMFs can be reduced to the time evolution of their sources. Such a dynamics can be mapped onto that of a harmonic spring mattress. Within this pictorial description, TDCS can be equated to the nonlinear effect generated by the application of a constant pressure to specific extended regions of the spring mattress. The applied pressure changes the harmonic dynamics of the mattress so that oscillations with principal frequencies (phonons) scatter with each other. This mechanical model might be useful to perform computer simulations of certain processes which are

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observed in TDCS. We note that the same model can give a pictorial representation of quantum fields dynamics [110]. Both ACS and TDCS provide evidence that brain EMFs are not ephemeral; they are correlated to the dynamics of their sources, but they also react back and influence both cognitive functions and emotions.

When studying brain dynamics on the mesoscopic scale of EMFs, it may seem that there is no necessity to invoke any quantum effect. However, observable coherent EMFs have by definition a well-defined phase. Quantum mechanically, phase and photon numbers are conjugate variables. This implies that coherent EMFs possess an intrinsic uncertainty in the number of photons, which is of purely quantum mechanical origin. In other words, coherent EMFs are composed of virtual photons [90], e.g., packets of energy in momentum space whose existence is ephemeral. Interestingly, experimental evidence shows that dendrimers can act as trap for photons [91, 92]. According to quantum electrodynamic [93], a trapped photon may be considered as a virtual photon. Thus, it is difficult to disentangle the action of EMFs from quantum effects in the brain [94].

III. PENROSE AND HAMEROFF'S ORCH OR

Orch OR theory [18–30] provides a detailed molecular mechanism for the time evolution of brain states. According to Orch OR theory [18–30], quantum effects in tubulin proteins (which are organized in arrays of microtubules inside the cytoplasm of brain cells) play an important role in brain function. Quantum dynamics of the electronic orbitals of carbon rings inside tubulins, time evolution of the nuclear spins, quantum energy transport among microtubules, and spontaneous collapse of microtubules' wave function are the main ingredients this theory. Upon collapse of the wave function, classical brain dynamics ensues. Thus, Orch OR theory may also be considered a QC theory of brain processes.

One peculiar characteristic of Orch OR is that neurons are not considered the fundamental units of information processing [17]. Instead, in Orch OR it is proposed that information processing takes place in ordered arrays of microtubules inside the cell. This idea slowly took form during the 1980s and the first part of the 1990s when Hameroff noticed the effects of anesthetics on networks of microtubules inside the cell. In a series of papers, Hameroff *et al.* [111–116] proposed that some kind of digital computation was taking place in arrays of microtubules. Such a computation was based on nonlinear electrodynamic effects [111–116]. However, the question of how the results of local digital calculations could be efficiently transferred between distant regions brain regions by classical diffusive mechanisms remained. Hence, Hameroff started his search for different mechanisms. On a different path, looking for a fundamental explanation of wave function collapse in QM, Penrose elaborated the theory of Objective Reduction (OR) [21–25].

In the standard interpretation of QM, the collapse of the wave function, *i.e.*, the transition from the worlds of possibilities to that of classical events [117, 118], is explained only through the stochastic interaction of the quantum system with a classical one. As a matter of fact, there are two sources of randomness in QM: one is the intrinsic randomness associated with the unpredictability of the state in which a quantum system collapses after interacting with a classical systems. The other source of stochasticity arises from the ignorance of the precise time and place in which the quantum system interacts with the classical system. Besides, considering that quantum particles are the fundamental building blocks of classical systems, without some physical process through which complex quantum systems can become classical, QM retains an aura of logical inconsistency. This is, in its essence, the infamous quantum measurement problem, which is basically unsolved till today [119]. OR proposes that the superposition of different stationary mass distributions becomes unstable because of quantum gravitational effects, and, beyond a certain threshold time interval, it naturally collapses according to the standard probabilistic rules of QM, but without any external intervention of a "measuring instrument". A simple way to discuss this process is to consider

$$\omega_{\rm Bohr} = \Delta E/\hbar \ , \tag{1}$$

as the Bohr frequency of the energy eigenvalues of two eigenstates involved in a certain superposition. Penrose gives a number of reasons why the superposition must become unstable in the presence of quantum gravitational effects. The lifetime of the superposition is given by

$$\tau \approx \frac{h}{\Delta E} \ . \tag{2}$$

Looking at Eqs. (1) and (2), one might say that, in a certain sense, the deterministic time evolution of the gravitational field acts as the instrument measuring the superposition. However, according to Penrose [21–25], there is an important difference between the measurement of the superposition by a classical instrument and by a quantum gravitational field. A measurement performed by a quantum gravitational field, is still a fully quantum mechanical process and as such it is intrinsically random and absolutely non computable. Penrose considered that brain dynamics is interspersed with discrete events (see Ref. [13] for experimental support of this idea). On a phenomenological basis, such events parallel the discontinuity of wakenfulness and awareness [13] and other rhythmic phenomena in the brain. Penrose identified discrete events in the brain with series of wave function collapses. Between one collapse and the other, the brain can evolve coherently so that new superpositions are formed. We note that such a coherent evolution of the wave function, interrupted by

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quantum gravitational collapses, is reminiscent of both piecewise deterministic processes in open quantum systems [120] and nonadiabatic dynamics of QC system in the adiabatic basis.

