

Quantum effects in the understanding of consciousness

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This paper presents a historical perspective on the development and application of quantum physics methodology beyond physics, especially in biology and in the area of consciousness studies. Quantum physics provides a conceptual framework for the structural aspects of biological systems and processes via quantum chemistry. In recent years individual biological phenomena such as photosynthesis and bird navigation have been experimentally and theoretically analyzed using quantum methods building conceptual foundations for quantum biology. Since consciousness is attributed to human (and possibly animal) mind, quantum underpinnings of cognitive processes are a logical extension. Several proposals, especially the Orch OR hypothesis, have been put forth in an effort to introduce a scientific basis to the theory of consciousness. At the center of these approaches are microtubules as the substrate on which conscious processes in terms of quantum coherence and entanglement can be built. Additionally, Quantum Metabolism, quantum processes in ion channels and quantum effects in sensory stimulation are discussed in this connection. We discuss the challenges and merits related to quantum consciousness approaches as well as their potential extensions.

Keywords: Quantum coherence; quantum biology; microtubules; consciousness.

1. Introduction

Does the study of consciousness belong in the realm of natural sciences or is it a philosophical or even metaphysical area of inquiry? These questions have been pondered by many scientists, philosophers and spiritual leaders whose opinions diverge due to the subjective nature of consciousness (Velmans, 1996). Obviously, the existence of this phenomenon cannot be denied as we all experience it as sentient humans

(Baars *et al.*, 2003). The authors of this paper firmly subscribe to the point of view that not only is consciousness a viable topic for scientific research (Crick & Koch, 1990) but, in fact, one of the most important unsolved scientific enigmas of our time (Koch, 2004). Moreover, through the use of quantum mechanics an objective aspect of consciousness can be properly developed.

At the turn of the 20th century, physics was perceived by its practitioners to be as solid as rock, only to be shaken to the core by the discovery of quantum mechanics. Today, perhaps the most dynamically expanding branch of science is molecular and cellular biology which is amassing impressive reams of data well ahead of its proper integration and deep analysis. Quantum biology is emerging gradually as a response to the challenge of explaining such important, yet poorly understood phenomena as photosynthesis, bioenergetics, vision, olfaction, bird navigation, etc. Yet, the grandest challenge of all is to explain how our brains work and, in particular, how does conscious behavior emerge from the structure and function of the human brain and its cellular and sub-cellular components. In this article we revisit some historical issues in the development of quantum physics, quantum biology and quantum consciousness aiming to provide new insights into this topic from both a physical and a historical perspective. Since consciousness requires a physical substrate in the form of a living organism, and in particular the human brain, quantum biology appears to provide a natural connection between quantum physics and a quantum theory of consciousness. Classical mechanics is not an appropriate framework within which consciousness could be properly elucidated (Stapp, 1995).

2. Quantum Coherence, Quantum Entanglement, Quantum Wave Function Collapse

At the dawn of the 20th century, Max Planck postulated that heat emission spectra, which were experimentally determined for physical objects, originate from the discrete nature of energy levels in physical systems that can be quantized by the general relation (Griffits, 2004):

$$E_n = nhf, \quad (1)$$

where n enumerates the energy levels and f is the characteristic frequency of internal oscillations. This assumption led to a revolutionary transformation of physical principles departing from the mechanistic laws of Newtonian physics to provide wave function descriptions of quantum physics. Newton's equations of motion were replaced by the Schrödinger (in the non-relativistic case) and Dirac (in the relativistic case) equations governing the time evolution of the wave functions describing the motion of microscopic objects such as elementary particles.

Quantum theory is the most fundamental theory of matter known today. The three main levels of quantum representation are determined by the extent to which the continuous variables of classical physics are converted to discrete variables, otherwise known as quantization. Quantum mechanics is a first-quantized or semi-classical theory of physics in which particle properties are discrete but field properties and

interactions are not. Quantum field theory is a second-quantized theory in which all particle properties, field properties and interactions are discrete except for those due to gravity. Quantum gravity is an incomplete third-quantized theory in which gravity is also made discrete. In quantum physics, objects possess both a wave aspect and a particle aspect, a view of the physical world known as the principle of wave-particle duality, or complementarity. The wave function of a particle describes the probability of finding a particle in a spatial location, thus information about the particle is described probabilistically rather than deterministically. Wave functions can diffract, and interfere together forming superpositions implying that quantum particles exist in multiple spatial locations and states simultaneously. When a measurement is made, one of the multiple states is chosen and the quantum superposition of states ends being reduced to a classical state in a process known as the collapse of the wave function. Another aspect of quantum theory is that when two consecutive measurements are made on certain pairs of variables, called complementary variables, there is a fundamental limitation on the precision of the two measurements. Thus, there is no state in which both complementary variables can be defined simultaneously with arbitrary accuracy. This property is known as the Heisenberg uncertainty principle. A related statement can be made about the particle's wave function that the product of its uncertainty in position $\Delta x(t)$ with its uncertainty in momentum $\Delta p(t)$ is always greater than $h/4\pi$, i.e., $\Delta x(t)\Delta p(t) > h/4\pi$. This is a manifestation of the inherent inability to determine simultaneously the expectation values of two complementary physical observables, for example, angle and angular momentum, two independent spin components and, perhaps most importantly, energy and time such that the uncertainties in the two variables satisfy: $\Delta E\Delta t > h/4\pi$.

While quantum mechanics was developed with elementary particles in mind, its subsequent applications extended its validity to systems of many particles such as those encountered in condensed matter physics, e.g., in the description of the conduction electron "sea", excitons, magnons, polarons, polaritons, etc. (Ashcroft & Mermin, 1976). This is very important in view of the potential importance of quantum effects in biology and in consciousness where not only are systems of many particles considered, but they function at high temperatures compared to those typically encountered in quantum physics. The types of quantum many-body systems studied by condensed matter physics exhibit macroscopic physical properties called collective excitations. A system of many particles under specific conditions cannot be separated into individual wave functions for each particle, rather it is described by a single wave function describing its collective behavior. This physical property is called quantum coherence and it is characterized by individual particles losing their separate identities such that the entire system acts as a whole. Particles that were once unified in a common quantum state remain physically connected even at a distance. Measurements made on one particle cause the collapse of the entire wave function for the system, resulting in an instantaneous effect for all particles no matter where they are spatially located. This interaction over distance is referred to as non-local quantum entanglement. Decoherence occurs when such a system interacts with its environment

