Astrocyte-Trapped Calcium Ions: the Hypothesis of a Quantum-Like Conscious Protectorate

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ABSTRACT

In this paper I propose a consciousness-supporting mechanism composed of two parts: a) a multitude of amplitude, frequency and phase-modulated dendritic (electric) fields embodying patterns that constitute the contents of consciousness, and b) a conscious protectorate, composed of a population of calcium ions trapped in astrocytes, receiving and integrating patterns from dendritic fields into unitary conscious episodes. This mechanism was inspired by the architecture of a large-scale ion-trap quantum computer.

Key Words: Astrocyte, Calcium Ions, Quantum Protectorate, Local Field Potentials, Consciousness.

1. Introduction

An explanation of the existence of consciousness in nature (the "Hard Problem of Consciousness"; Chalmers, 1995, 1996) should contain three parts: the physical explanation (a combination of laws, principles, initial and boundary conditions generating a system that manifests phenomenal properties of consciousness); the biological explanation (brain information-processing mechanisms that support the formation of conscious contents) and the psychological explanation (how the interaction of brain mechanisms with the living body and environment generates subjective experiences).

In this theoretical essay I present the outline of a physicalist explanation for the existence of consciousness in nature. It is based on a set of special initial and boundary conditions defining a "quantum protectorate" (Laughlin and Pines, 2000). I hypothetize that consciousness is supported by a protectorate formed by a population of calcium ions trapped in the astrocytic syncytium and interacting with neuronal electric fields. The special initial condition is given by the evolution of life on earth, assigning to

calcium ions a central signaling role in the living cell, while the special boundary condition is composed of brain-wide low entropy states produced by membrane-gated neuronal ion channels (operating like a neurobiological "Maxwell Demon").

The concept of a "quantum protectorate" has been used to explain extraordinary phenomena as superconductivity (Anderson, 2000). In this case, the protectorate is formed by means of the cooling of an electronic system to ultra-low temperatures, shielding it from phonon perturbations. In the context of the hot, wet and noisy living brain, a different strategy is adopted: neurobiological mechanisms constrain the evolution of phonon patterns of ionic systems to create quantum-like coherent macro-states. Therefore, in superconductivity a condensate is formed in the *relative absence* of phonons, while in the conscious brain phonons are *abundantly present* and controlled by neurobiological mechanisms to generate a large-scale coherent state. To avoid conceptual confusion, in the second case I refer to a *quantum-like* protectorate.

This paper is focused on physical and biological aspects of the proposed consciousness-supporting mechanism. The architecture of a large-scale artificial Ion-Trap Quantum Computer (ITQC; see Kielpinski et al., 2002) is used for the description of the structure and 'modus operandi' of this system, but 'strict sensu' quantum computing is proposed to occur only in the sub-system composed of trapped calcium cations.

The psychological explanation is based on the assumption that electric patterns of neuronal local field potentials affecting the ionic system constitute *elementary contents* of consciousness, while the integration of patterns from distributed fields by means of synchronized oscillations constitute *episodic contents*. The temporal sequence of contents, defined in the domain of interaction of brain, body and environment, compose the flux of consciousness. A sketch of the process is presented here, while an explanation of phenomenal properties based on the model is going to appear in another paper (departing from Pereira Jr., 2007a).

2. **Astrocytes and Cognitive Processing**

Several roles of astrocytes in brain function were recently discovered. Besides supporting and "gluing" neurons, astrocytes participate in the control of arterial blood flow (Abbott et al., 2006; Haydon and Carmignoto, 2006) and balance of neuronal excitation/inhibition (Fellin et al., 2006). These findings add to the known role of astrocytes in large-scale brain integration by means of calcium waves (Giaume and Venance, 1998).

Evidence that astrocytic function is closely related to cognitive and conscious processes is given by the following scientific facts:

a) General anesthetics disturb intercellular communications mediated by gap junctions between astrocytes (Mantz et al., 1993);
b) Activation of astroglial protein predicts regain of consciousness after cardiac arrest (Hachimi-Adrissi et al., 2002);
c) Astrocytes are involved in the formation of conscious memory (Robertson, 2002);
d) Minor head trauma causes unconsciousness, possibly by perturbation of astrocytic calcium waves (Antanitus, 1998);
e) Astrocytes are involved in the onset of oscillatory synchrony, a phenomenon that is closely correlated to conscious processing (Fellin et al., 2004);
f) Altered calcium waves contributes to perturbation or loss of consciousness in (respectively) schizophrenia and epilepsy (Halassa et al., 2007).