While Penrose put forth the idea that OR could have an important role in brain dynamics, Hameroff fleshed out the detailed biomolecular mechanisms. Inside each tubulin protein making up a given microtubule, Hameroff hypothesized the existence of quantum matter systems able to support stable quantum dynamics in between OR events. One example is given by carbon rings and their delocalized molecular orbitals, which can evolve coherently in a superposition of states.. The carbon rings are pushed by hydrophobic forces into the tubulin's interior, shielding them from the decoherence [121] caused by the polar environment outside the protein. The carbon rings forms helical structures inside each microtubule. They also create oriented arrangements that can act as quantum channels [26, 27] through which quantum signals travel among the lattice of microtubules inside the cell's cytoskeleton.

Various types of quantum oscillators are therefore found in microtubules' ordered structures, *e.g.*, time-dependent electric fields arising from the dynamic polarization of molecular charges (which produce van der Waal and Casimir-Polder forces), magnetic fields originating from electron spin dynamics, etc. Notably, it has also been suggested [28] that nuclear spins can play an important role in Orch OR theory since they are shielded from decoherence for longer time intervals than other quantum systems in the brain. Recently, this theory [28] has gained experimental support [29]. The frequencies of all such quantum oscillators range from kilohertz to terahertz. Orch OR theory requires the feedback [30] between the quantum coherent evolution of microtubules and, for example, the classical dynamics of microtubule-associated proteins (MAPs) [122, 123]. Notably, the classical dynamics of MAPs and CAMKII, *viz.*, the direction of motion, the place where to halt their motion, interacting or non interacting with the tubulins, the event of interaction or non-interaction, and the precise time whe they interact, are determined by the coherent evolution of the microtubule' wave function, before the OR takes place.

Lately, there has been a convergence of ideas between the approach to brain dynamics *via* quantum EMFs [90–92] and Orch OR [130]. The physical process underlaying quantum signaling in Orch OR has been assumed to be photon emission. Due to the work of Alexander Gurwitsch, it has been known since the beginning of the 20th century, that tissues inside the body emit biophotons [131–133]. Such biophotons may be supported by the hydrophobic interior region of tubulins, where tryptophanes, with their indole rings of π electron orbital forming optically active molecular orbitals, are found. The packing of indole rings may give rise to resonant energy transfer between molecular orbitals [130] much in the same way Förster resonant energy transfer takes place between close chromophores. Kurian *et al* [134] represented the microtubule as a chain of two-level systems and calculated the coupling constants in the Hamiltonian by means of Molecular Dynamics simulations and quantum chemical calculations. Exciton propagation was performed by means of the Haken and Strobl method [135]. Their main result is that energy transfer occurs on a length scale of microns, at least. What is even more interesting from the Quantum Optical perspective is that Kurian et al's simulation [134] does not consider the geometric structure of the left-handed helixes of microtubule in mammals. There are reasons to believe that superradiance can be important in such complicated geometric arrangements [136–138]. Very recently, the experimental study of Kalra et al [139] found that photonic energy transfer in microtubules occurs over 6.6 nm, it cannot be explained in terms of Föster theory, and it is damped by anesthetics. The idea that electromagnetic resonance is the fundamental mechanism of communications among molecules was first proposed by Velijko Veljkovic, who also suggested that such a mechanism could provide a long-range effective communication [140].

At this stage, we believe that a unification of the EMF and Orch OR theories of brain dynamics is conceptually very probable [94].

IV. THE DISSIPATIVE QUANTUM MODEL OF BRAIN

Although fundamentally quantum in nature, DQMB also involves the roles of classical processes. In their seminal paper [31], Ricciardi and Umezawa [31] introduced DQMB as a mesoscale model of brain's dynamics based on quantum field theory (QFT). According to this model, dissipation is ascribed to excited thermal states, while a classical nature is assigned to neurons and glia cells. Due to its mesoscopic nature, DQMB does not aim to describe the behavior of the single fundamental constituents of the brain, *e.g.*, neurons, glia cells, membranes, neurotransmitters or other macromolecules. Today, we know that all these structures form brain clusters [141, 142] that, once stimulated [82–85, 87, 88] can influence human behavior [86]. Since normal mesoscopic brain dynamics is not chaotic, brain response to stimuli cannot be expected to depend on the number N of the fundamental constituents of the clusters. Hypothesizing quantum properties of the brain, the above feature leads to the existence of well-defined brain coherent fields because of the indeterminacy relation $\Delta\Phi\Delta N \geq 1$. The virtual independence of brain dynamics on ΔN, together with the very large number N of molecules in the brain, make necessary to approach the brain as a complex statistical system. From this perspective, the brain is treated as a very complicated condensed matter systems, interacting throughs quantum fields. For example, when it is locally stimulated, there is substantial proof [82–85, 87, 88] that the brain responds with simultaneous excitations in several regions [141, 142], which are far from one another. Hence, the idea that a quantum theory can explain such nonlocal correlations naturally arises [67].