in an irreversible thermodynamic way resulting in different particles in the quantum superposition no longer being able to interfere with one another. Importantly, the description of solids such as crystals or semiconductors, requires a proper introduction of energy quantization even at finite temperature T . By defining a dimensionless variable $x = hf/kT$, where k is the Boltzmann constant, Paul Debye was able to accurately quantify the specific heat of a solid where quantization is hidden in the temperature dependence (Ashcroft & Mermin, 1976). It can be shown that quantum nature of solids manifests itself at temperatures up to the characteristic value, T_D , called the Debye temperature, which depends on the size of the solid and its rigidity, which determines the propagation velocity of the sound waves (phonons). As a consequence of collective behavior of many-body systems, hallmarks of quantum mechanics can be seen in the properties of macroscopic objects such as crystals or ferromagnets, even above room temperature. Functional dependence of properties such as specific heat and magnetic susceptibility is different in the quantum and classical regimes. There are also more exotic direct manifestations of quantum behavior in macroscopic systems such as superconductors (with no measurable resistance to electrical current and ideal diamagnetism) or superfluids (with no viscosity and infinite vorticity). However, these latter two examples have so far been limited to rather low temperatures. Yet a precise location of the boundary (in terms of size and temperature) between quantum and classical regimes is still under debate. This is why extensions of quantum mechanics to biological matter, including cognitive processes, pose a major challenge. However, it should be kept in mind that Nature has had millions of years of evolution and immense numbers of replicas of experiments at its disposal to arrive at solutions to these very difficult problems.

3. From Quantum Chemistry to Quantum Biology

Extensions of quantum mechanics to chemical compounds and chemical reactions proved to be exceedingly successful and an entire field of quantum chemistry was developed as a consequence. In order to understand the creation of chemical bonds, especially covalent bonds in which electrons are shared between atoms of a molecule, a quantum mechanical wave function must be introduced into the formalism. All chemistry including biochemistry is based on the creation and destruction of bonds between atoms and hence on quantum interactions, so living systems, like non-living systems, depend on quantum states at the level of chemical bonds. The same can be said about biochemical reactions taking place in the brain such as ligands binding to receptors sending signals through neurons. However, these types of quantum physical properties found in living systems are considered rather trivial since they do not explain more profound characteristics of animate matter. In particular, the unitary oneness and ineffability of living systems have suggested that higher level quantum properties such as Bose–Einstein condensation, quantum coherent superposition and entanglement may be required to operate in biology in order to explain some of the more enigmatic features of life in general and consciousness in particular.

However, quantum effects are commonly claimed to be washed out at scales larger than individual atoms or sub-atomic particles, at warm temperatures, and in aqueous media which provide a noisy environment for particle interactions. Thus the likelihood of quantum states playing functional roles at mesoscopic or macroscopic scales in “warm, wet and noisy” biological systems seems problematic at face value due to environmental decoherence effects. As stated above, it is reasonable to expect that evolution through the process of natural selection over billions of years of experimentation and countless parallel attempts of trial and error may have solved the decoherence problem so that mesoscopic/macroscopic quantum states are essential features of biological systems. If organized quantum states exist in cells, they are presumably integrated among their components and organelles. Conversely, collective quantum states of cells may lead to entanglements between cells and coherence over organs and tissues, e.g., the entire brain or regions of the brain. This brings another important issue to the fore, namely the hierarchical multi-scale organization of living matter must have a means of not only integrating information across scale but also an efficient way of filtering noise must be present.

Schrödinger’s famous book *What is Life?* (Schrödinger, 1944), paved the way for the birth of molecular biology in the 1950s. More than half a century later, the hope that quantum mechanics would elegantly explain life processes as it had explained other states of matter so distinctively and comprehensively, has not materialized yet. In spite of the rapid progress in the use of classical physics methodology to meso-scale systems of relevance to biology, there have been persistent claims that quantum mechanics can and should play a fundamental role in biology. For example, biological coherence could emerge through coherent superpositions, tunneling and entanglement. These claims range from plausible ideas like quantum-assisted protein conformational changes to more speculative suggestions, such as the genetic code having its origin in quantum computation algorithms, or quantum-mediated cognitive processing in the brain. Unfortunately, biological systems are so large and complex compared to standard physical systems that it is hard to separate “pure” quantum effects from a large number of essentially classical processes that are also present. There is thus plenty of scope for disagreement about the extent to which life in general and cognition in particular utilizes non-trivial quantum processes.

Why should quantum mechanics be relevant to life and consciousness, beyond explaining the basic structure and interaction of molecules? For one, quantum effects can facilitate processes that are either too slow or impossible according to classical physics. Properties such as discreteness, quantum tunneling, superposition and entanglement produce novel and unexpected phenomena. Given that the basic processes of biology take place at a molecular level, harnessing quantum effects does not seem *a priori* implausible. Quantum coherence, collective modes of excitation and condensation phenomena also offer attractive features that could shed light on the mechanisms of robustness and integrity of biological organisms, especially the amazing power of the human brain.

Since both physics and chemistry crucially depend on the power of quantum mechanics to provide fundamental insights into the world around us, it is natural to inquire whether biology offers examples of phenomena where quantum mechanics is the only viable explanation. This is indeed becoming increasingly clear although examples of quantum effects in biology can so far be considered only a minor part of life processes as we know them. Below, we provide a brief overview of the efforts to apply quantum principles to biology.