3. The Operation of Artificial ITQC

Both neurons and astrocytes contain membrane receptors controlled by ligands (e.g., transmitters as glutamate). Cellular functions are carried by means of signal-transduction pathways, usually activated by the binding of a ligand with membrane receptors. However, as the astrocyte membrane generates a static electric field, the physiology of this kind of cell is different from neurons. Astrocytic excitation is not tranduced to a change in membrane voltage, but to internal calcium ion waves (see Roth et al., 1995 for a mathematical model of calcium waves).

Astrocyte physiology is similar to the operation of a ITQC. For this reason, I use basic knowledge about ITQC to hypothetize about how calcium waves in astrocytes could support cognitive and conscious processing. In a simple artificial ITQC (see Hughes et al., 1997) one or more calcium ions are trapped in a magnetic quadrupole and manipulated by means of lasers. In the model of a large-scale ITQC proposed by Kielpinski et al. (2002), the computer is divided in two, "memory" and "interaction" regions (Fig. 1).

The operation of the Kielpinski computer can be summarized as follows:

a) Trapped ions in the memory region repel each other according to Coulomb's Law, and get entangled;
b) Some of these ions are moved to the interaction region;
c) A laser is used to change the state of one ion at the interaction region;
d) The change of state of this ion affects the state of the other (entangled) ions;
e) Another laser decoheres and reads the state of one ion in the interaction region;
f) The state of this ion gives information about the state of the others.

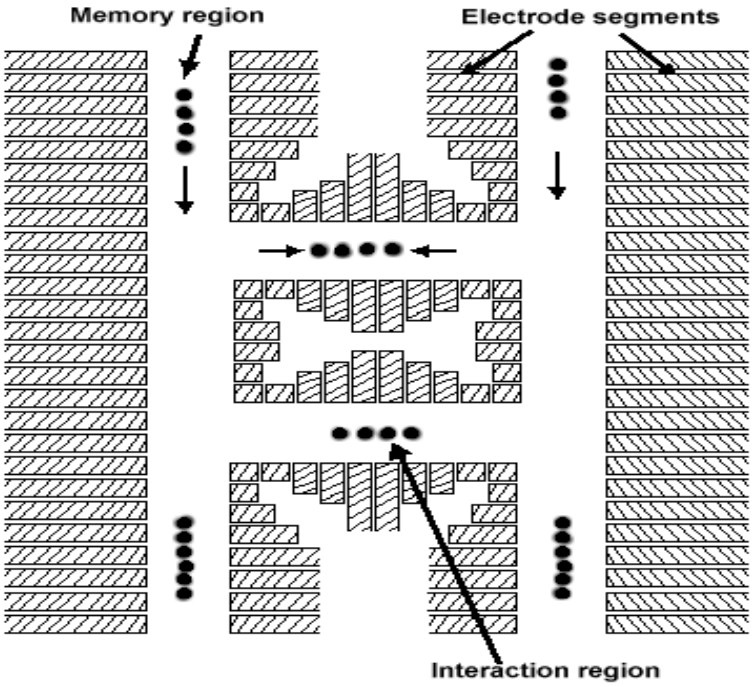

Fig. 1 – Large-Scale Ion Trap Quantum Computer (based on Kielpinski et al, 2002)

Quantum information in a ITQC refers to vibratory (phonon) patterns of the ionic population, and the related distribution of electronic states in the ions. Both levels of processing are more closely related in cooled systems (a procedure that eliminates noisy phonons); this is one reason why engineers who design artificial computers prefer to work with ultracold systems. However, there are several schemes for quantum computing with hot ions waiting for technological implementation (see Poyatos, Cirac and Zoller, 1998; Molmer and Sorensen, 1999; Milburn, Schneider and James, 2000; Sasura and Steane, 2002).

