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Medical Physics

A REVIEW OF QUANTUM PHYSICS IN BIOLOGICAL SYSTEMS

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ABSTRACT This review on quantum biology, a burgeoning field at the intersection of life and the bizarre rules of the quantum world, is investigating how phenomena like tunneling, superposition, and entanglement might influence biological processes. From the dance of odor molecules and smell receptors, potentially influenced by tunneling for odor discrimination, to the mind-bending possibility of entangled electrons guiding bird migration, the field is uncovering a hidden language within life. In photosynthesis, superposition allows light-excited electrons to explore multiple pathways, maximizing their efficiency in converting light into energy. Enzymes, the masterminds of countless reactions, might benefit from tunneling, allowing substrates to overcome energy hurdles, and coherence, enhancing selectivity. The radical pair mechanism, with its entangled electrons, is a potential explanation for how birds navigate with Earth's magnetic field. Finally, the article ventures into the uncharted territory of consciousness, pondering the possibility of quantum effects playing a role in neuronal ion channels, though significant challenges remain in verifying and understanding these effects within the brain's complex environment. Overall, this exciting nascent field holds the potential to illuminate intricate biological mechanisms and offer glimpses into the enigmatic realm of consciousness.

KEYWORDS : quantum biology, tunneling, superposition, odorant molecules, magnetoreceptors, microtubules, quantum entanglement

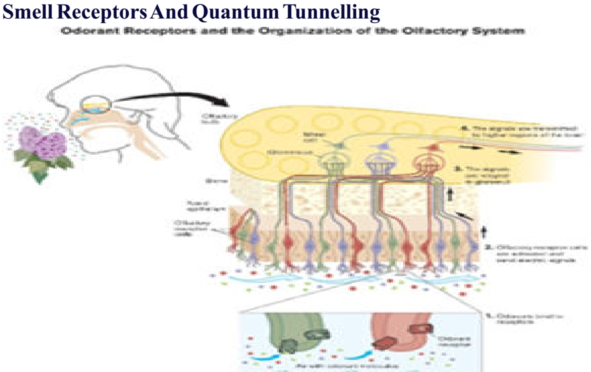
INTRODUCTION

Quantum physics is the branch of science that studies the behaviour of energy and matter at the tinniest of scales. It reveals phenomena that defy the common sense of classical physics, such as superposition, entanglement, tunnelling, and uncertainty. While quantum physics is usually associated with technology, such as lasers, transistors, and cryptography, there is growing evidence that it also plays a role in biological processes that are essential for life. This field of study is known as quantum biology.

Quantum biology investigates how quantum effects influence the structure and function of biomolecules, cells, and organisms. It aims to uncover the mechanisms and benefits of quantum phenomena in biological systems, as well as the challenges and limitations they pose.[1] Quantum biology also explores the possibility of using quantum principles to design novel biotechnologies and therapies.

In this article, we review some of the most intriguing applications of quantum physics in the field of biology, covering topics such as the sense of smell, photosynthesis, enzyme catalysis, animal navigation, and consciousness. We discuss the current state of the art, the open questions, and the future directions of this emerging and interdisciplinary field.

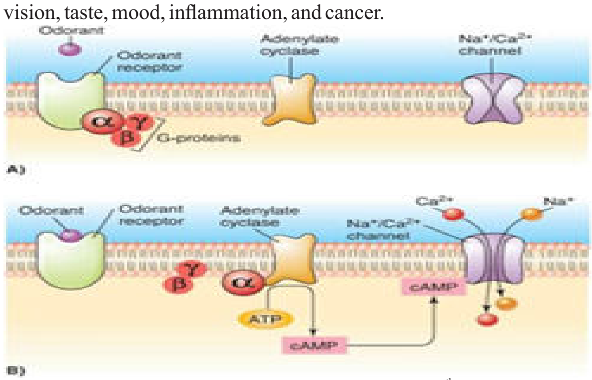
Smell Receptors And Quantum Tunnelling



Source: Rinaldi, A. (2024). The scent of life. PubMed 8(7):629-33
Figure 1: Odorant receptors and organization of the olfactory system.

