Coherent Energy Transfer and the Potential Implications for Consciousness

J. Tory Toole[1,2], P. Kurian[3,4], T. J. A. Craddock[2,5]

College of Psychology, Nova Southeastern University, Ft. Lauderdale, FL 33328, USA[1]
Clinical Systems Biology Group, Institute for Neuro-Immune Medicine, Nova Southeastern University, Fort Lauderdale, FL 33328, USA[2]
Department of Medicine, Howard University College of Medicine, Washington, DC 20059, USA[3]
Quantum Biology Laboratory, Howard University, Washington, DC 20059, USA[4]
Departments of Psychology & Neuroscience, Computer Science, and Clinical Immunology, Nova Southeastern University, Fort Lauderdale, FL 33314, USA[5]

Abstract

The argument that biological systems are too "warm and wet" to support quantum effects is becoming increasingly antiquated as research in the field of quantum biology progresses. In fact, not only is it becoming apparent that quantum processes may regularly take place in biological systems, but these processes may underlie the mechanisms of consciousness and propel our models of conceptualizing the human brain into the next era of scientific understanding. The phenomena of consciousness have allured scientists and philosophers for thousands of years, while a precise technical understanding has remained elusive. If possible, developing this understanding will likely be one of humanity's greatest achievements. Knowing the fundamental processes that create conscious experience has far-reaching implications, from the potential birth of true artificial intelligence to a better

Journal of Cognitive Science 19-2:115-124, 2018

understanding of mental health disorder etiologies and treatments. One major challenge in the mental health professions, and, ultimately, in empathy of any kind, is being able to see from and appreciate another person's unique, subjective experience. Discoveries in the field of consciousness could help bridge this gap.

Keywords: *Consciousness; Coherent energy transfer; Quantum biology*

MAIN

Consciousness has proven to be one of the most elusive ideas for scientists and philosophers to fully understand. The primary reason for this lack of understanding lies in the tension between the personalized and subjective nature of consciousness, on the one hand, and the scientific belief that observable phenomena constitute an objective external reality, on the other. We may, for example, be able to agree on the number of people in a room, but it is quite another matter to assess how the people in a room make one *feel*. While consciousness can be described as the subjective experience of any one person, the fundamental limit to knowing another person's unique first-person experience creates a gap in truly understanding the phenomena of consciousness. This seemingly unbridgeable gap between first-person subjective "qualitative" experience and third-person "objective" reality has placed conscious awareness just beyond the reach of traditional quantitative scientific observation. While some believe consciousness and subjective experiences (i.e. qualia) to be human constructs to describe a series of mental processes with physiological correlates, others believe this concept transcends our classical understanding of the inner workings of the brain, with notions suggesting that qualia are physically real but beyond physical observation (Beshkar, 2018). However, since the creation of the computer, the brain has been reduced to a machine of inputs and outputs, effectively a biological computer that follows the deterministic rules of classical physics. Certain aspects of the brain, however, have challenged this concept, with consciousness chief among them.

As such, in the early 1990s Sir Roger Penrose, a mathematical physicist, made the conjecture that consciousness may be related to quantum phenomena, just beyond the reach of our current understanding and models of the brain (Penrose 1991). This work, furthered by collaboration with the anesthesiologist Stuart Hameroff (Penrose, 1994; Hameroff & Penrose, 1996; 2014), suggested that quantum processing may occur in the network of protein structures maintaining the architecture of brain cells, namely within neuronal microtubules. This idea that consciousness occurs on a quantum level, while commonly attributed to Penrose and Hameroff, is not an isolated discovery, beginning in germinal form with the founders of quantum mechanics (Bohr, Schrödinger, Wigner, etc.) and continuing in the recent past with Satinover (2001), Woolf et al. (2009), Reimers (2009), Vaziri and Plenio (2010), Lowenstein (2013), Craddock et al. (2014), Al-Khalili and McFadden (2014), Fisher (2015), and Jedlicka (2009; 2017) and others theorizing in one way or another that quantum processes have something to do with the workings of the mind.