The main feature of DQMB [31] is that it can qualitatively describe both memory storage and long range correlations between distant clusters of neurons. It turns out that the explanation for the creation of correlations between distant clusters of neurons naturally arises from the possibility of memory storage. On the basis of general principles, Ricciardi and Umezawa [31] assume the existence of bosonic variables, which we may now identify with the quantum oscillators considered in Orch OR theory and discussed in Sec. III. From the perspective of QFT, such bosonic oscillators become the normal modes of quantum bosonic fields. The condensation of such quantum bosonic fields leads to inequivalent subspaces that cannot be connected by unitary transformations. Hence, when a given state is localized into anyone of these unitarily inequivalent subspaces, the natural unitary dynamics cannot determine its transition to another subspace; the initial state can only evolve within the initial subspace and remains, so to say, trapped. Such a mechanism stores class of quantum states inside specific inequivalent subspace for long times and, thus, can represent long-term memory [31]. Excited energy surfaces can be used for the explanation of short-term memory. We note that the description of memory processes from a quantum point of view [31] may have repercussions on recent suggestions about the interplay between memory and consciousness [143].

It is important to appreciate that DQMB predicts that correlations between distant excited areas of the brains do not occur *via* chemical transport but by means of an entirely different mechanism. The SSB of the ground state causes the proliferation of long-range Nambu-Goldstone bosonic excitations [144–146]. These provides the physical agent required for establishing such long-distance correlations among different areas of the brain.

DQMB does not specify the physical nature of the bosonic fields of the brain. However, after Ricciardi and Umezawa's proposal (and before Orch OR theory [18–30]), a number of physicists, among which were Giuliano Preparata, Emilio Del Giudice e Giuseppe Vitiello [147–149], suggested a reasonable choice for the bosonic variables in the brain, namely the dipoles of water molecules [147–149]. According to the theory put forth in [147–149], when water molecules have a high density, the approximation of weak coupling to the electromagnetic vacuum field [150] may not hold. It has been suggested that water in the cytoplasm is found in a structured state [151], so that the considerations of Refs. [147–149] are definitely relevant for brain dynamics. Since a water molecule is dipolar, a coherent superposition of the dipoles of many water molecules can be described by a coherent quantum dipolar field. Hence, in this model it is the condensation of the quantum dipolar field to produce a ground state with broken symmetry, *i.e.*, and many unitarily inequivalent subspaces. Consequently, Nambu-Goldstone modes arise for restoring symmetry at long range.

In DQMB [31], neurons and glia cells are considered purely classical objects. Since their theory is fundamentally a QFT, DQMB cannot explicitly describe classical objects with atomistic details, as Molecular Dynamics simulations are able to do. Dissipation is considered by means of thermal excitations, as described by Umezawa's Thermo Field Dynamics [152, 153]. The dynamical variables of DQMB are doubled upon introducing creation and annihilation operators of physical dipolar wave quanta, $\hat{a}^\dagger, \hat{a}$, respectively, and dual creation and annihilation operators of fictitious dipolar wave quanta, $\hat{v}^\dagger, \hat{v}$, respectively. For example, the Hamiltonian of the noninteracting dipolar wave quanta might be defined as [39]:

$$\hat{H}_0 = \sum_k \hbar\omega_k \left(\hat{a}_k^\dagger \hat{a}_k - \hat{v}^\dagger \hat{v}_k\right) \ , \tag{3}$$

where ω_k is the oscillation frequency of each mode. The interaction between the physical modes and their doubles can be taken as

$$\hat{H}_\mathrm{I} = i\sum_k \hbar\gamma_k \left(\hat{a}_k^\dagger \hat{v}^\dagger - \hat{a}_k \hat{v}_k\right) \ , \tag{4}$$

where γ_k is the damping constant of each mode. Finally, the total many-body Hamiltonian of the thermal system is

$$\hat{H} = \hat{H}_0 + \hat{H}_\mathrm{I}. \tag{5}$$

A thorough study of the Hamiltonian in Eq. (5), and its associated equations of motion has led to finding a number of interesting results over the years [34].

DQMB has been applied by Vitiello and collaborators to study various brain processes [33]. Some applications include nonlinear dynamics [35], cortical patterns in perception [36], the relation between fractal properties and the coherent states in the brain [37], rhythmic generators in the cortex [38], and correlations of brain regions that are realized through entanglement [39]. DQMB dynamics has also been adopted by Jack Tuszynski and collaborators in a number of works [154–156]. In Ref. [154], one notes that the phenomenon of superradiance, which is expected to occur in complicated geometric arrangements of microtubules, also occurs in DQMB.