The sense of smell is one of the most complex and fascinating senses in humans and animals. It allows us to perceive and identify a variety of odours, from food and flowers to danger and disease. But how do we actually smell? What are the molecular and physical mechanisms that enable us to detect and discriminate different odorants? We will explore the role of smell receptors and quantum tunnelling in the process of olfaction, and discuss some of the implications and applications of this phenomenon.

Smell receptors are proteins that are expressed in the cell membranes of olfactory receptor neurons, which are specialized sensory cells located in the nasal cavity. Smell receptors belong to the family of G protein-coupled receptors (GPCRs), which are the largest and most diverse group of membrane receptors in the human genome GPCRs are involved in many physiological and pathological processes, such as vision, taste, mood, inflammation, and cancer.



Source: Ganong's Review of Medical Physiology, 24th Ed.
Figure 2: Signal transduction in an odorant receptor

Smell receptors are responsible for binding and recognizing odorant molecules, which are volatile chemicals that have an odour. Each smell receptor can bind to a range of odorant molecules with varying affinities, depending on their physicochemical properties, such as shape, size, and polarity Conversely, each odorant molecule can bind to multiple smell receptors with different affinities, creating a combinatorial code that encodes the identity and intensity of the odour[2]

When an odorant molecule binds to a smell receptor, it triggers a conformational change in the receptor, which activates a G protein on the inside of the olfactory receptor neuron. This G protein activates an enzyme, adenylate cyclase which converts ATP into cyclic AMP (cAMP). cAMP opens ion channels that allow sodium and calcium ions to enter the cell, causing depolarization and generating an action potential that carries the information to the brain.

The process of odorant binding and receptor activation seems straightforward, but there is a mystery that remains unsolved: how do some odorant molecules, such as hydrogen sulphide and ammonia, which are very small and have no obvious shape or polarity, bind to smell receptors.[3] These molecules are also very common and abundant in the environment, so how do we distinguish them from other odorants.

One possible answer to this puzzle is quantum inelastic tunnelling[4], a quantum mechanical phenomenon that allows particles, such as electrons or protons, to pass through a potential energy barrier that they wouldn't have enough energy to overcome based on classical physics. Quantum tunnelling is a consequence of the wave nature of matter, where particles are described by wave functions that have a finite probability of being found in different locations. Quantum tunnelling is observed in many physical phenomena, such as nuclear fusion, radioactive decay, and superconductivity.

Quantum tunnelling may also play a role in olfaction, according to the vibration theory of smell, which was first proposed by Malcolm Dyson in 1938 and later developed by Luca Turin and others The vibration theory of smell suggests that smell receptors detect not only the shape and polarity of odorant molecules, but also their vibrational frequencies, which are determined by the bonds and atoms that make up the molecules.

According to this theory, when an odorant molecule binds to a smell receptor, it transfers an electron to the receptor through quantum tunnelling, creating a charge transfer complex. The electron then tunnels back to the odorant molecule, but only if the vibrational frequency of the molecule matches the energy difference between the donor and acceptor states. This process creates a current that is modulated by the vibration of the odorant molecule, and this current is detected by the G protein and converted into a signal.[5]

The vibration theory of smell can explain how we can distinguish between molecules that have similar shapes and polarities, but different vibrations, such as isotopes and enantiomers. For example, deuterated acetone, which has two heavy hydrogen atoms instead of normal hydrogen atoms, smells different from normal acetone, even though they have the same shape and polarity. Similarly, carvone, which has two mirror-image forms, smells like spearmint or caraway, depending on the orientation of a single carbon atom.

The vibration theory of smell is not universally accepted, and there are many challenges and criticisms that it faces. For instance, some argue that quantum tunnelling is too rare and too fast to be relevant for olfaction, and that the energy difference between donor and acceptor states is too small to be selective for different vibrations. Others point out that there is no direct evidence for the existence of charge transfer complexes or currents in olfactory receptor neurons, and that the shape theory of smell can account for most of the experimental data on olfaction.

The debate between the shape theory and the vibration theory of smell is still ongoing, and more research is needed to test and validate the hypotheses and predictions of both theories. The study of smell receptors and quantum tunnelling is not only important for understanding the molecular and physical basis of olfaction, but also for developing new applications and technologies, such as artificial noses, Odor sensors, and Odor-based communication.