The double-slit experiment informs us that a conscious observer can alter the outcome of a quantum measurement. But what does "quantum" have to do with the brain? The unique conjecture of Penrose rests on the idea that human understanding, subjective experience, and conscious awareness are in and of themselves non-algorithmic, and therefore they require a biological substrate capable of supporting non-algorithmic processes. Quantum mechanics describes such a set of laws that govern nature on the microscopic scale. Trivially, these laws determine the energy levels of electrons, the properties of atoms, and the behavior of photons, among other things, and in this sense they apply in a straightforward manner to all matter, including the brain. But these quantum laws also predict more "exotic" properties of matter, which are observed to stem from coherent quantum states formed from entanglement (multiple particles that cannot be described independently even at large distances), superposition (a single particle simultaneously existing in multiple states), and tunneling (a particle passing through a classically insurmountable barrier). These properties of quantum systems are directly responsible for much of the digital technological growth of the last century, and they have led to the harnessing and use of electricity, the creation of the computer, and the development of cell phones. However, these same non-trivial quantum phenomena afford a biological system like the brain a degree of non-deterministic (i.e. non-algorithmic) behavior.

The connection between large-scale and small-scale physics has been another elusive quest for modern physicists, manifesting most notably in the irreconcilability between general relativity and quantum mechanics. Strides have been made to use quantum understanding to better human life in a myriad of ways, from the light bulb and the early computer to quantum processing, imaging, and cryptography. Biology, the study of life and its dizzying array of complex systems, has traditionally been described by physicists as large-scale and without quantum effects, with proponents arguing that biological systems are too “warm, wet, and noisy” for quantum processes to take place. This mainly stems from the difficulty in setting up and maintaining a system in a stable quantum state, which often requires near-complete isolation from the environment at extremely cold temperatures (~-273℃) and shielded from stray electromagnetic fields. Recent research, however, is suggesting that this is not the case. Quantum coherent transport in photosynthesis, magnetoreception in birds, olfaction (Lambert et al., 2013), and single-photon effects in vision (Fleming et al., 2011) are just a few examples of how quantum effects in biology are possible. For example, in 2007, quantum oscillations attributed to electronic coherence were observed in the Fenna-Matthews-Olsen (FMO) photosynthetic light-harvesting complex (LHC) at the relatively warm temperature of -196℃, challenging the idea that quantum phenomena and biology do not mix (Engel et al., 2007). This experiment was then conducted at 4℃, nearing physiological temperature, and observed not only in the FMO complex but in LHCs in plants (LHCII), bacteria (LH2), and phycobiliproteins (Chenu et al., 2007; Hildner et al., 2015).

Many quantum biological systems currently known seem to be comprised of a pigment (or small, non-protein molecule such as a ligand, odorant, or flavin) in a protein environment (Brookes, 2017). The theoretical basis of the coherent energy transfer in photosynthesis involves the unique light-capturing nature of chlorophyll and the elegant geometrical arrangement of these pigments in the LHCs of plants and bacteria. Due to these characteristics, light energy can be efficiently captured and funneled from the environment to reaction centers within the cell. This light harvesting depends on the quantum mechanism through which light-induced excitations hop between pigments (also known as chromophores). The structure of chlorophyll molecules allows energy to be transferred from an excited group of atoms to a neighboring group of atoms via the resonance between their energy levels. This is analagous to the phenomenon that occurs when striking a tuning fork and placing it near a second tuning fork. The sound waves from the struck tuning fork resonate with the second fork, causing it to vibrate as well. This phenomenon, however, is not unique to photosynthesis, and is simply attributable to the specific structure and arrangement of chromophores within a protein.