V. THE QUANTUM-CLASSICAL DISSIPATIVE MODEL OF BRAIN

Our aim is to model multi-scale brain dynamics, explicitly treating classical and quantum DOF on the same footing. To this end, our approach considers Mixed Weyl symbols of dynamical variables (represented by operators in the standard formulation of quantum mechanics) and a Mixed Weyl symbol of the statistical operator (corresponding to the density matrix of the systems in the standard representation of QM) [40–60]. We imagine that the brain is described by quantum operators $(\hat{r}, \hat{p}, \hat{R}, \hat{P})$, where $(\hat{r}, \hat{R})$ are position operators while $(\hat{p}, \hat{P})$ are momenta operators. Now, $(\hat{r}, \hat{p}) = \hat{x}$ corresponds to the brain DOF with a long de Broglie wavelength that, for this reason, must be treated quantum mechanichally, while $(\hat{R}, \hat{P}) = \hat{X}$ can be treated semiclassically because of their much shorter de Broglie wavelength. A partial Wigner transform over the $(\hat{X})$ operators [46] introduces the Mixed Weyl symbols $\tilde{\mathcal{O}}(X)$ and $\tilde{\mathcal{W}}(X)$ arising from $\hat{\mathcal{O}}(\hat{x}, \hat{X})$ and $\rho(\hat{x}, \hat{X})$, respectively. Please, note that the following notation is adopted: when a quantum operator depends both on quantum and classical DOF, a $\tilde{}$ is written on it, while if the quantum operator does not depend on X a $\hat{}$ is used. No hat is used in the case of a dynamical variable depending only on X. A practical example of a possible application of this mixed QC representation can be given when considering molecular orbitals, electron and nuclear spins, light ions, neurons, glia cells, and electromagnetic interactions. Conformational dynamics of cells might be represent through phonons, *i.e.*, harmonic DOF. Other harmonic DOF can be used to describe coherent EMFs. The inclusion of non-Harmonic perturbation terms provides a description of non-trivial interactions among all the DOF of the model. Zero-point effects on the motion of classical-like DOF can be described by means of advanced algorithms that will be explained in the following. As in the case of DQMB, the goal is to set up a mesoscale approach to brain dynamics, only that in our case the QC dynamical variables are explicitly represented.

If we now introduce the coordinates of the EMF modes $(Q, \Pi) = \Upsilon$, a possible model Mixed Weyl symbol of the Hamiltonian $\tilde{\mathcal{H}}(X, \Upsilon)$ can be written as

$$\tilde{\mathcal{H}}(X, \Upsilon) \;=\; \hat{\mathcal{H}}_{\rm S} + \mathcal{H}_{\rm B}(X) + \mathcal{H}_{\rm F}(\Upsilon) + \tilde{\mathcal{V}}_{\rm SB}(R) + \tilde{\mathcal{V}}_{\rm SEM}(Q) \tag{6}$$

In Eq. (6), $\hat{\mathcal{H}}_{\rm S}(t)$ is the Hamiltonian operator of the quantum subsystem with quantum variables $\hat{x}$. The phononic Hamiltonian is

$$\mathcal{H}_{\rm B}(X) = \sum_{J=1}^{N_{\rm PH}} \left(\frac{P_J^2}{2} + \frac{(\omega_J^{\rm PH})^2}{2} R_J^2 \right) \;, \tag{7}$$

where $\omega_J^{\rm PH}$, $J = 1, ..., N_{\rm PH}$, are the frequencies of each phonons. Similarly, The EMF Hamiltonian is

$$\mathcal{H}_{\rm B}(\Upsilon)=\sum_{K=1}^{N_{\rm EM}}\left(\frac{\Pi_K^2}{2}+\frac{(\omega_K^{\rm EM})^2}{2}Q_K^2\right)\ , \tag{8}$$

where $\omega_K^{\rm EM}$, $K=1,...,N_{\rm EM}$, are the frequencies of the EMF modes. The interaction operators $\tilde{\mathcal{V}}_{\rm SB}(R)$ and $\tilde{\mathcal{V}}_{SEM}(Q)$ describe the coupling of the phonons and of the EMF to the quantum subsystem, respectively. Assuming a bilinear approximation these can be written as

$$\tilde{\mathcal{V}}_{\rm SB}(R) = -\sum_{J=1}^{N_{\rm PH}} C_J R_J \hat{\chi} \tag{9}$$

$$\tilde{\mathcal{V}}_{\rm SF}(Q) = -\sum_{K=1}^{N_{\rm M}} F_K Q_K \hat{\zeta}\ , \tag{10}$$

where the C_J and the F_K are the coupling constants of the quantum operators $\hat{\chi}$ and $\hat{\zeta}$, respectively. The operators $\hat{\chi}$ and $\hat{\zeta}$ acts on the same space of $\hat{x}$.

The dynamics of the Mixed Weyl symbol $\tilde{\mathcal{O}}(X,\Upsilon,t)=\tilde{\mathcal{O}}(X,\Upsilon,t)$ of an of an arbitrary operator $\hat{\mathcal{O}}$ is given by a QC bracket [40–60]. The QC bracket is a quasi-Lie bracket [55–58] that breaks the time-translation invariance of its algebra because it does not satisfy the Jacobi relation. In the case of a system with both phononic and EMF modes, it can be written by introducing two antisymmetric matrices, $\boldsymbol{\Omega}=\boldsymbol{\Omega}^{-1}$ and $\boldsymbol{\Lambda}=-\boldsymbol{\Lambda}^{-1}$:

$$\boldsymbol{\Omega}=\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \tag{11}$$

and

$$\boldsymbol{\Lambda}=\begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \\ -\mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & -\mathbf{1} & \mathbf{0} & \mathbf{0} \end{bmatrix} \tag{12}$$