The calcium atom electronic structure is 1s2 2s2 2p6 3s2 3p6 4s2. (Nxe, where **N**=Shell number; **x**=Subshell label with same N and different angular momentum, and **e**= number of electrons: see Figure 2).

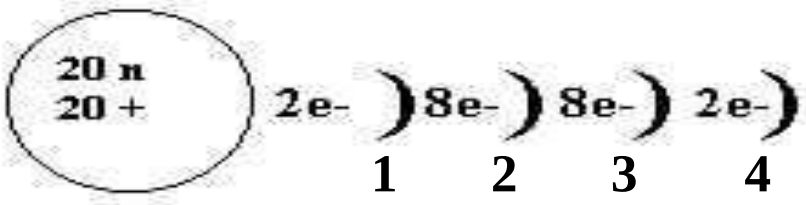

Fig. 2

The Hughes et al. (1997) model uses some kinds of states available to C^+ to implement logical gates (Figure 3). The chosen kinds are called "ground", "excited" and "dark". If the ion is in the *ground* state (electron in **4s**) and receives a photonic pulse, it goes to an *excited* state (electron in **4p**). As this state is unstable, with a short life (around 7 nanoseconds), the ion will spontaneously return to the ground state, emitting an electromagnetic radiation, or will change to the *dark* state (electron in **3d**) without an immediate photonic emission:

Ground State (Bottom)…**1s2 2s2 2p6 3s2 3p6 4s1**
Excited State (Top)……**1s2 2s2 2p6 3s2 3p6 [4s0] [3d0] 4p1**
Dark State: (Right)……**1s2 2s2 2p6 3s2 3p6 [4s0] 3d1**

When the ion decays spontaneously to the ground state it emits a stronger detectable signal. This difference allows the experimenter to use the system as a binary device .

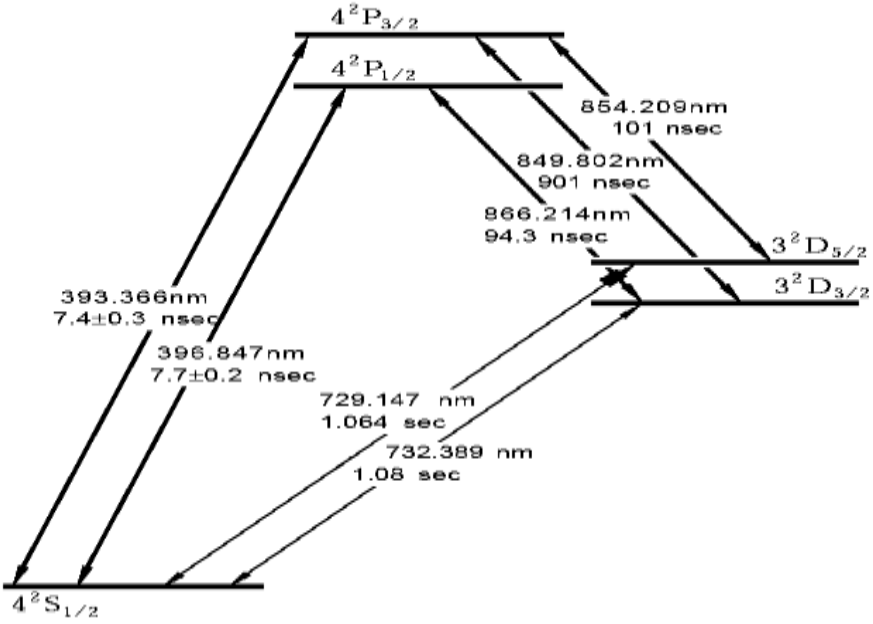

Figure 3: One-C^+ Quantum Computing, where the highest energy electron jumps from the ground to two other energy levels, allowing the computer to be used as a binary device (diagram based on Hughes et al., 1997). The figure shows the frequencies necessary to change the distribution, and the time for each transition.

4. ITQC in the Brain

An interesting analogy can be made between a large-scale hot ITQC and the dynamics of calcium ions trapped in the astrocytic syncytium, under the influence of neuronal electric fields (called Local Field Potentials, abbreviated LFP). Of course, the photonic fields that interact with trapped ions in the brain are not lasers, but neuronal LFPs.