One potential site of interest for understanding how quantum processes may occur in the human brain is the microtubule, a hollow cylindrical polymer of the protein tubulin. These structures are among the most abundant in the cytoskeleton of the cell and are responsible for maintaining cell morphology, trafficking cell cargo, cell motility, and possibly playing a role in signal transduction. They are essential to maintaining the complex architecture and inner workings of brain cells. Tubulin, the microtubule constituent protein, possesses a network of chromophoric tryptophan (Trp) amino acids. These aromatic chromophores, with their specific structure and arrangement in tubulin, may also support coherent quantum effects. Craddock et al. (2014) investigated the biological feasibility of this type of coherent energy transfer in tubulin and found that it is theoretically possible for energy to be transferred via this quantum process. This suggests that the structure of microtubules in the brain can feasibly use coherent energy transfer, similar to photosynthesis, as a mechanism for signaling and information processing.

The spatial distribution and orientation of the Trp amino acids in tubulin are shown to be comparable to that of chromophores found in other light-harvesting biological systems (e.g., cryptophyte marine algae), which have also been shown to support quantum-coherent transfer of electronic excitation. As mentioned, spatial distribution and orientation of chromophores are key hallmarks of this quantum process. Craddock et al. (2014), using modeling and simulations, found that the electronic characteristics and spatial orientation of Trps within microtubules are comparable to light-harvesting structures in plants and bacteria, and that it is very feasible that the quantum processes experimentally observed to occur in these plant/bacteria structures may take place within the Trp network in tubulin. This is indeed noteworthy, as it suggests that not only can quantum-coherent energy transfer occur in photosynthetic systems, but it may happen more generally in eukaryotic cells, including cells in the human brain.

The possibility of coherent energy transfer occurring in the human brain carries with it many exciting implications. For one, these underlying quantum phenomena could be an important clue in better understanding the mechanisms of neurodegenerative tauopathic disorders such as Alzheimer's disease and Parkinson's disease-related dementia. These specific types of disorders are characterized by altered forms of the microtubule-associated protein (MAP) tau, which is a key protein in stabilizing the microtubule architecture that regulates neuron morphology and synaptic strength. It is this uniquely elegant architecture that gives rise to the possibility of coherent energy transfer. MAP tau is a very important protein in neuronal axons. It acts to stabilize the microtubule cytoskeleton and, when compromised, allows the cytoskeleton to disintegrate. This type of neurodegeneration is the hallmark of these tauopathic diseases. Understanding the mechanisms by which the microtubule cytoskeleton becomes destabilized may lead to new diagnostics and therapies for these illnesses.

One prominent early event in tauopathy, or the pathological aggregation of the MAP tau protein, is oxidative stress. In a biological context, reactive oxygen species (ROS) are chemically reactive chemical species containing oxygen. They are the natural byproduct of oxygen metabolism and play important roles in the functioning of the cell (Wilson et al., 2015). While the production of ROS is a natural part of aerobic life, a surplus can be detrimental. Oxidative stress occurs when there is an imbalance between the amount of ROS being naturally produced and the body's ability to detoxify the reactive intermediates or repair resulting damage. While these ROS reactions can interact in a variety of ways throughout the body, certain chemical processes result in excited-state molecules that release photons (particles of light) of specific energies ranging from the ultraviolet through the visible to the infrared (Cifra and Pospisil, 2014; Van Wijk, 2014; Mei, 1994; Slawinska and Slawinski, 1983). Exposure to light in the near-ultraviolet range causes absorption by proteins, primarily mediated by the aromatic amino acids tryptophan, tyrosine, and to a lesser extent phenylalanine. Therefore, it is possible that as ROS reactions cause the emission of photons in the cell, these photons are absorbed and transferred through the microtubules via amino acids such as tryptophan. The degree and extent of this process, and whether or not this absorption and emission involves coherent energy transfer, however, remains an open question. Yet, as we have discussed, this process appears to be theoretically possible and achievable under biological conditions, meaning that energy transfer within cells could occur, at least in part, through quantum coherence. Furthermore, because ROS reactions can be a catalyst for this energy transfer, oxidative stress can cause destabilizing effects in tubulin and the microtubules of the cell due to disruptions of such coherent energy transfer.