In conclusion, smell receptors and quantum tunnelling are two fascinating topics that reveal the complexity and beauty of the sense of smell. Smell receptors are proteins that bind and recognize odorant molecules, and quantum tunnelling is a quantum mechanical phenomenon that allows particles to pass through potential energy barriers. The role of quantum tunnelling in olfaction is controversial, and there are two competing theories of smell: the shape theory and the vibration theory. The study of smell receptors and quantum tunnelling may lead to new insights and innovations in the field of olfaction and beyond.

Photosynthesis

Quantum superposition is a phenomenon in which a quantum system, such as an electron, can exist in a combination of two or more states at the same time. This means that the system can explore multiple possibilities simultaneously, until an observation collapses it into one definite state. Quantum superposition has been observed in various biological processes, such as photosynthesis[6], the process by which plants and some bacteria convert light energy into chemical energy.

Photosynthesis consists of two main stages: light harvesting and charge separation. In the light harvesting stage, the photons from sunlight are absorbed by pigment molecules, such as chlorophyll, that are arranged in antenna complexes within the cells. The absorbed photons excite the electrons in the pigment molecules, creating what is called an exciton, a pair of an electron and a hole (a positive charge left behind by the electron). The exciton then travels through the antenna complex to reach a reaction centre, where the charge separation stage occurs. In this stage, the exciton is split into an electron and a hole, which are transferred to different molecules to create a charge difference that drives the production of chemical energy.[7]

The efficiency of photosynthesis depends on how fast and how well the excitons can reach the reaction centres without losing their energy or getting trapped.[8] Quantum superposition plays a crucial role in this process, as it allows the excitons to take multiple paths through the antenna complex at the same time, increasing the probability of finding the optimal route to the reaction centre. Quantum superposition also helps the excitons to avoid interference from noise and fluctuations in the environment, as they can switch between different energy levels and frequencies to adapt to the changing conditions.

This has been experimentally verified by using different polarizations of light to probe the excitons in the antenna complexes. The results showed that the excitons exhibited quantum coherence, meaning that they maintained a fixed phase relationship between their superposed states, for up to a few hundred femtoseconds (10^-15 seconds). This is long enough to influence the transport of excitons to the reaction centres and enhance the efficiency of photosynthesis.[9]

Quantum superposition in photosynthesis is an example of how quantum mechanics can explain and improve the understanding of biological phenomena. It also provides inspiration for the development of artificial light-harvesting devices that can mimic the quantum effects of natural systems and achieve high performance and sustainability.

Enzymes

Another area where quantum biology has been explored is the functioning of enzymes, the complex protein molecules that catalyse chemical reactions in living cells.

Enzymes work by lowering the activation energy of a reaction, which is the minimum amount of energy required for the reactants to transform into the products. They do this by binding to the reactants, called substrates, and forming a transition state complex, which is a highly unstable intermediate state that leads to the formation of the products[10,11]. The rate and efficiency of an enzyme-catalysed reaction depend on how well the enzyme can stabilize the transition state complex and lower the activation energy barrier.

One of the ways that quantum biology can explain the functioning of enzymes is by invoking the phenomenon of quantum tunnelling.[12] Quantum tunnelling is the process by which a particle, such as an electron or a proton, can pass through a potential barrier that is higher than its kinetic energy, without having to overcome it. This is possible because the particle has a wave-like nature and can exist in a superposition of states, meaning that it can be in more than one place at the same time. Quantum tunnelling can increase the rate of an enzyme-catalysed reaction by allowing the substrates or the products to move through the activation energy barrier, instead of having to climb over it. Quantum tunnelling has been observed in several enzyme-catalysed reactions, such as the oxidation of hydrogen by hydrogenase, the reduction of nitrate-by-nitrate reductase, and the transfer of methyl groups by methyltransferase[13]. These reactions involve the movement of electrons or protons between the enzyme and the substrates or the products, which can be facilitated by quantum tunnelling. The evidence for quantum tunnelling in these reactions comes from measuring the temperature dependence of the reaction rate. According to classical physics, the reaction rate should increase with increasing temperature, as the particles gain more kinetic energy and can overcome the activation energy barrier more easily. However, some enzyme-catalysed reactions show a decrease in the reaction rate at higher temperatures, which suggests that quantum tunnelling is involved. This is because quantum tunnelling depends on the overlap of the wave functions of the particles, which can be reduced by thermal fluctuations and vibrations at higher temperatures

Bird Migration

Imagine you are a bird that migrates thousands of kilometres every year, crossing continents and oceans, without getting lost. How do you do it? You might think that you use the sun, the stars, or the landmarks to guide you, but that is not enough. You also need a compass that tells you which direction is north, and that compass is inside your eye.