4. Biological Coherence and the Functioning of the Brain

Almost a century ago, Gurvitsch introduced the concept of biophotons and attempted to elucidate embryology through the action of so-called morphogenic fields, a yet unproven hypothesis (Belousov *et al.*, 1997). Following in his footsteps, Popp and his collaborators demonstrated that photons, or electromagnetic energy quanta can be both absorbed and emitted by DNA molecules and this involves low-intensity ultraviolet ranges of the spectrum (Cohen & Popp, 1997). Albrecht-Buehler (1995) demonstrated experimentally that living cells perceive infrared electromagnetic waves with a peak of their sensitivity close to the wavelength of 1000 nm. He hypothesized that mitochondria, by proton transfer involved in energy production, release photons. Conversely, centrioles, dubbed by him the eye of the cell, are intricately structured to absorb these photons and trigger a signaling cascade. Albrecht-Buehler (1995) has been advocating a theory of cell functioning based on his conviction that the centriole plays the key role in orchestrating cellular activities by being both an eye and a brain of the cell. Cell movement is not random but directed and intentional. This is a crucial characteristic that distinguishes living from non-living matter. Cells control the movement of every part of their body. Furthermore, various parts of the cell can be likened to parts of the human body in their functional roles. Plasma membrane and cortex correspond to the skin and the musculature of a cell and it consists of small autonomously moving “microplasts”. Their autonomy implies that cells contain a control system preventing the autonomous units from moving independently and randomly. The bulk cytoplasm including the mitochondria, organelles and intermediate filaments comprises the actual cell body excluding the nucleus, and correspond to the “guts” and “innards” of the cell body. Its main cytoskeletal components are the intermediate filaments although microtubules traverse this compartment everywhere (Dustin, 1978). Microtubules mediate between the control center (the centriole) and the autonomous domains. The control center detects objects and other cells by pulsating near infrared signals. In response to external electromagnetic signals, the centrosome is expected to send destabilizing signals along the array of microtubules radially emanating from it. The signal is then transduced into a mechanical or electrical wave that can propagate along the microtubules similar to action potentials along nerves. The work of Albrecht-Buehler (1995) is of great importance since it could be interpreted as providing a well-studied example of proto-consciousness at the cell level where the cell receives signals from its

environment, analyzes them and reacts appropriately. These signals can be electromagnetic and at least some of the processing involves quantum effects. Along these lines, [McFadden \(2002\)](#) proposed an electromagnetic field theory of consciousness.

Almost 50 years ago [Fröhlich \(1968\)](#) theorized that the efficiency of biological processes is largely due to quantum coherence effects which were hypothesized by him to involve the nonlinear coupling of vibrations of cellular membranes to dipole modes of the phospholipid molecules. He further postulated that a Bose–Einstein condensation phenomenon is at play leading to the occupation of a single mode of quantum excitation and an associated phenomenon of long-range order. While normally Bose–Einstein condensates are properties of systems at very low temperatures, according to Fröhlich, biological systems found a way of using this effect at physiological temperatures due to the nonlinear coupling involved. Moreover, thermal energy is used to drive the process as an incoherent pump. Fröhlich condensates have never been definitively demonstrated experimentally, but recently there has been renewed interest and some experimental support, at least for weak condensates ([Abbott *et al.*, 2008](#)). The latter could play a dramatic role in chemical kinetics of far-from-equilibrium biological nano-systems. Fröhlich further postulated that quantum coherence is an inherent property of living cells, which utilize it for long-range interaction purposes including synchronization of cell division processes and cell–cell recognition. Unfortunately, so far only scant experimental evidence exists to support these claims.

[Engel *et al.* \(2007\)](#) investigated photosynthesis from the point of view of quantum energy transfer and accomplished a major breakthrough. Photosynthesis is known to be a very complex process of light energy harvesting in which a water molecule is split by photon energy creating a set of subsequent chemical reactions. The amazing efficiency of this process is an example of evolutionary achievement by fine-tuning the performance of physical systems to near perfection. Chromophores are the molecules which are the primary receptors of light that become excited and pass the excitation energy in a multi-stage process to the final reaction center which leads to charge separation. Since the photon wavelength is many times larger than the size of the molecular complex, a quantum superposition state is created which covers many excited pigment molecules with a lifetime of hundreds of femtoseconds. They investigated the process using lasers to excite and probe the pulses and the associated relaxation process of the light harvesting systems. They detected a quantum beating effect in which the maximum amplitude of the excitation repeatedly positions itself with different molecules of the complex in a coherent fashion. Proper timing used in the process allows the system to capture the coherent excitation with a greater probability compared to the one obtained if it were simply distributed according to the rules of classical statistics ([Blankenship & Engel, 2010](#)). As a consequence, a significant speed-up of the energy transfer process is accomplished. It is important to stress that the molecular architecture of the complex is highly condensed which is suggestive of being the result of an optimized design process aimed at exploiting long-range quantum coherence processes. It is highly probable that a particular molecular

architecture has been selected over millions of years of evolution in order to maximize these coherence effects in terms of efficiency and performance. In the light-sensitive complexes, reaction centers capture individual photons and transfer exciton energy by tunneling avoiding decoherence even at room temperatures, which has been invoked on numerous occasions as a serious impediment to quantum biology (Tegmark, 2000) but also defended on various grounds (Hagan *et al.*, 2002) as will be discussed below. These recent advances in the use of quantum principles to elucidate photosynthesis are very important in view of the energy transduction being a key.

Since the discovery of potassium K^+ channels, a surge of interest has been aroused to explain their fascinating molecular mechanisms. These complexes that are assembled by several proteins creating circular pores through the membrane operate in a fast and precise manner. KcsA is a potassium channel conducting K^+ ions with a high efflux rate ($\sim 10^7 - 10^8$ ions per second) (MacKinnon, 2003) while selecting K^+ over Na^+ with a remarkable rate of 10^4 to 1 (Doyle *et al.*, 1998). It is worth noting that the difference in atomic radii of K^+ and Na^+ is about 0.38 nm. In many ion-channel proteins, flow of ions through the pore is controlled by a gate, comprised of a selectivity filter that can be activated by electrical, chemical, light, thermal and/or mechanical interactions. Following the determination of an atomic resolution structure of the bacterial KcsA channel, it became clear that classical models such as the “snug-fit” model (Noskov *et al.*, 2004), might not be able to adequately explain such a delicate selectivity process. Vaziri & Plenio (2010) and Ganim *et al.* (2011) proposed a quantum coherence mechanism for the selectivity filter and studied vibrational excitations in K^+ ion-channels. They predicted that resonances at the picoseconds (ps) scale in the backbone amide groups play a role in mediating ion-conduction and ion-selectivity in the selectivity filter. Summhammer *et al.* (2012) also investigated the interaction of a single potassium ion within the surrounding carbonyl dipoles by analyzing solutions of the Schrödinger equation for the bacterial KcsA ion-channel. They showed that alkali ions can become highly delocalized in the filter region even at physiological temperatures. The importance of the ion channels to neurophysiology is undeniable. If ion channels can operate using the principles of quantum mechanics, then the next logical step is to demonstrate their potential interactions and entanglement which would then lead to collective quantum states in neuronal membranes. As will be discussed below, within neurons arguments can be made about the quantum behavior of their cytoskeletal filaments such as microtubules. Consequently, the cytoskeleton can interact with ion channels using quantum entanglement.