Astrocytes form with neurons tripartite synapses, containing the pre-synaptic neuron, the post-synaptic neuron and the astrocyte (Figure 4).

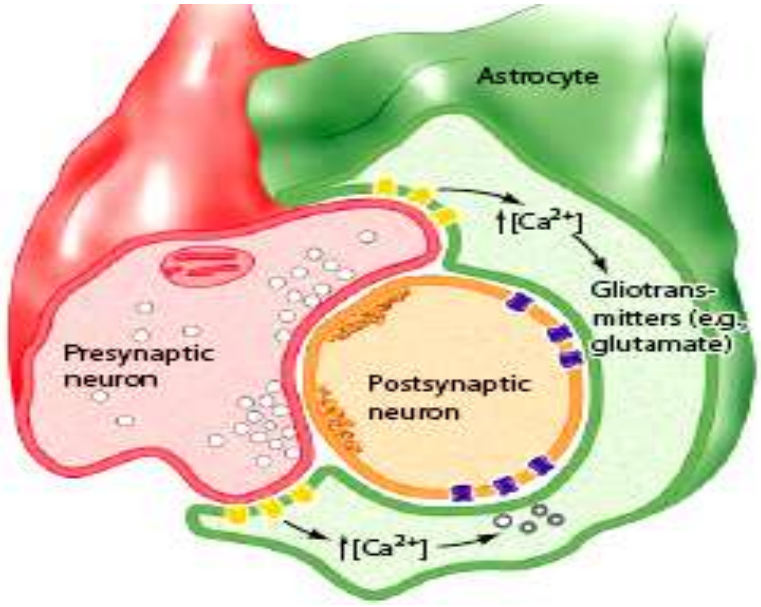

Fig. 4 – The Tripartite Glutamatergic Synapse (adapted from Fellin et al., 2006).

Glutamate (Glu) is the main excitatory transmitter in the brain, acting both on neurons and astrocytes. Glu release from the pre-synaptic neuron and binding with astrocytic receptors promote calcium waves inside the astrocyte directed to the activated membrane sites (see illustration in Fig. 4). When calcium ions reach this target, they contribute to open vesicles of astroglial Glu, which in turn binds to membrane receptors of the post-synaptic neuron (not shown in the figure). One of the possible functions of this astrocyte-mediated excitation of the post-synaptic neuron is to sustain the excited state during the time necessary for the onset of neuronal oscillatory synchrony (Pereira Jr., 2007b).

Astrocytes are connected by gap junctions that allow the passage of ions and small molecules (Figure 5).

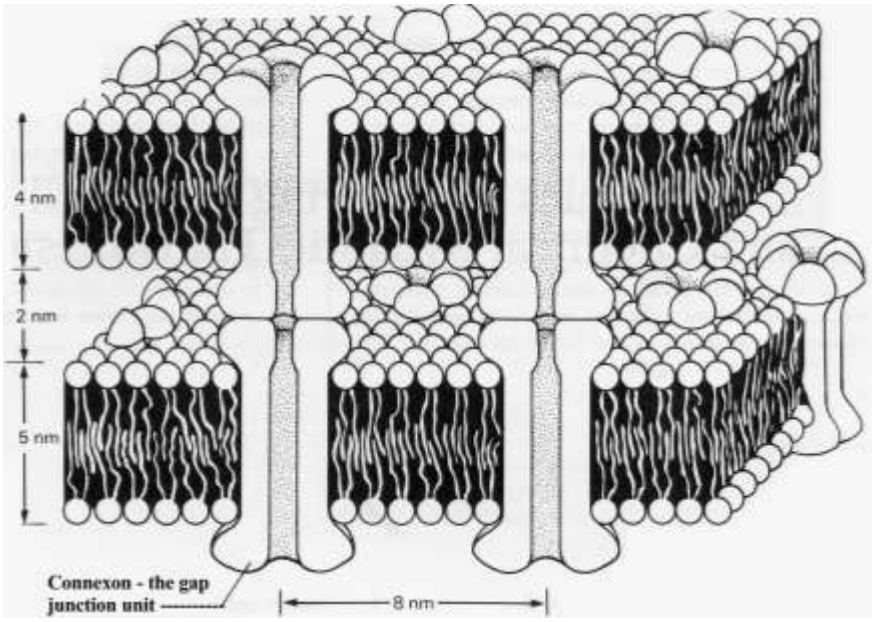

Fig. 5 - Gap Junctions Between Astrocytes form a Syncytium

The ensemble of astroglial cells in the brain form a large network, called the *astrocytic syncytium* (Figure 6).