where $\boldsymbol{\nabla}^{X,\Upsilon}=((\partial/\partial R),(\partial/\partial Q),(\partial/\partial P),(\partial/\partial\Pi))$ is the phase space gradient operator. The first term in the lhs of Eq. (19) is the quantum commutator while the other two terms are Poisson brackets. All terms are written in matrix form [55–58]. The super propagator associated to the QC bracket is

$$\begin{aligned}\tilde{\tilde{\mathcal{U}}}(t) &= \exp\left\{(it/\hbar)\left[\begin{array}{cc}\tilde{\mathcal{H}} & \ldots\end{array}\right]\boldsymbol{\Omega}\left[\begin{array}{c}\tilde{\mathcal{H}} \\ \ldots\end{array}\right]-(t/2)\left(\tilde{\mathcal{H}}\overleftarrow{\boldsymbol{\nabla}}^{X,\Upsilon}\boldsymbol{\Lambda}\overrightarrow{\boldsymbol{\nabla}}^{X,\Upsilon}\ldots\right)\right.\\ &+ \left.(t/2)\left(\ldots\overleftarrow{\boldsymbol{\nabla}}^{X,\Upsilon}\boldsymbol{\Lambda}\overrightarrow{\boldsymbol{\nabla}}^{X,\Upsilon}\tilde{\mathcal{H}}\right)\right\}\end{aligned} \tag{13}$$

The super-operator $\tilde{\tilde{\mathcal{U}}}(t)$ defines the dynamics of Mixed Weyl symbols of standard operators as

$$\tilde{\mathcal{O}}(t) = \tilde{\tilde{\mathcal{U}}}(t)\tilde{\mathcal{O}} , \tag{14}$$

where $\tilde{\mathcal{O}} = \tilde{\mathcal{O}}(t = 0)$. QC averages are calculated using the formula

$$\langle \tilde{\mathcal{O}}(t) \rangle = \mathrm{Tr}' \int dX d\Upsilon \, \tilde{\mathcal{W}}(X, \Upsilon)\tilde{\mathcal{O}}(X, \Upsilon, t) , \tag{15}$$

while QC correlation functions can be defined as

$$\langle \tilde{\mathcal{O}}_1(t)\tilde{\mathcal{O}}_2 \rangle = \mathrm{Tr}' \int dX d\Upsilon \, \tilde{\mathcal{W}}(X, \Upsilon)\tilde{\mathcal{O}}_1(X, \Upsilon, t)\tilde{\mathcal{O}}_2(X, \Upsilon) . \tag{16}$$

The operator Tr' found in Eqs. (15) and (16) takes the trace over the quantum operators $\hat{x}$, while $\tilde{\mathcal{O}}_1$ and $\tilde{\mathcal{O}}_2$ are two arbitrary Mixed Weyl symbols.

A. Constant Temperature Quantum-Classical Dynamics

In order to illustrate the advanced techniques for controlling the temperature of the harmonic modes, we consider a simple systems with just two phononic modes with coordinates (X_1, X_2) and two NHC chains of length one (which is usually enough to generate ergodic dynamics for stiff harmonic degrees of freedom) [157]. Thus, the extended phase space point can be written as $X^{\mathrm{e}}=$ $(R_1,\eta_1^{(1)}$, $\eta_2^{(1)}$, R_2, $\eta_2^{(1)}$, $\eta_2^{(2)}$, P_1, $P_{\eta_1}^{(1)}$, $P_{\eta_1}^{(2)}$, P_2, $P_{\eta_2}^{(1)}$, $P_{\eta_2}^{(2)})$, consequently, the extended phase space gradient is $\boldsymbol{\nabla}^{\mathrm{e}}=$ $((\partial/\partial R_1)$, $(\partial/\partial\eta_1^{(1)})$, $(\partial/\partial\eta_2^{(1)})$, $(\partial/\partial R_2)$, $(\partial/\partial\eta_1^{(2)})$, $(\partial/\partial\eta_2^{(2)})$, $(\partial/\partial P_1)$, $(\partial/\partial P_{\eta_1}^{(1)})$, $(\partial/\partial P_{\eta_2}^{(1)})$, $(\partial/\partial P_2)$, $(\partial/\partial P_{\eta_1}^{(2)})$, $(\partial/\partial P_{\eta_2}^{(2)})$. If we now define the antisymmetric matrix $\boldsymbol{\mathcal{R}} = -\boldsymbol{\mathcal{R}}^{-1}$ as

$$\boldsymbol{\mathcal{R}} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 & -P_1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & P_1 & 0 & -P_{M_{\eta_2}}^{(1)} & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & P_{M_{\eta_2}}^{(1)} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & -P_2 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & P_2 & 0 & -P_{\eta_1}^{(2)} \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & P_{\eta_1}^{(2)} & 0 . \end{bmatrix} \tag{17}$$

together with the Mixed Weyl symbol of the extended Hamiltonian

$$\tilde{\mathcal{H}}^{\rm e}(X^{\rm e}) \;=\; \hat{\mathcal{H}}_{\rm S} + \mathcal{H}_{\rm B}(X) + \tilde{\mathcal{V}}_{\rm SB}(R) + \sum_{I=1}^{2}\sum_{L=1}^{2} \frac{P_{\eta_L}^{(I)}}{2M_{\eta_L}} + \sum_{I=1}^{2}\sum_{L=1}^{2} k_{\rm B}T^{(I)}\eta_L^{(I)} \,. \tag{18}$$