Beck & Eccles (1992, 2003) argued that the process of neurotransmitter release in the functioning of synapses is governed by the quantum uncertainty principle and involves quantum tunneling. They further suggest that the introduction of quantum indeterminacy into neurotransmitter release mechanisms would allow for human free will of action. Their notion is that a quantum process, such as an electron tunneling through an energy barrier, triggers exocytosis. The sheer size of the vesicle and the large number of neurotransmitter molecules contained in it make it next to impossible

to lend itself to quantum tunneling processes. Although the Beck–Eccles model contains very attractive ideas, the crux of the theory appears to be incompatible with the present-day molecular biology of vesicular neurotransmitter release (Smith, 2009).

Lowenstein (2013) in his recent book made a powerful argument for the usefulness of quantum processes in receptor functions involving molecular recognition. All sensory inputs depend on this type of activity (olfaction, vision, sound, touch) and they all involve single molecules being triggers for amplification of these signals up to the neuron level and eventual brain activation. This amplification mechanism of the quantum signaling connects the microscopic and macroscopic levels which is critical to our understanding of the binding problem.

At the level of organs and tissues, it has been demonstrated that the human eye is capable of detecting light at an extremely low threshold, perhaps as few as 2–3 photons at a time (Levine, 2000). Similarly, recent work of Franco *et al.* (2011) has provided strong arguments to claim that the sense of smell (olfaction) is based on a quantum resonant energy transfer mechanism involving vibrational degrees of freedom of aromatic molecules and receptors in the membranes of olfactory nerves.

Although the foregoing examples have been in the literature for a number of years, they have not led to a widespread acceptance that quantum physics is important for biology.

5. Quantum Metabolism: The Key to Life

The specific heat of solids satisfies certain empirical relations, as embodied in the Dulong and Petit law stating that at sufficiently high temperatures, the specific heat of a solid is proportional to $3Nk$, where N is the number of atoms, k the Boltzmann constant. At low temperatures, the relationship between specific heat and temperature is a cubic dependence on absolute temperature. The quantum theory of solids, as developed by Debye, was proposed to explain these empirical relations. The crucial observation in these models was the consideration of the heat capacity as associated with the vibrations of atoms in a crystalline solid.

However, living organisms are essentially isothermal. Energy flow in living organisms is mediated by differences in the turnover time of various metabolic processes in the cell, which occur cyclically. Demetrius (2003) has shown that the cycle time of these metabolic processes is related to the metabolic rate, that is the rate at which the organism transforms the free energy of nutrients into metabolic work. The recently proposed theory of Quantum Metabolism (Demetrius, 2003) exploits the methodology of the quantum theory of solids to provide a molecular level explanation of these empirical relations.

Debye (see for example Ashcroft & Mermin, 1976) considered the heat capacity as associated with the harmonic vibrations of atoms in a crystalline solid. The vibrations were treated according to quantum theory and satisfied the following tenet. The energy stored by an oscillator with frequency ω can only be an integral multiple of a fundamental energy quantum $h\omega$: $E_n = nh\omega$, $n = 1, 2, 3, \dots$. The model

proposed by Debye, which proved to be consistent with empirical observations, assumed that the atoms in the solid execute coupled vibrations about the fixed lattice site leading to the propagation of waves in the solid and the frequencies of these vibrations span a range of values from zero to a maximum (Debye) frequency.

The production of adenosine triphosphate (ATP), the energy currency of living organisms is mediated by the coupling of two molecular chains: (a) The redox chain, which describes the transfer of electrons between redox centers within the electron-transport chain. (b) The ATP-ase motor, which is involved in the phosphorylation of adenosine diphosphate (ADP) to ATP. There are two distinct mechanisms by which these two events are coupled: oxidative phosphorylation, which involves an electrical process, and substrate phosphorylation, which implicates a purely chemical process. The transit time of this cyclic process determines the total metabolic flux, that is, the number of proton charges released by the redox reactions. This transit time, or the metabolic cycle time, denoted τ , plays a fundamental role here. In oxidative phosphorylation, which occurs in the mitochondria, the electron transport between redox centers is coupled to the outward pumping of protons across the mitochondrial membrane thus generating an electrochemical gradient, called the proton motive force, Δp . Substrate phosphorylation, which is localized within the cytosol is driven by a set of enzymes which couple ADP phosphorylation to the electron transport chain.

The molecular dynamics model proposed to investigate this coupling by electrical and chemical means assumes that the energy generated by the redox reactions can be stored in terms of coherent vibrational modes of enzymatic oscillators embedded in the cellular organelles. Quantum Metabolism rests on the notion that the enzymatic oscillations in cellular organelles and the material oscillators in crystalline solids can be analyzed in terms of the same mathematical formalism used by Debye in the quantum theory of solids. This realization is deduced from a formal correspondence between the thermodynamic variables in physical systems, and the metabolic quantities in biological processes. The principal variables in the quantum theory of solids are the specific heat, the Gibbs–Boltzmann entropy and the absolute temperature T . The fundamental unit of energy is given by $E = k_B T$, the typical thermal energy per molecule. The critical variables in the theory of Quantum Metabolism are the metabolic rate, the entropy production rate and the mean cycle time, τ . This quantity describes the mean turnover time of the redox reactions within the cellular organelles. The fundamental unit of energy is now given by: $E(\tau) = g\tau$. Here, the value assumed by g depends on the mechanism, electrical or chemical, by which the electron transport chain is coupled to ADP phosphorylation. Note that since physical systems are described here at thermodynamic equilibrium, their parameters involve thermodynamic variables. Biological systems operate far from thermodynamic equilibrium (albeit close to steady states), hence their bioenergetic quantities involve fluxes, i.e., rates of change of energetic values.

Demetrius (2003) introduced the term enzymatic oscillator since enzymes undergo electrochemical oscillations about their fixed positions. These oscillations are generated by the metabolic energy associated with the transfer of electrons between

donor and acceptor pairs in the electron transfer chain in mitochondria. Since their power spectrum exhibits an exponent vastly different from that for random behavior, a description of the metabolic activity involving mitochondrial proteins involves coupled quantum oscillators of the Debye type.