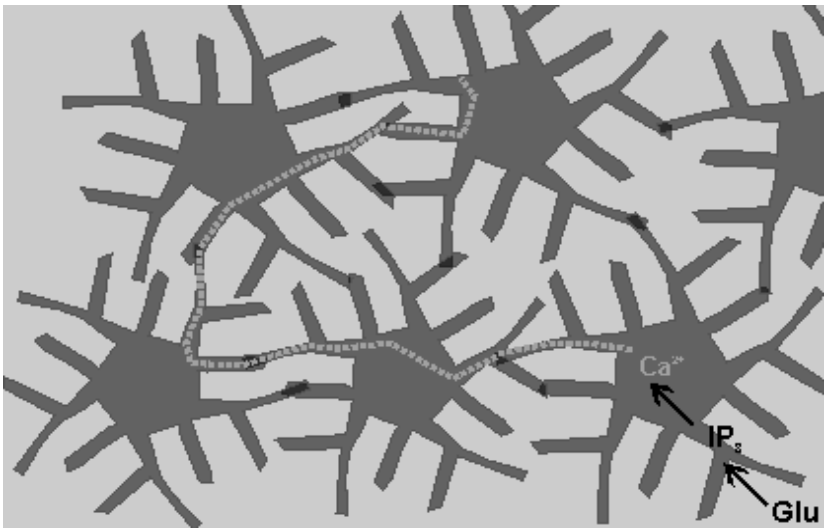

Fig. 6 - The Astrocytic Syncytium (adapted from: http://synapses.mcg.edu)

Calcium ion populations in astrocytes are trapped by a static electric field (corresponding to the *memory region* of the ITQC). The forced conviviality causes them to get entangled. In this condition, calcium waves activated by glutamatergic binding from the pre-synaptic neuron to the astrocyte displace parts of the ionic population to the neighborhood of neuronal electric fields (corresponding to the *interaction region* of the ITQC). At different brain locations there are different, amplitude, frequency and phase-modulated electric fields (local fields). As astrocytes are star-shaped, they can interact simultaneously with several neurons (Fig. 7).

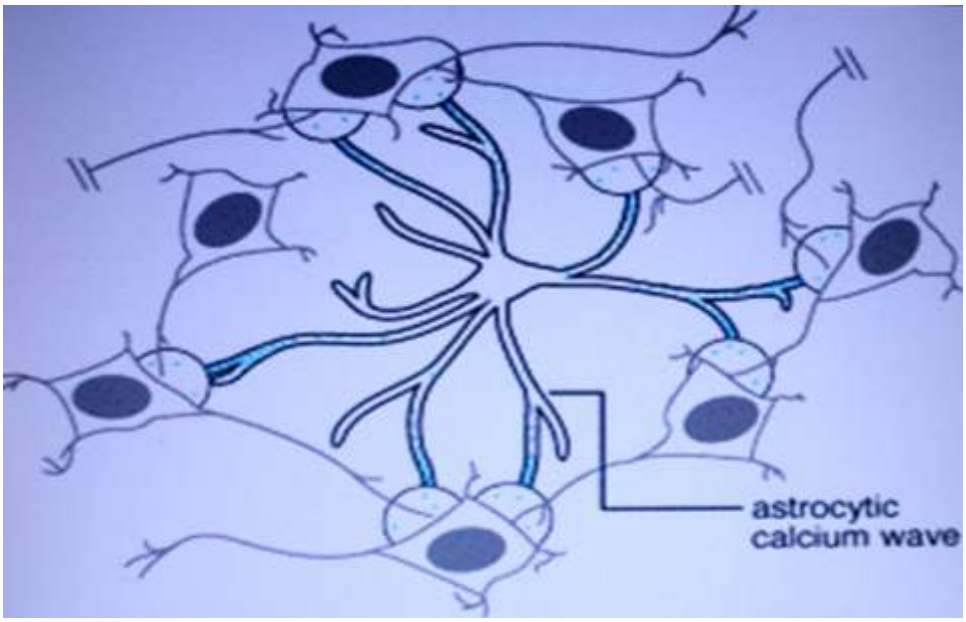

Fig. 7 - Calcium Ion Waves in Astrocyte Interacting with Neurons (adapted from www.antanitus.com)

