



Quantum biology

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Abstract: Quantum biology is the study of applications of quantum mechanics and theoretical chemistry to biological objects and problems. Many biological processes involve the conversion of energy into forms that are usable for chemical transformations, and are quantum mechanical in nature. Such processes involve chemical reactions, light absorption, formation of excited electronic states, transfer of excitation energy, and the transfer of electrons and protons in chemical processes, such as photosynthesis, olfaction and cellular respiration.

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Quantum biology is the study of applications of quantum mechanics and theoretical chemistry to biological objects and problems. Many biological processes involve the conversion of energy into forms that are usable for chemical transformations, and are quantum mechanical in nature. Such processes involve chemical reactions, light absorption, formation of excited electronic states, transfer of excitation energy, and the transfer of electrons and protons in chemical processes, such as photosynthesis, olfaction and cellular respiration.^[1]

Quantum biology may use computations to model biological interactions in light of quantum mechanical effects.^[2] Quantum biology is concerned with the influence of non-trivial quantum phenomena,^[3] which can be explained by reducing the biological process to fundamental physics, although these effects are difficult to study and can be speculative.^[4]

History

Quantum biology is an emerging field; most of the current research is theoretical and subject to questions that require further experimentation. Though the field has only recently received an influx of attention, it has been conceptualized by physicists throughout the 20th century. Early pioneers of quantum physics saw applications of quantum mechanics in biological problems. Erwin Schrödinger's 1944 book *What is Life?* discussed applications of quantum mechanics in biology.^[5] Schrödinger introduced the idea of an aperiodic crystal that contained genetic information in its configuration

of covalent chemical bonds. He further suggested that mutations are introduced by quantum leaps. Other pioneers Niels Bohr, Pascual Jordan, and Max Delbrück argued that the quantum idea of complementarity was fundamental to the life sciences.^[6] In 1963, Per-Olov Löwdin published proton tunneling as another mechanism for DNA mutation. In his paper, he stated that there is a new field of study called quantum biology".^[7]

Applications

Photosynthesis

Organisms that undergo photosynthesis initially absorb light energy through the process of electron excitation in an antenna. This antenna varies between organisms. Bacteria can use ring-like structures as antennas, whereas plants and other organisms use chlorophyll pigments to absorb photons. This electron excitation creates a separation of charge in a reaction site that is later converted into chemical energy for the cell to use. However, this electron excitation must be transferred in an efficient and timely manner, before that energy is lost in fluorescence or in thermal vibrational motion.

Various structures are responsible for transferring energy from the antennas to a reaction site. One of the most well studied is the FMO complex in green sulfur bacteria. FT electron spectroscopy studies show an efficiency of above 99% between the absorption of electrons and transfer to the reaction site with short lived intermediates.^[8] This high efficiency cannot be explained by classical mechanics such as a diffusion model.

A study published in 2007 claimed the identification of electronic **quantum coherence**^[9] at -196 C (77 K). A later study further claimed exceptionally long-lived quantum coherence at 4 C that was further postulated to be responsible for the high efficiency of the excitation transfer between different pigments in the light-harvesting stage of photosynthesis.^[10] It was, thus, suggested that nature through evolution had developed a way of protecting quantum coherence to enhance the efficiency of photosynthesis. However, critical follow-up studies question the interpretation of these results and assign the reported signatures of electronic quantum coherence to nuclear dynamics in the chromophores.^{[11][12][13][14][15][16][17]} The claims of unexpected long coherence times sparked a lot of research in the quantum physics community to explain the origin. A number of proposals were brought forward trying to explain the claimed long-lived coherence. According to one proposal, if each site within the complex feels its own environmental noise, the electron will not remain in any local minimum due to both quantum coherence and **thermal** environment, but proceed to the reaction site via **quantum walks**.^{[18][19][20]} Another proposal is that the rate of quantum coherence combined with electron **tunneling** creates an energy sink that moves the electron to the reaction site quickly.^[21] Other work suggested that symmetries present in the geometric arrangement of the complex may favor efficient energy transfer to the reaction center, in a way that resembles perfect state transfer in quantum networks.^[22] However, experiments with artificial dye molecules casted doubts on the interpretation that quantum effects last any longer than one hundred femtoseconds.^[23]

In 2017, the first control experiment with the original FMO protein under ambient conditions confirmed that electronic quantum effects are washed out on a time span of 60 femtoseconds, while the overall exciton transfer takes a time on the order of a few picoseconds.^[24] In 2020 a review based on a wide collection of control experiments and theory concluded that the original claim of quantum effects as long lived electronic coherences in the FMO system does not hold.^[25]

DNA mutation

Deoxyribonucleic acid, **DNA**, acts as the instructions for making proteins throughout the body. It consists of 4 nucleotides guanine, thymine, cytosine, and adenine.^[26] The order of these nucleotides gives the recipe for the different proteins.