In very recent work, Kurian et al. (2017) modeled the effects of ROS-induced excitonic propagation via coherent energy transfer in aromatic networks of linear tubulin polymers. They found that this process is significant on at least the micron scale, suggesting the physiological relevance of such coherent dynamics. This finding also alludes to the possibility that such excitations resulting from metabolic activities may influence neural firings, which are dictated by rates of ion flow through sodium, potassium, and other channels via changes in the microtubule cytoskeleton. This coherent energy transfer in any one instant may be inconsequential behaviorally. However, coherent energy transfer across multiple microtubules in a neuron and across many brain cells via synchronous neuron firing may have implications in brain activity, behavior, and even consciousness.

Yet, while this mechanism in and of itself is not tied to a specific theory of consciousness, it is consistent with propositions made by others regarding the quantum nature of conscious processes. In regards to the study of subjective consciousness, if such a system is capable of generating physically real but physically unobservable properties (Beshkar, 2018), or if it can be considered as an indefinite causal structure (Hardy, 2009), this may provide room for a physical description of unmeasureable (i.e. subjective) qualia, and therefore consciousness. Just as the discovery of quantum mechanics was a paradigm shift for our understanding of matter, the possibility of quantum biology not only occurring in the brain, but being responsible for the manifestation of consciousness, could be a major paradigm shift in the way we conceptualize the mind, the brain, psychiatric disorders, and neurodegenerative diseases. Furthermore, understanding the connections between the mechanisms of the brain and the underlying quantum phenomena could lead to new questions and answers about the connections between macroscale phenomena and quantum physics. As we further our understanding of the various roles quantum processes can play in human experience, we take steps towards a potentially more complete understanding of consciousness.

References

Algar, W. R., & Krull, U. J. (2008). Quantum dots as donors in fluorescence resonance energy transfer for the bioanalysis of nucleic acids, proteins, and other biological molecules. *Analytical and bioanalytical chemistry*, 391(5), 1609-1618.

Al-Khalili, J., and McFadden, J. (2014). Life on the Edge: The Coming of Age of Quantum Biology. London: Bantam Press.

Beshkar, M. (2018). A thermodynamic approach to the problem of consciousness. Medical Hypotheses.

Brookes, J. C. (2017, May). Quantum effects in biology: golden rule in enzymes, olfaction, photosynthesis and magnetodetection. In *Proc. R. Soc. A* (Vol. 473, No. 2201, p. 20160822). The Royal Society.

Chenu, A., & Scholes, G. D. (2015). Coherence in energy transfer and photosynthesis. Annual review of physical chemistry, 66, 69-96.

Choi, A. O., Brown, S. E., Szyf, M., & Maysinger, D. (2008). Quantum dot-induced epigenetic and genotoxic changes in human breast cancer cells. *Journal of molecular medicine, 86(3)*, 291-302.

Cifra, M. & Pospisil, P. Ultra-weak photon emission from biological samples: definition, mechanisms, properties, detection and applications. J Photochem Photobiol B 139, 2–10 (2014).

Craddock, T. J. A., Friesen, D., Mane, J., Hameroff, S., & Tuszynski, J. A. (2014). The feasibility of coherent energy transfer in microtubules. *Journal of the Royal Society Interface*, 11(100).

Craddock, T. J., Priel, A., & Tuszynski, J. A. (2014). Keeping time: Could quantum beating in microtubules be the basis for the neural synchrony related to consciousness?. *Journal of integrative neuroscience*, 13(02), 293-311.

Engel GS, Calhoun TR, Read EL, Ahn TK, Mancal T, Cheng YC, Blankenship RE, Fleming GR. (2007). Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems. *Nature*, 446, 782 – 786.

Fisher, M. P. A. (2015). Quantum cognition: the possibility of processing with nuclear spins in the brain. Ann. Phys. 362, 593–602. doi: 10.1016/j.aop.2015. 08.020

Fleming, G. R., Scholes, G. D., & Cheng, Y. C. (2011). Quantum effects in biology. *Procedia Chemistry*, 3(1), 38-57.