The ions located deeper in the astrocyte are not intensely affected by neuronal fields, while ions that move to the proximity of neurons decohere according to the pattern of the local field. The deeply located ions are *indirectly* affected when the peripheral ions decohere, because they were all previously entangled. Therefore, a complex phonon pattern, related to electronic (quantum informational) states, is formed in the trapped calcium ion population, as an effect of the conjoint interaction of several parts of the population with different local fields.

The relation of these processes with consciousness is proposed to be the following. The calcium population trapped in the astrocytic syncytium develop a dynamic interaction with neuronal LFPs around excitatory tripartite glutamatergic synapses. These fields provide the calcium system with information that putatively constitutes the *elementary contents* of consciousness (including the so-called '*qualia*').

Conversely, astrocyte-released glutamate-induced calcium ion entry in neurons sustains electric fields, and contribute to the onset of oscillatory synchrony. Synchronization acts back (by means of the summation of quasi-simultaneous electric potentials) on the astroglial trapped calcium population, defining neuro-astroglial assemblies selected to compose a integrated waveform that embodies the content of a *conscious episode*.

An "inner world" emerges in the protectorate, as the result of a almost-continuous sequence of quantum-like coherent states. This "inner world" is dynamically correlated with an immediate "external world" constituted by neuronal local electric fields. The events that occur in the "inner world" can have causal effect on the "external world", by means of the action of calcium ions from astrocytes on neuronal enzymes. The "inner world" is functionally reversible, thus allowing the occurrence of all kinds of logical and mathematical operations. The protectorate combines informational patterns received from local fields to form more complex patterns - corresponding to conscious episodes - by means of the vectorial combinatorial properties described by Quantum Field Theory.

For instance, in perceptual processes membrane potentials transduce sensory information from sensors to the central nervous system, by means of population frequency and spike timing encodings. The features of the stimulus are represented by means of amplitude, frequency and phase modulation of the generated EM fields. The activation of cortical feature detectors is a process of resonance between the EM wave input and LFPs already existing in a brain region. After several spatially distributed LFPs are activated in the cortex, the onset of oscillatory synchrony occurs and then the binding process takes place in the protectorate, generating a conscious episode.

5. On the Role of Entanglement for Consciousness

Superposition and entanglement are here considered to be the physical basis for the integration of brain distributed information that supports consciousness. Such quantum phenomena develop a dynamical interplay with classical processes, defining the information patterns selected to compose the contents of consciousness.

An attractive solution to the problem of information integration in the brain is to combine classical computational mechanisms with Ca^{++} superposition/entanglement, since this ion is active at all brain regions and could function as a communication channel to integrate classically encoded messages. The combination of sustained LFPs with Ca^{++} entanglement would support the phenomenon of psychological "binding", the union of features processed in several areas of the brain into a unitary moment of consciousness.

The phenomenal flux of consciousness putatively supported by this mechanism would be composed of a sequence of coherent states maintained for (very) small

periods of time and newly generated again and again, thereby composing a *dynamical* quantum-like protectorate. Soon after a moment of consciousness is generated and evolves into another one, the results of Ca^{++} quantum communication/computation determine in each neuron the conformational state of Calmodulin-Dependent Protein Kinases, by means of the interaction of the Ca^{++} ions with Calmodulin. As the kinases control the phosphorylation of membrane ionotropic receptors, consciousness has a way to influence brain activity and the resulting behavior.