This is another amazing discovery that scientists have made in the last few decades, as they unravelled the mystery of how some birds can sense and use the Earth's magnetic field to orient themselves. This sense, called magnetoreception, is one of the most fascinating and puzzling phenomena in nature.[11]

Scientists believe that quantum entanglement is the key to understanding how birds can detect the magnetic field. The leading candidate for the quantum basis of magnetoreception is the radical pair mechanism. According to this mechanism, light activates a protein called cryptochrome in the bird's eye, which produces a pair of radicals with unpaired electrons. The spins of these electrons can be influenced by the magnetic field, and this in turn affects the chemical reactions and signals that the bird perceives.[14]

The radical pair mechanism is supported by several lines of evidence, such as the behavioural experiments with robins, the molecular identification of cryptochrome, the quantum coherence and entanglement of the radical pair, and the sensitivity and robustness of the quantum compass. However, there are also some challenges and controversies, such as the effects of light and radio frequency fields, and the alternative hypotheses based on magnetite, a type of iron that also responds to magnetic fields.[15]

The research on quantum bird navigation is still ongoing, and there are many open questions and future directions to explore. For example, how does the bird process the information from the quantum compass? How does the quantum compass interact with other sensory cues? How widespread is quantum magnetoreception among different species of animals? How did quantum magnetoreception evolve in the first place?

Consciousness And Neuronal Ion Channels

Consciousness is one of the most profound and elusive mysteries of science and philosophy. How does the brain, a complex network of neurons and synapses, give rise to the subjective experience of awareness, perception, and thought? What is the physical basis of consciousness, and how does it emerge from matter and energy?

One of the most controversial and intriguing hypotheses in this field is the quantum mind or quantum consciousness, which suggests that quantum phenomena, such as entanglement and superposition, play an important role in the brain's function and could explain critical aspects of consciousness. According to this hypothesis, local physical laws and interactions from classical mechanics or connections between neurons alone cannot account for consciousness, and quantum-mechanical effects, interacting in smaller features of the brain than cells, may be essential for the emergence of consciousness.

One of the main proponents of this hypothesis is the Nobel Prize winning UK mathematician, Roger Penrose, together with the American anaesthetist, Stuart Hameroff. They have developed a theory called Orchestrated Objective Reduction (Orch OR)[16], which proposes that quantum coherence in neuronal microtubules, which are major components of the cell structural skeleton, is capable of quantum computing and is the substrate for consciousness.[17] They suggest that quantum vibrations in microtubules are orchestrated by synaptic inputs and memories stored in microtubules, and are terminated by Penrose's objective reduction, a process that collapses the quantum state into a classical state and produces a moment of conscious experience. They also suggest that deeper level microtubule vibrations might be responsible for EEG rhythms (brain waves).

Although Orch OR has generated a great deal of discussion and criticism, unfortunately it has not received significant support in either the physics or neuroscience community. Many critics have argued that the brain is too warm, wet, and noisy for quantum coherence to be maintained for long enough to be relevant for consciousness, and that there is no clear evidence for quantum effects in microtubules or their role in consciousness.

Instead, in this article we shall delve into what might be more likely a substrate for quantum mechanical effects in the brain: neuronal ion channels. Neuronal ion channels play a fundamental role in any nerve and the brain. They are transmembrane proteins that allow the flow of ions across the cell membrane, depending on their electrochemical gradient and the voltage difference across the membrane. They are responsible for generating and propagating electrical signals along the nerve axons, and for mediating synaptic transmission between neurons.