Quantization of metabolic energy is due to integer ATP numbers being produced in the cell's mitochondria and their relatively low energy content comparable to physical quantum processes. The almost universal energy currency in biological systems is the ATP molecule. ATP synthesis in a mitochondrion or a chloroplast requires approximately 60 kJ/mol of energy delivered through electron transport reactions or absorption of photons, respectively. ATP hydrolysis releases 30.5 kJ/mol of free energy ($\Delta E = 5 \times 10^{-20}$ J), which can be viewed as a biological energy quantum. It is interesting to note that the particle-wave duality principle indicates that the wavelength of electromagnetic energy that corresponds to the biological energy quantum ΔE can be estimated as:

$$\lambda = hc/\Delta E = 9 \times 10^{-6} \text{ m}, \quad (2)$$

which corresponds very closely to the average size of a living cell. It is also interesting to estimate the Debye temperature for the biological energy quantum assuming that enzymatic reactions involving ATP production occur in a cyclical but correlated manner in a grid or lattice reminiscent of the Debye solid. We find that $T_D = \Delta E/k_B = 3 \times 10^3$ K and since the physiological temperature is $T_0 = 300$ K, it appears that $T_0/T_D < 1$ meaning that in the statistical sense, cellular metabolism operates in the quantum regime. This is of crucial importance since metabolism is a basic condition for sustaining life. In general, energy transduction in living systems involves three major modalities: photosynthesis (in plants and some bacteria), ion gradients and oxidative phosphorylation or glycolysis (in animal cells). If all energy transduction processes in living systems involve quantum mechanisms, then this becomes a fundamental property of living matter. The human brain is no exception. Moreover, its amazing efficiency manifested by a miniscule power consumption of 25 W for an enormous information processing capability of perhaps up to 10^{20} flops (compared to the supercomputer power consumption on the order of 1 MW and processing rate of 10^{15} flops), could be much more readily explained if it worked using quantum computation instead of classical digital or analog methods.

6. Quantum Processes in Microtubules?

Empirically, a host of studies indicate that the microtubule (MT) matrix in dendrites is structurally reorganized with learning and memory. Using an associative learning paradigm combined with immunohistochemistry, fear conditioning to either tone or to the training context induced significant changes in the microtubule associated protein (MAP2) in circumscribed regions of the cerebral cortex or hippocampus, with alterations correlating with the type of training (Woolf *et al.*, 1994, 1999).

In terms of molecular biophysics, based on their ability to propagate signals through the neuron (Brown & Tuszynski, 1997), MTs and actin filaments can be viewed as computationally relevant nanowire networks that operate within neurons (Woolf *et al.*, 2010). Rather than inputs to neurons being limited to causing discrete responses, this viewpoint offers the possibility of local and global neuroplasticity, based on the cytoskeleton computing and storing templates that translate patterns of inputs across widespread synapses into the “behavioral” output of the neuron (Abbott & Regehr, 2004). This behavioral output of the neuron is not limited to axonal firing and dendritic integration of electrochemically mediated inputs. Instead, it includes connecting the cell nucleus with the postsynaptic density, initiating transport of receptor molecules, membrane proteins, organelles and mRNA, regulating neurite motility, restructuring of spines and complex dendrite architecture, the lateral movement of receptor and membrane proteins of neurons, governing the availability of ion channels in the membrane and more. Potential computational modes for MTs and actin filaments are beginning to be understood (Priel *et al.*, 2006).

There is empirical evidence that shows signaling, communication and conductivity in microtubules (Gundersen & Cook, 1999) and theoretical models have demonstrated their potential for both digital and quantum information processing. Arguments for and against the existence of quantum effects in MTs are numerous. To investigate the existence of quantum computation in microtubule protein assemblies Craddock *et al.* (2009) modeled this system via cellular automata using both classical and quantum neighbor rules. Using a typical MT configuration and a tubulin neighborhood in a hexagon configuration, they represented the interior of tubulin electrostatically and showed that it contains two areas of positive charge separated by a negative potential region constituting a double well potential. The position of a mobile electron within this double potential well was the determining factor for the state of an individual tubulin dimer, with transitions determined by the minimization of the systems energy associated with electrostatic interactions of neighboring electrons and thermal effects. Classically the model allows transitions for electrons with sufficient energy to overcome the potential barrier (taken as 100–150 meV) in which the new configuration lowers the system’s energy, or if the configuration raises the systems energy with a finite probability of $\exp(-\Delta E/kT)$. The quantum cellular automaton model allows the electron to tunnel through the potential barrier with transitions for which the energy is lowered even if the electron does not possess the necessary energy to overcome the potential barrier. These simulations have shown that information processing at physiological temperatures is feasible provided a global clocking mechanism is present. However, it should be emphasized that many of the simulation parameters are not known empirically.

7. The Decoherence Problem

With the examples provided above, we have tried to make a case for the role of quantum effects in biology. However, there are strong arguments calling for caution

in making such claims due to a serious and fundamental problem involving effects such as coherence, entanglement, superposition, etc. The major issue is how such systems avoid decoherence due to environmental interactions, in particular thermal effects at physiological temperatures. Specifically, thermal noise at such high temperatures (by physical standards) is expected to lead to decoherence manifested by the creation of mixed states and an eventual transition to classical behavior. Therefore, the main question is how biological systems could find a way to reduce decoherence to allow quantum effects to persist for sufficiently long times to assist in such tasks as quantum search algorithms or tunneling phenomena.

Quantum decoherence has been recently the subject of keen interest of physicists and information scientists working in the area of quantum computation. A quest to build quantum computers has been underway over the past two decades or so in order to vastly increase the computational power and speed using coherent quantum states as basic logical units. Decoherence represents a source of computational error, so the idea is to design architectures that minimize the impact of decoherence. In the case of quantum computation decoherence is a source of error that grows with the temperature of the environment necessitating the use of extremely low temperatures for quantum computation such as those found in superconductors or cold atom traps.