the QC equation of motion at constant temperature can be written in compact form [55–58] as

$$\partial_t \tilde{\mathcal{O}}^{\rm e}(t) \;=\; \frac{i}{\hbar}\left[\begin{array}{cc}\tilde{\mathcal{H}}^{\rm e} & \tilde{\mathcal{O}}^{\rm e}(t)\end{array}\right]\boldsymbol{\Omega}\left[\begin{array}{c}\tilde{\mathcal{H}}^{\rm e}\\ \tilde{\mathcal{O}}^{\rm e}(t)\end{array}\right] - \frac{1}{2}\tilde{\mathcal{H}}^{\rm e}\overleftarrow{\boldsymbol{\nabla}}^{\rm e}\boldsymbol{\mathcal{R}}\overrightarrow{\boldsymbol{\nabla}}^{\rm e}\tilde{\mathcal{O}}^{\rm e}(t)$$
$$+\;\frac{1}{2}\tilde{\mathcal{O}}^{\rm e}(t)\overleftarrow{\boldsymbol{\nabla}}^{\rm e}\boldsymbol{\mathcal{R}}\overrightarrow{\boldsymbol{\nabla}}^{\rm e}\tilde{\mathcal{H}}^{\rm e} \,, \tag{19}$$

where $\tilde{\mathcal{O}}^{\rm e}(t) \;=\; \tilde{\mathcal{O}}^{\rm e}(X^{\rm e},t)$, the NHC variables are $(\eta_L^{(I)}, P_{\eta_L}^{(I)})$, with I and L running over the phonons and the coordinates of the chain, respectively; $k_{\rm B}$ is the Boltzmann constant and $T^{(I)}$ is the temperature of each mode and $M_{\eta_L^{(I)}}$ are the inertial parameters of the NHC variables.

Constant temperature averages and correlation functions can be calculated chosing the Mixed Weyl symbol $\tilde{\mathcal{W}}^{\rm e}(X^{\rm e})$ of the statistical operator in extended space as

$$\tilde{\mathcal{W}}^{\rm e}(X^{\rm e}) \;=\; \hat{w}_{\rm S}\mathcal{W}^{\beta}(X)\prod_{I=1}^{2}\prod_{L=1}^{2}\delta\left(\eta_L^{(I)}\right)\delta\left(P_{\eta_L}^{(I)}\right) \tag{20}$$

where $\hat{w}_{\rm S}$ is the Mixed Weyl symbol of the statistical operator of the quantum subsystem while

The thermal Mixed Weyl symbol of the statistical operators of the phonons is

$$\mathcal{W}^{\beta}(X) \;=\; \prod_{I=1}^{2}\frac{\tanh(\beta\omega_I/2)}{2}\exp\left[-\frac{2\tanh(\beta\omega_I/2)}{\omega_I}\left(\frac{P_I^2}{2}+\frac{\omega_I^2}{2}R_I^2\right)\right] \,, \tag{21}$$

where $\beta \;=\; 1/K_{\rm B}T$ and ω_I is the frequency of phonon I. If in the Mixed Weyl symbol of the Hamiltonian in Eq. (18) one defines $T^{(I)} = T \quad \forall I$, then the dynamics defined by Eq, (19) defines constant-temperature evolution. Instead, the choice of $T^{(I)} = 1/k_{\rm B}\beta^{(I)}$, with

$$\beta^{(I)} = \frac{2\tanh(\beta\omega_I/2)}{\omega_I} \,, \quad \forall I \,. \tag{22}$$

describes a time evolution of the phonons where zero-point effects are taken into account. The structure of the extended QC super-propagator $\tilde{\tilde{\mathcal{U}}}^{\rm e}$ is similar to that displayed in Eq. (13):

$$\tilde{\tilde{\mathcal{U}}}^{\rm e}(t) \;=\; \exp\left\{(it/\hbar)\left[\begin{array}{cc}\tilde{\mathcal{H}}^{\rm e} & \ldots\end{array}\right]\boldsymbol{\Omega}\left[\begin{array}{c}\tilde{\mathcal{H}}^{\rm e}\\ \ldots\end{array}\right] - (t/2)\left(\tilde{\mathcal{H}}^{\rm e}\overleftarrow{\boldsymbol{\nabla}}^{\rm e}\boldsymbol{\mathcal{R}}\overrightarrow{\boldsymbol{\nabla}}^{\rm e}\ldots\right)\right.$$
$$\left.+\;(t/2)\left(\ldots\overleftarrow{\boldsymbol{\nabla}}^{\rm e}\boldsymbol{\mathcal{R}}\overrightarrow{\boldsymbol{\nabla}}^{\rm e}\tilde{\mathcal{H}}^{\rm e}\right)\right\} \,. \tag{23}$$