Neuronal ion channels have pores only around 0.1 nm diameter, small enough to ensure that ions travel in single file through the channels. They are of a scale that might conceivably exhibit quantum phenomena, such as quantum tunnelling, quantum interference, and quantum entanglement. Quantum tunnelling is the phenomenon where a particle can pass through a potential barrier that it would not normally be able to cross, due to its wave-like nature. Quantum interference is the phenomenon where two or more quantum waves can combine to produce a new wave pattern, depending on their relative phase. Quantum entanglement is the phenomenon where two or more quantum particles can share a quantum state, and remain correlated even when separated by large distances.

Some researchers have suggested that quantum phenomena in neuronal ion channels could have significant implications for the brain's function and consciousness. For example, quantum tunnelling could enhance the speed and efficiency of ion transport, and quantum interference could modulate the ion selectivity and conduction. Quantum entanglement could also create quantum correlations between different ion channels, neurons, and brain regions, and could potentially explain some of the features of consciousness, such as unity, coherence, and nonlocality.

One of the most well-studied neuronal ion channels is the bacterial KcsA potassium channel, which exhibits several exceptional features that suggest the possibility of quantum mechanical enhancement. For instance, the KcsA channel has a very high ion selectivity, allowing only potassium ions to pass through, and rejecting sodium ions, which are slightly smaller. This selectivity is conferred by a portion of the protein known as the selectivity filter, which discriminates between different ions based on their diameter and charge. However, classical electrostatic models cannot fully explain the selectivity of the KcsA channel, and some researchers have proposed that quantum interference effects may play a role. Based on this theory, when ions traverse the channel, they shed their surrounding hydration layer prior to entering the pore, proceeding through the channel one by one. Within the selectivity filter, closely preserved patterns of charged elements attract the ions within the channel, driven by the Coulombic forces of interaction.[18, 19] The ions then form a quantum wave that interferes constructively or destructively with the quantum wave of the channel, depending on the ion type. Potassium ions interfere constructively, and are transmitted through the channel, while sodium ions interfere destructively, and are rejected by the channel.[20,21]

Another remarkable feature of the KcsA channel is its very high ion conduction, allowing up to 10^8 ions per second to flow through the channel. This conduction is regulated by the voltage difference across the membrane, which switches the channel between its open and closed state via long-range protein motions in a specialized segment known as the voltage-sensing domain. However, classical kinetic models cannot fully explain the conduction of the KcsA channel, and some researchers have proposed that quantum tunnelling effects may play a role. According to this hypothesis, the ions passing through the channel are subject to a potential barrier that depends on the voltage difference across the membrane. The ions can overcome this barrier by quantum tunnelling, which increases the probability of ion transport. The quantum tunnelling rate also depends on the quantum coherence of the ions, which can be influenced by external factors, such as light and magnetic fields.

A third intriguing feature of the KcsA channel is its possible involvement in quantum entanglement. Some researchers have suggested that the ions passing through the channel may become entangled with each other, and with the channel itself, due to their quantum interactions. This entanglement could create quantum correlations between different ion channels, neurons, and brain regions, and could potentially affect the brain's function and consciousness. For example, quantum entanglement could enhance the synchronization and coherence of neural activity, which are important for information processing and integration. Quantum entanglement could also explain some of the nonlocal and holistic aspects of consciousness, such as the binding problem, the unity of consciousness, and the global workspace theory.

The research on quantum biology and the mystery of consciousness is still in its infancy, and there are many challenges and uncertainties to overcome. For example, how can quantum coherence and entanglement be maintained and measured in the noisy and complex environment of the brain? How can quantum effects in neuronal ion channels be distinguished from classical effects? How can quantum effects in neuronal ion channels be linked to the higher-level phenomena of neural activity and consciousness? How can quantum effects in neuronal ion channels be tested experimentally and verified empirically?

These questions are not only important for understanding the amazing abilities of the brain, but also for advancing the field of quantum biology, which studies how quantum physics influences the processes of life. Quantum biology is a new and exciting frontier of science, and it has potential applications in medicine, technology, and even artificial intelligence.

Quantum biology and the mystery of consciousness is a fascinating and challenging topic that reveals the wonders of nature and the power of physics. It challenges our common sense and our imagination, and it inspires us to think critically and creatively about the world. It is a reminder that there is still so much to discover and understand, and that we are all connected by the quantum fabric of reality.

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