Therefore, living cells at first glance appear to be a very challenging system in which to look for quantum effects, since they function at relatively high temperatures, are present in an aqueous environment and are subjected to thermal and environmental noises. In spite of preliminary calculations indicating very short decoherence times in living cells (less than a ps), there are some reasons to believe biological systems may be not as susceptible to decoherence as expected. An important aspect which is often overlooked is that biological systems are highly non-linear, are open to external influences, and operate far from thermodynamic equilibrium, all these aspects put them in a different category than most physical systems considered for comparison. The physics of open, non-equilibrium non-linear systems is still poorly understood and many surprising properties may be discovered including their quantum behavior. More detailed calculations lead to less pessimistic results. For instance, [Cai *et al.* \(2010\)](#) studied two-spin quantum systems driven from equilibrium which exhibited coherence even when subjected to thermal noise. [Leggett \(2002\)](#) investigated a spin-boson model coupled to low-frequency phonons and found extended decoherence times as well as a mismatch between the immediate and distant environment effects on the quantum system which would lead to prolonged coherence at low acoustic frequencies. It is important to stress that biological systems may generally operate at the classical regime except for some, specifically engineered modes of behavior that avoid quantum decoherence due to the environment.

At least two ways exist through which decoherence can be diminished for long enough time periods in order to enable the role of quantum processes in biology. First, a biological subsystem can be screened or isolated from the decohering environment

enabling its operation in the quantum regime. In this connection, thermodynamic gradients may effectively lead to temperature reduction in local areas such as is the case with the slow release of ATP energy in actomyosin complexes leading to an effective temperature of only 1.6×10^{-3} K. One should also recall the lessons learned from the physics of high-temperature superconductivity which indicate that in complex non-linear systems, simple “ kT reasoning” can be misleading since such systems do not satisfy the equipartition theorem.

Second, decoherence-free spaces may be created within the Hilbert space where coupling of the system to the environment does not exist. This is a consequence of the quantum Zeno effect where a paradoxical result is obtained such that strong coupling of some degrees of freedom to the environment allows other degrees of freedom to produce coherent superpositions and persistent entanglement (Davies, 2004). An example of this effect is a double-well potential in 1D where a particle is placed in the ground state of one well leading to a repeated tunneling through the barrier generating specific oscillations. Placing the particle in an excited state will result in a different frequency of these oscillations. Creating an initial superposition state of the ground and excited state leads to an evolution of a complicated combination of oscillating states gradually getting out of phase. Paradoxically, allowing the oscillating particle to interact with a thermal bath forces the various oscillations into synchrony maintaining partial coherence of the system as a direct consequence of environmental interactions. Could this be a metaphor for biological coherence? Was the idea of Frohlich intuitively correct but only technically flawed?

Finally, the basic premise that quantum states are destroyed by increased temperature is of limited validity if one considers the possibility, for example, of laser-like coherent pumping suggested to occur in biological systems with periodic structural arrangements such as microtubules (Fröhlich, 1968). Perhaps more importantly, recent experimental evidence shows that quantum spin transfer between quantum dots is *more* efficient at room temperature than at absolute zero (Ouyang & Awschalom, 2003). The key aspect in these experiments is that the temperature-enhanced quantum effect occurs via a benzene ring, an organic molecule with delocalized electron charge density. Also, experiments have shown quantum wave behavior of biological porphyrin molecules (Hackermüller *et al.*, 2003). By analogy, in living cells delocalizable electrons in aromatic amino acids, for example, may allow proteins to harness thermal environmental energy to promote, rather than destroy, quantum states. Quantum interactions among tryptophans in hydrophobic pockets (nonpolar, water excluding intra-protein regions) govern protein folding (Klein-Seetharaman *et al.*, 2002) and similar effects appear to mediate potassium channel function (Jiang *et al.*, 2003).

Finally in this connection, special attention must be paid to the structural hierarchical organization of biological systems which in turn translates into an interlocking hierarchy of time scales. Faster time scales may inform processes at slower time scales

about rapid processes taking place at a small spatial level. Amazingly, neural rhythms operate on time scales that vary from milliseconds to seconds, synchronize the forebrain and are mediated by neurotransmitter systems such as acetylcholine, norepinephrine, and serotonin (Woolf *et al.*, 2010). The neurotransmitter systems further fluctuate according to endogenous, circadian rhythms that also fluctuate according to the season of the year, which ultimately leads to an enormous range of time scales spanning between 8 and 10 orders of magnitude or even more if atomic fluctuations are included. Since neural events at the millisecond time scale can affect neural states at the circadian level, by extension it is entirely possible that quantum states at the ps scale could affect neural activity at the millisecond scale and above. Hence, it is not necessarily a requirement for MT information processing to avoid decoherence up to millisecond time scales to have effects on neural events. It is essential that multiple oscillators be interdependent and sensitive to redundant patterns. Such interdependence might enable events operating at the shortest time scales and tapping into quantum mechanisms to affect larger scale events. Once again, coupling between scales and amplification effects may offer a solution to some of these issues.

8. Quantum Gravity and Quantum Consciousness

The problem of consciousness has defied conventional approaches which view the brain as a classical computer, with neurons and synapses playing the roles of bit states. Specifically, the following enigmatic features remain unexplained: (1) the “hard problem” of the nature of conscious experience, “qualia”, our “inner life”, (2) binding of disparate brain processes into unified concepts, objects and sense of “self”, (3) transition from pre-conscious processes to consciousness itself, (4) free will, or non-algorithmic (e.g., intuitive) processes, (5) subjective flow of time, (6) nonlocality.

Conventional neuronal-level computational approaches suggest conscious experience “emerges” at a critical level of complexity. Binding is proposed to be accounted for by temporal synchrony (e.g., coherent 40 Hz oscillations) but with no sense of the nature of conscious experience, temporal synchrony is merely correlative rather than explanatory. Perhaps the most potentially tractable problem is the transition from preconscious processes to consciousness itself. It is generally agreed upon that the vast majority of brain processes are non-conscious and that consciousness is the “tip of an iceberg” of brain activity. However no specific brain area houses consciousness; neural activity in a given area may be non-conscious at one moment, and correspond with consciousness at another. What causes the transition? The classical approach suggests a critical level of complexity results in the transition via emergence of consciousness, but again no threshold, biological correlate nor testable prediction have been put forth. Free will, subjective time flow and nonlocality have not been seriously addressed by conventional approaches (except to deny their existence).