Since we are interested in thermal and zero-point QC averages and correlation functions of non-fictitious dynamical variables, we must consider Mixed Weyl symbols $\tilde{\mathcal{O}}(X)$ that at $t = 0$ do not depend on the extended phase space point $X^{\rm e}$ but they depend on the non-fictitious phase space point X. However, the key of temperature control is that the phase space variable dependence found at $t = 0$ is not preserved at $t \neq 0$. We have $\tilde{\tilde{\mathcal{U}}}^{\rm e}(t)\tilde{\mathcal{O}}(X) = \tilde{\mathcal{O}}(X^{\rm e}, t)$. Finally, we can write the expression for thermal (or zero-point) QC averages as

$$\langle\tilde{\mathcal{O}}(X,t)\rangle_{\rm e} = {\rm Tr}'\int dX^{\rm e}\, \mathcal{W}^{\rm e}(X^{\rm e})\tilde{\mathcal{O}}(X^{\rm e},t)\;, \tag{24}$$

$$\langle\tilde{\mathcal{O}}_1(X,t)\tilde{\mathcal{O}}_2(X)\rangle_{\rm e} = {\rm Tr}'\int dX^{\rm e}\, \mathcal{W}^{\rm e}(X^{\rm e})\tilde{\mathcal{O}}_1(X^{\rm e},t)\tilde{\mathcal{O}}_2(X)\;. \tag{25}$$

VI. THE QUANTUM-CLASSICAL PERSPECTIVE ON THE BRAIN AND CLINICAL PSYCHOLOGY

The understanding of both quantum and QC processes in the brain [66–68] might lead to a novel Weltanschauung of clinical psychology. Over history, one often founds a cross-fertilization between the disciplines of physics and psychology [160]. Freud developed his psycho-dynamics modeling it on the thermodynamics of Helmoltz. His idea was furtherly developed by Gustav Fechner, who attempted to unify physics and psychology in a single mathematical formalism. William James was highly influenced by Fechner [161] and, in turn, Niels Bohr took the idea of *complementarity* from James. We believe that, as it already occurred in the past, the full appreciation of the quantum features of the brain in psychology may inspire novel ideas about the structure of the unconscious and the origin of meaning. In turn, such conceptual developments might lead to furtherly improve the clinical assistance of patients. Indeed, the quantum way of thinking can already be found in certain psychological approaches. Sometimes, this happened without any awareness of the coincidence (or, we might say, of the synchronicity). In this paper, we consider three psychological approaches where a quantum mechanical Weltanschauung finds its place, namely Korzybski's General Semantics [69, 70, 164], Jung and Pauli's Synchronicity [72–76], and Blanco's Bi-logic [77–80].

A. General Semantics

Roughly speaking, GS is a specific instance of Process Philosophy [162]. However, it has the specific goal of improving mental health and adaptation to the world [69, 70]. One key aspect of this approach is that a non-Aristotelian logic is more conform to reality. Once non-Aristotelian logic is accepted as the correct way of thinking, our language must be adjusted accordingly. GS's link with QM has been briefly mentioned in the famous book "The Tao of Physics" [163].

Although it constitutes the historical roots of many modern philosophical point of view and many areas of man's knowledge, GS is often not acknowledged in contemporary theories. The premises of GS are "A map is not the territory", "A map does not represent all of a territory", and "A map is self-reflexive", meaning that an 'ideal' map would include a map of the map, etc., indefinitely" [71]. These assumptions can be translated to daily life in order to improve the menthal sanity of human beings [70]. In this case, GS premises become "A word is not what it represents", "A word does not represent all of the facts", and "Language is self-reflexive" in the sense that in language we can speak about language. Alas, human being reactions to verbal communication are largely based on unconscious beliefs, violating the first two assumptions and disregarding the third. Mathematics and GS are the only languages that rigorously take into account the above non-Aristotelian premises at all times. For such a reason, Korbizski strongly suggested to psychologists to study mathematical structures. At page 280 of his "Science and Sanity" [69], we find a discussion of the importance of the Theory of Aggregates and the Theory of Groups in Psychology, something that it will be furtherly examined in Blanco's Bi-logic [77–80].

It is very common to find that the influence of Korzybski's GS on various approaches is not properly acknowledged [164]. Luckily, there are exceptions. For example, Ellis acknowledges Korzybski's influence on his Rational Emotive Behavior Therapy [165]. Almost similarly, Wysong pays the dues of Gestalt Therapy to GS by writing a commentary in The Gestalt Journal [166]. How much Gestalt Therapy owes to GS can also be discussed in the thesis of Allen Richard Barlow [167], which is downloadable from The University of Wollongong Thesis Collection on-line. One of many counter-examples [164] is given by Family Therapy [168, 169], where it is stressed that one must be aware of abstractions leading to disregarding the wholeness of processes [168] (non-elementalism [69, 70]) and it is also underlined the difference between the verbal and the non-verbal [169], but without citing GS. Hence, GS may be considered (either directly or indirectly) as the hidden root of various therapeutic practices.

Given the above discussion, it is not difficult to see the logical connections between GS and QM. If we consider that scientific theories are "maps" of reality, with classical theories providing a first level of abstraction, then QM clearly is characterized by a second level of abstraction. QM does not provides laws for the dynamics of models of real phenomena. It provides laws for the probability amplitudes that models of real phenomena display a certain dynamics [7, 8, 170], *i.e.*, QM provides laws for models of models. GS classifies this as language self-reflexiveness. The influence of QM Weltanschauung on the formulation of GS was explicitly acknowledged by Korzybski [69]. From this perspective, we can consider GS an application of certain QM concepts to clinical psychology.