Hameroff, S., & Penrose, R. (1996). Orchestrated reduction of quantum coherence in brain microtubules: A model for consciousness. *Mathematics and computers in simulation, 40*(3-4), 453-480.

Hameroff, S., & Penrose, R. (2014). Consciousness in the universe: A review of the 'Orch OR'theory. Physics of life reviews, 11(1), 39-78.

Hardy, L. (2009). Quantum gravity computers: On the theory of computation with indefinite causal structure. In Quantum reality, relativistic causality, and closing the epistemic circle (pp. 379-401). Springer, Dordrecht.

Hildner, R., Brinks, D., Nieder, J. B., Cogdell, R. J., & van Hulst, N. F. (2013). Quantum coherent energy transfer over varying pathways in single light-harvesting complexes. Science, 340(6139), 1448-1451.

Jedlicka, P. (2009). Quantum Stochasticity and Neuronal Computations. Availableat: http://dx.doi.org/10.1038/npre.2009.3702.1

Jedlicka, P. (2017). Revisiting the Quantum Brain Hypothesis: Toward Quantum (Neuro) biology?. *Frontiers in molecular neuroscience*, 10, 366.

Kurian, P., Obisesan, T. O., & Craddock, T. J. A. (2017). Oxidative species-induced excitonic transport in tubulin aromatic networks: Potential implications for neurodegenerative disease. *Journal of Photochemistry and Photobiology B: Biology, 175*, 109-124.

Lambert, N., Chen, Y. N., Cheng, Y. C., Li, C. M., Chen, G. Y., & Nori, F. (2013). Quantum biology. *Nature Physics, 9*(1), 10.

Loewenstein, W. R. (ed.). (2013). Physics in Mind: A Quantum View of the Brain (New York, NY: Basic Books).

Mei, W. P. About the nature of biophotons. Journal of Biological Systems 2, 25–42 (1994).

Panitchayangkoon, G., Hayes, D., Fransted, K. A., Caram, J. R., Harel, E., Wen, J., ... & Engel, G. S. (2010). Long-lived quantum coherence in photosynthetic complexes at physiological temperature. *Proceedings of the National Academy of Sciences, 107*(29).

Penrose, R. (1991). The emperor's new mind. RSA Journal, 139(5420), 506-514.

Penrose, R. (1994). Shadows of the Mind (Vol. 4). Oxford: Oxford University Press.

Reimers, J. R., McKemmish, L. K., McKenzie, R. H., Mark, A. E., & Hush, N. S. (2009). Weak, strong, and coherent regimes of Fröhlich condensation and their applications to terahertz medicine and quantum consciousness. *Proceedings of the National Academy of Sciences of the United States of America, 106*(11), 4219–4224. http://doi.org/10.1073/pnas.0806273106

Satinover, J. (2001). The Quantum Brain: The Search for Freedom and the nextGeneration of Man. New York, NY: JohnWiley & Sons, Inc.

Slawinska, D. & Slawinski, J. Biological Chemiluminescence. Photochemistry and Photobiology 37, 709–715 (1983).

Van Wijk, R. Light in Shaping Life: Biophotons in Biology and Medicine. (Meluna, Geldermalsen, 2014).

Vaziri, A., and Plenio, M. (2010). Quantum coherence in ion channels: resonances, transport and verification. New J. Phys. 12:85001. doi: 10.1088/1367-2630/12/8/085001

Wilson, C., & González-Billault, C. (2015). Regulation of cytoskeletal dynamics by redox signaling and oxidative stress: implications for neuronal development and trafficking. Frontiers in cellular neuroscience, 9.

Woolf, N. J., Priel, A. & Tuszynski, J.A. (2009). Nanoneuroscience: structural and functional roles of the neuronal cytoskeleton in health and disease. Springer Science & Business Media.