Another shortcoming of conventional approaches is that neurons and synapses are considered as simple switches, whereas real biological cells are far more complex. For example single cell organisms such as *Paramecium* swim, avoid obstacles and predators, learn, find food and mates, all without possessing a single synapse. These cognitive functions can potentially be accomplished by the cell's cytoskeletal structures, primarily microtubules which will be discussed below.

Inspired by the application of quantum theoretical methods to the study of the brain and other biological structures scientists began to investigate brain functioning from the microscopic level of quantum physics. Perhaps the first attempt to describe the brain using the terminology of quantum physics was made by Ricciardi & Umezawa (1967). Based on experimental observations of brain activity they proposed that the brain could be conceived of as a spatially distributed system placed into particular quantum states by stimuli from the external environment. Thus, information can be thought of as being coded into the brain in the form of metastable excited states representative of short-term memory. This code would then be later on transferred to the ground state of the system by means of a condensation to the ground state in the manner of Bose-Einstein condensation accounting for learning and long-term memory. This model proposes that brain functions are manifestations of spontaneous symmetry breaking in the dynamics of the brain regulated by long-range correlations. The model put forth by Ricciardi & Umezawa (1967) and Stuart *et al.* (1978) relating macroscopic quantum states to brain function, memory specifically, was later extended proposing that the brain is a mixed physical system (Jibu & Yasue, 1995). In this model the brain is considered to consist of two distinct interacting parts, the first part consisting of the classical electrochemical interactions of the neurons of the brain, and the second being the macroscopic quantum state responsible for the creation and maintenance of memory at a molecular level.

Alternatives to computational emergence (Scott, 1995) include dualism (consciousness lies outside science), pan-protopsyism (precursors of conscious experience are fundamental, irreducible components of reality) and quantum information processing approaches (Litt *et al.*, 2006). Major effort has been specifically placed on the explanation of the role of protein polymers and their networks located within individual cells and known collectively as the cytoskeleton (Hameroff, 1997, 1998; Hameroff & Watt, 1982).

Penrose (1989, 1994) examined the relationship between consciousness and modern physics in a *tour de force* exposition of Turing machines, Gödel's theorem, chaos, classical and quantum mechanics, thermodynamics, relativity, cosmology, quantum gravity, quasi-crystals and brain neurophysiology. He introduced mathematics as a bridge from the artificial world of computers to the natural world of physics and argued via Gödel's incompleteness theorem that human consciousness is non-algorithmic, and thus that physical theories of brain function are incomplete due to their dependence on computable algorithmic laws. He further hypothesized

that quantum effects play a fundamental role in the understanding of human consciousness by enabling the brain to perform non-computable operations. In his explanation of the new physics required to explain the mind and consciousness, he examined the division between classical and quantum physics, specifically the measurement problem, and related the collapse of the wave function to conscious events using the notion of objective reduction. This led to the suggestion that microtubules within neurons provide the brain with structures capable of orchestrating the collapse of the wave function via quantum information processing. This union has been known as the Penrose–Hameroff Orchestrated Objective Reduction (Orch OR) theory (Hameroff & Penrose, 2014).

The basic idea is that microtubules within the brain's neurons function as quantum computers, with microtubule protein subunits ("tubulins") existing transiently in quantum superposition of two or more states (i.e., as quantum bits, or "qubits"). According to Orch OR, tubulin qubits in quantum superposition interact/compute with other superpositioned tubulins in microtubule lattices (Roberts & Hyams, 1979) by nonlocal quantum entanglement, eventually reducing ("collapsing") to particular classical tubulin states after 25 milliseconds or so (e.g., at 40 Hz). The quantum state reductions yield conscious perceptions and volitional choices, which then govern neuronal actions. This is essentially the same idea on which technological quantum information processing is based, except that in Orch OR the proposed qubits are tubulin protein conformations, and the reduction/collapse occurs due to a specific objective threshold (objective reduction) rather than environmental interaction. Objective reduction is a solution to the measurement problem in quantum theory, which considers the superposition of quantum states as a separation in underlying reality at its most basic level, the Planck scale. The solution involves a description of loop quantum gravity, which identifies wave function superpositions as curvatures of opposite direction in space-time, and thus a separation in fundamental space-time geometry. These separations are considered unstable and reduce to a single space-time curvature once an objective threshold is reached. The theory considers a conscious event as a quantum information processing, which concludes via objective state reduction. The biological conditions in the brain, including synaptic activity, are considered to influence the quantum information processing thus orchestrating the collapse of the qubits and giving rise to a conscious event. Orch OR is an attempt to place consciousness within the empirical sciences as a fundamental concept in science.

The central postulate of the Orch OR theory is that the site of action of consciousness is located within the brain's microtubules which operate at the interface between classical neurophysiology and quantum gravitational forces. These are very bold claims that have found both ardent supporters and vocal critics in the scientific community. However, the enduring power of attraction of Orch OR for a solid base of support across science, philosophy and beyond is a testament to the creative influence of this work on the field.

The main concerns with Orch OR can be broadly separated into the following three categories (Grush & Churchland, 1995; Koch & Hepp, 2006; Seife, 2000)

- (1) The empirical evidence demonstrating how the activity of a single synapse enters into the dynamics of neural assemblies is lacking, thus the relevance of quantum processes in mental phenomena remains a claim requiring validation.
- (2) As of yet, there appears to be no specific quantum mechanical properties needed to explain psychological and neurological phenomena. The relevance of quantum effects to the structure and function of the brain does not necessitate their involvement in explaining consciousness. Although this point can be argued in view of the hard problem.
- (3) Structures such as microtubules and neurons are large, high temperature systems from the quantum mechanical point of view. As such, it is next to impossible for them to remain in states of linear superposition capable of coherently interfering with one another, thus decoherence eliminates any possibility of quantum effects playing a role in brain processes. This point has been already discussed above and is still an open issue.