B. Pauli and Jung's Synchronicity

The goal of the collaboration between Jung and Pauli was to find a unified view of reality in terms of both the psychological and the physical. Jung's approach to the psyche was based on certain in-forming (in the sense of having the power of giving "form") structures that he called archetypes [171]. As universal regulators of the psyche, archetypes transcended the individual and belonged to a collective unconscious, common to all humankind.

Pauli was one of the founders of QM. He interpreted QM in term of the concept of statistical causality. This facilitated the collaboration with Jung. He explained to Jung that QM is about 'forms', e.g., wave amplitudes, and it is also intrinsically probabilistic. While the causality of the classical world requires the exchange of physical quantities (such as energy, momentum, angular momentum and so on), statistical causality describes correlations between systems that exchange energy (and other physical quantities) through synchronic events, even if they may potentially interact in a classical way.

At the same time, Jung considered random coincidences in the classical world as the analogue of the statistical causality in the quantum world. Moreover, the origin of subjective meaning in the psyche was assigned to random coincidences themselves. According to Jung, the organizing principle of reality, which he called Synchronicity, is found in meaningful coincidences. Afterwards, the concept of Synchronicity was furtherly generalized to include acausal correlations without any psychological component. With this extended meaning, the concept of Synchronicity can be linked to that of quantum entanglement [4–6, 66].

An importan progress in Jungian psychology could be to use the entanglement/synchronicity analogy for devising novel clinical therapies. The concept of entanglement focus the attention to relations as roots of reality. Moreover, within an entangled reality of relations, as QM shows, maximum information about the whole implies minimal information on the part. In the era of the web and of the metaverse, the concept of entanglement may provide an effective language for the understanding of the psychological uneasiness of man in the contemporary age. Of course, this is an area of open research.

C. The Psychology of Bi-Logic

Korzybiski's GS [69] proposes a new psychology founded on mathematical structures and, to this end, briefly dealt with both set and group theory. However, it is only in the work of Blanco [77–80] that these ideas are fully exploited in order to generalize Freud's formulation of the unconscious. While Freud defined the unconscious in a qualitative way, *i.e.* what is hidden and repressed in the psyche, Blanco describes it as a bipartite structure. Such a bipartite structure has one side that is asymmetric (which we may call Aristotelian by following GS language), pertaining man's common-day experience, and another side that is symmetric (which we may call non-Aristotelian), where space and time do not exist and the logical principle of non-contradiction is no longer valid. Blanco stated that both logics are at work in the human psyche [77–80] and that clinical practice must accurately take into account this point.

Blanco's and GS's conceptual structures share concepts taken from QM. However, while GS is fully non-Aristotelian (without any form of classical-like logic attached to it), Blanco's Bi-logic has an Aristotelian component (congruent with a classical Weltanschauung) and another non-Aristotelian component (in agreement with the logic of QM). Taking both aspects into account, we conclude that Blanco's Bilogic formulates a QC conceptual perspective of the psyche, reflecting the QC nature of the phenomenological world. A full acknowledgement of this parallelism and its possible consequences on clinical practice are a matter of novel researches.

VII. CONCLUSIONS

In this paper, we considered the topic of quantum models of brain processes. We have reviewed the EMFs approach and have proposed the idea that coherent electromagnetic fields may give rise to quantum effects in brains dynamics. We also discussed two inherently quantum mechanical formalisms of brain dynamics. One is Orch OR theory, which considers the brain as some kind of quantum computer that calculates and controls the chemical activity of classical-like macro-molecules. Interestingly, recent results have predicted the occurrence of quantum optical effects in the Orch OR model, suggesting a unified point of view between the EMF and Orch OR approaches. The DQMB model, whixh is based on QFT and SSB, was also reviewed. DQMB describes the memory storage process in terms of the SSB of the brain ground state. Long-range correlations between distant brain regions are explained by means of Nambu-Goldstone bosons.

Exploiting key features from the three aforementioned approaches, we formulated a QC approach to brain dynamics and wrote down a general Hamiltonian that can serve as an abstract model for the numerical simulation of various brains processes. The ultimate goal of the proposed QC approach is to calculate averages and response functions, and compare them to experimental results in neuroscience. We believe that our work proposes various ideas that are worth inves-

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tigating. From a technical point of view, the QC model proposed herein represents dissipative brain dynamics in terms of thermal effects. However, the model can be easily extended to include non-Hermitian Hamiltonians and/or other time dependent interactions describing the influence of an enviroment. Theoretically, one can also try to reformulate the EMF, Orch OR, and DQMB approaches in a more precise way.

Finally, we discussed how quantum and quantum-classical world-views are reflected in interesting approaches to clinical psychology. Such a Weltanschauung is found General Semantics, Synchronicity, and Bi-logic. All the aforementioned psychological systems can be related to non-Aristotelian logic. In particular, Bi-logic appears to have a direct connection with the logic behind QC systems. This link opens the way for novel studies of the human psyche and possible generalizations of clinical psychology.

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