The generation and maintenance of Ca^{++} entanglement in the brain to support conscious processing requires the formation of a protectorate to avoid decoherence. However, this protectorate is not of the kind found in superconductivity phenomena. It is a *sui generis* protectorate that occurs in the presence of abundant phononic activity. In the proposed model, the brain's strategy to generate entanglement is - as in the case of artificial hot ITQCs - to confine the vibratory energy (phononic patterns) of the ions, forcing them to get entangled. The brain's protectorate is therefore generated by *the conversion of phononic noise into information*. This mechanisms is continuously operating inside astrocytes, regenerating the entanglement while ions that interact with LFPs decohere and affect the population that remained entangled. The conscious state would then be physically based on the *survival of a multi-particle entanglement affected by the decoherence of some of the previously entangled particles.*

6. How to Test The Hypothesis

Scientifically-based hypotheses aimed to explain consciousness must be experimentally testable. The optimal design for the testing of quantum theory-inspired hypotheses cannot be an input-output, or stimulus-response paradigm. In the case of the explanatory hypothesis presented here, the conscious process is proposed to be supported by coherent patterns generated in a population of Ca^{++} ions, allowing entanglement and quantum computing. Since behavior occurs after the decoherence of the ions that (putatively) participated in the conscious protectorate, behavioral differences cannot be taken alone as indicative of success or failure of the explanation.

The stream of consciousness is possibly composed of a sequence of coherent states along time. As the quantum computations interplay with classical computations in the brain, the selection of informational patterns composing the contents of the stream of consciousnes includes classical operations. In this context, a crucial experiment for the hypothesis should be aimed to measure the quantum process supporting conscious experience, but not the classical counterpart.

A criterium for the design of the experiment could be the following. As measuring a quantum process interferes with the process, measuring the population of Ca^{++} ions that supports consciousness should - according to the framework assumed here - interfere with subjective experience.

In order to measure the conscious coherent state (also interfering with it) a new kind of technology is required: a structured laser, used in frequencies that resonate with the Ca ions' phononic patterns (ultraviolet frequencies), but with low intensity – to avoid damage to brain tissues.

Three kinds of experiments could be done:

1) Mesuring specifically such a ionic activity in human subjects (and nothing more) and letting them report changes in couscious content;
2) Two lasers at ultraviolet range are focused on two spatially separated brain regions during conscious processing that involves such areas. If quantum coherence (a non-local effect) is found, then the hypothesis is confirmed;
3) Weak laser beams are focused on a brain region A, related to conscious processing X (e.g. pain from noxious stimulus applied at some body regions). A sensor is positioned on the other side. Pain processing by means of vibratory (phononic) patterns at A interfere with the laser beam that is passing through. A stimulus is given and then the difference between before, during and after the stimulation is measured by the sensor. Then laser stimulation is given in the absence of the noxious stimulus and if the subject feels pain the hypothesis is confirmed.

7. Concluding Remarks

This paper presents a new explanatory hypothesis for consciousness.

Universal laws and principles of nature, under special initial and boundary conditions, can generate systems ("quantum protectorates") that display special properties.

The phenomenal properties of human consciousness are considered to be an outcome of the operation of a quantum-like protectorate, composed of a population of calcium ions trapped in the astrocytic syncytium and interacting with structured neuronal electric fields.

The initial condition is established by evolution, assigning to calcium ions a central signaling role in the cell, while the boundary condition is established by neuronal membrane gated ion channels that maintain a low entropy environment (an ensemble of LFPs).

The consideration of Ca^{++} dynamics and its modulation by LFPs open a new possibility of explaining the biophysical processes underlying consciousness. Ca^{++} dynamics in astrocytes is proposed to play an important role in the binding of distributed information, supporting the formation of unitary conscious states in the brain.

The phenomenal flux of consciousness is conceived as composed of sequences of coherent states in a multiparticle entangled system, which is able of surviving to the decoherence of some elements, composing a *sui generis* quantum-like protectorate that appears in the first-person perspective as a continuous process.

In conclusion, I suggest that consciousness is supported by an alkaline metallic ionic system operating under specific neurobiological conditions. Therefore, I disagree with those who understand that consciousness has an intrinsic biological nature, since biological constraints are necessary only to establish the right kind of initial and boundary conditions for consciousness to emerge from an inorganic medium.

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