There have been many debates concerning whether the quantum description of consciousness is valid, realistic or needed. However, only recently have advances in nanotechnology allowing for serious empirical investigation into the biophysical workings of sub-cellular structures been made. As such, the lack of evidence in support of quantum brain theories should not be taken as proof against these theories, but rather as an area in need of careful and vigorous scientific investigation. The several enigmatic features of consciousness mentioned previously are still, for the most part, left unexplained by classical theories. The apparent ability of quantum theories to answer these questions may provide new avenues of investigation into consciousness. It is known that macroscopic quantum phenomena such as superconductivity, superfluidity and laser action exist at relatively high temperatures (albeit requiring very finely tuned conditions) and that these phenomena cannot be explained via classical means, but rather require the idea of macroscopic quantum coherence within a condensate. Therefore, it can be stated that not all phenomena observed in large-scale systems can be expected to behave classically. Thus, while the first two arguments against quantum consciousness represent a general resistance to the idea, the third is an argument of worthwhile concern. Macroscopic quantum phenomena such as superconductivity, and superfluidity require high isolation from their environment in order to avoid the effects of decoherence. In order for such phenomena to exist in the brain, nature would need to provide mechanisms to isolate against decoherence. The subject of decoherence in relation to quantum information processing in microtubules particularly has been widely discussed and strong arguments have been made on both sides of the discussion.

Tegmark (2000) made a major objection specifically to the Orch-OR theory, and the notion of a quantum brain in general, based on calculations of neural decoherence

rates for both regular neuron firings and for kink-like polarization excitations in microtubules. He claimed that the degrees of freedom in the human brain should be considered classical rather than quantum. Tegmark found decoherence time-scales for superpositions of solitons moving along a microtubule of approximately 10^{-13} – 10^{-11} s, which are much shorter when compared with the relevant time-scale for cognitive processes of 10^{-3} – 10^{-1} s. Thus, he concluded that quantum coherence within the brain is not feasible. However, Hagan *et al.* (2002) pointed out that Tegmark's calculations are based on an incorrect model of the Orch-OR process. Accounting for this discrepancy, as well as for the effects that screen thermal fluctuations, such as layers of ordered water and actin gel states surrounding microtubules, Hagan *et al.* (2002) found new decoherence rates of 10^{-5} – 10^{-4} s that are in line with relevant dynamical times of biological phenomena. These arguments are both refuted by Rosa & Faber (2004) who find, based on decoherence calculations, that the Orch-OR model based on gravitational collapse is incompatible with decoherence, but that the notion of quantum phenomena in the brain are still feasible if decoherence is taken as a quantum collapse mechanism rather than a quantum gravity effect. Coherence times can be extended by counterion shielding, actin shielding, intrinsic error correction, among other properties; nonetheless, decoherence remains as an issue (Hagan *et al.*, 2002). However, as discussed above, recent experiments have shown room temperature quantum effects in photosynthesis (Engel *et al.*, 2007) and conjugated polymer chains (Collini & Scholes, 2009). Nonthermal radiation at 8.085 MHz has been observed from MTs, and while not necessarily an indication of a quantum condensate or coherence, it remains a possibility (Pokorný *et al.*, 2001). Reimers *et al.* (2009) and McKemmish *et al.* (2009) state that this radiation could only be the result of a weak condensate that could not result in the coherent motion necessary for the Penrose–Hameroff model, however their results are based on a linear chain of coupled oscillators rather than the cylindrical geometry of MTs leaving the question still open. Another issue at hand is the range of motion in tubulin dimers when they are polymerized into stable MTs, bringing into question whether intact MTs allow two potential conformations of tubulin dimers. McKemmish *et al.* (2009) clearly demonstrate that repeated exchanges between the GTP and GTP-bound forms of tubulin within MTs are not supported by current experimental evidence. While the conformational states are generally identified as tubulin-GTP and tubulin-GDP the Penrose–Hameroff model does not specify the precise nature of the conformational states envisaged, so alternatives remain a possibility, however the consistency of the timescales between such interactions and the Penrose–Hameroff requirements remains an open question. Clearly, these issues are not completely resolved. Thus, investigations into the quantum nature of microtubules are still badly needed.

At any rate, crucial validation or falsification of Orch OR must come from experimentation. This is very challenging since the current “gold standard” in neuroscience is fMRI whose spatial resolution is on the 1 mm scale while temporal resolution is on the 1 s scale. This is orders of magnitude higher than the 1 nm and

1 ns scales of tubulin's size/time operational dimensions as studied by molecular biophysics, let alone the quantum gravity effects hypothesized by Orch OR to be occurring on the Planck scale of space-time geometry (10^{-35} m; 10^{-44} s). This huge gap between the current experimental capabilities and the predictions made by Orch OR poses the greatest challenge to the acceptance of these tenets.

9. Future Outlook

We foresee major progress in bridging the gap between nanoscience and consciousness in the area of nano-neuroscience where MT's, actin filaments and motor proteins connect between neurophysiology and molecular biology. Studying the neural phenomena at a nanoscale will lead to monumental breakthroughs in science and medicine and aid in consciousness studies.

Further possibilities involving physically-based quantum mechanisms of consciousness should also be considered. The basic idea is to investigate if there are other quantum network architectures that could be operating in the brain. First of all, quantum entanglement in such a network could provide at least a partial answer to the binding problem of consciousness allowing for a delocalized quantum state involving many neurons. This requires a thorough understanding of quantum networks. It is worth emphasizing that quantum networks may lead to quantum memories whereby entangled states would store information such as visual inputs. Moreover, quantum networks could generate communication channels that would transport information and process it performing complex operations.

Recent experiments involving solid state physics devices based on nuclear spins demonstrated quantum information storage on the time scale of minutes or even hours is possible as demonstrated by Thewalt's group in their research on super-long quantum information storage using phosphorus ions in silicon (Saeedi *et al.*, 2013).

However, several challenging issues remain to be addressed. First of all, due to thermal fluctuations, a magnetic field of sufficient strength would be required to prepare the spin system in a pure enough state. On the other hand, there are no naturally occurring large magnetic fields and we also know that strong magnetic fields such as those in MRI machines do not have a significant effect on the state of consciousness of the person subjected to MRI scans. Regarding quantum communication channels, photon emission and absorption is the best candidate mechanism for such phenomena. Biophotonics is an emerging field in spite of its long history of false starts and intermittent periods of dormancy. A recent review (Cifra *et al.* 2014) summarizes the landscape in this field emphasizing a relatively narrow range of wavelengths between 350 nm and 1300 nm. It is also interesting to consider signal amplification and transmission over macroscopic distances along axons and dendrites of neurons.

Quantum computation in the brain would surely be beneficial from an evolutionary standpoint, and biology has had 4 billion years to solve the decoherence problem. Understanding the biological basis for sustained quantum coherent

superposition and entanglement would not only help to solve the enigmatic features of consciousness, but also enable future quantum information technologies.

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