Whenever a cell reproduces, it must copy these strands of DNA. However, sometimes throughout the process of copying the strand of DNA a mutation, or an error in the DNA code, can occur. A theory for the reasoning behind **DNA mutation** is explained in the

Lowdin DNA mutation model.^[27] In this model, a nucleotide may change its form through a process of **quantum tunneling**. Because of this, the changed nucleotide will lose its ability to pair with its original base pair and consequently changing the structure and order of the DNA strand.

Exposure to ultraviolet lights and other types of radiation can cause DNA mutation and damage. The radiations also can modify the bonds along the DNA strand in the **pyrimidines** and cause them to bond with themselves creating a dimer.^[28]

In many prokaryotes and plants, these bonds are repaired to their original form by a DNA repair enzyme photolyase. As its prefix implies, photolyase is reliant on light in order to repair the strand. Photolyase works with its cofactor **FADH**, flavin adenine dinucleotide, while repairing the DNA. Photolyase is excited by visible light and transfers an electron to the cofactor **FADH**. **FADH**- now in the possession of an extra electron gives the electron to the dimer to break the bond and repair the DNA. This transfer of the electron is done through the tunneling of the electron from the **FADH** to the **dimer**. Although the range of the tunneling is much larger than feasible in a vacuum, the tunneling in this scenario is said to be superexchange-mediated tunneling, and is possible due to the protein's ability to boost the tunneling rates of the electron.^[27]

Vibration theory of olfaction

Olfaction, the sense of smell, can be broken down into two parts; the reception and detection of a chemical, and how that detection is sent to and processed by the brain. This process of detecting an **odorant** is still under question. One theory named the **shape theory of olfaction** suggests that certain olfactory receptors are triggered by certain shapes of chemicals and those receptors send a specific message to the brain.^[29] Another theory suggests that the olfactory receptors detect the vibration of the molecules that reach them and the smell is due to different vibrational frequencies, this theory is aptly called the vibration theory of olfaction.

The **vibration theory of olfaction**, created in 1938 by Malcolm Dyson^[30] but reinvigorated by Luca Turin in 1996,^[31] proposes that the mechanism for the sense of smell is due to G-protein receptors that detect molecular vibrations due to inelastic electron tunneling, tunneling where the electron loses energy, across molecules.^[31] In this process a molecule would fill a binding site with a **G-protein** receptor. After the binding of the chemical to the receptor, the chemical would then act as a bridge allowing for the electron to be transferred through the protein. As the electron transfers that usually would be a barrier for the electrons and would lose its energy due to the vibration of the molecule recently bound to the

receptor, resulting in the ability to smell the molecule.^{[31][32]}

While the vibration theory has some experimental proof of concept,^{[33][34]} there have been multiple controversial results in experiments. In some experiments, animals are able to distinguish smells between molecules of different frequencies and same structure^[35] other experiments show that people are unaware distinguishing smells due to distinct molecular frequencies.^[36] However, it has not been disproven, and has even been shown to be an effect in olfaction of animals other than humans such as flies, bees, and fish.

Vision

Vision relies on quantized energy in order to convert light signals to an action potential in a process called **phototransduction**. In phototransduction, a photon interacts with a **chromophore** in a light receptor. The chromophore absorbs the photon and undergoes **photoisomerization**. This change in structure induces a change in the structure of the photo receptor and resulting **signal transduction** pathways lead to a visual signal. However, the photoisomerization reaction occurs at a rapid rate, in under 200 **femtoseconds**,^[37] with high yield. Models suggest the use of quantum effects in shaping the **ground state** and **excited state** potentials in order to achieve this efficiency.^[38]

Quantum vision implications

Experiments have shown that the sensors in the retina of human eye is sensitive enough to detect a single photon.^[39] Single **photon** detection could lead to multiple different technologies. One area of development is in quantum communication and **cryptology**. The idea is to use a biometric system to measure the eye using only a small number of points across the **retina** with random flashes of photons that “read” the retina and identify the individual.^[40] This biometric system would only allow a certain individual with a specific retinal map to decode the message. This message cannot be decoded by anyone else unless the eavesdropper were to guess the proper map or could read the retina of the intended recipient of the message.^[41]

Enzymatic activity

Enzymes may use **quantum tunneling** to transfer electrons long distances. It is possible that protein quaternary architecture may have evolved to enable sustained quantum entanglement and coherence.^[42] More specifically, they can increase the percentage of the reaction that occurs through hydrogen tunneling.^[43] Tunneling refers to the ability of a small mass particle to travel through energy barriers. This ability is due to the principle of **complementarity**, which hold that certain objects have pairs of properties that cannot be measured separately without changing the outcome of measurement. Electrons have both **wave and particle**

properties, so they can pass through physical barriers as a wave without violating the laws of physics. Studies show that long distance electron transfers between **redox** centers through quantum tunneling plays important roles in **enzymatic** activity of **photosynthesis** and **cellular respiration**.^{[44][45]} For example, studies show that long range electron tunneling on the order of 15–30Å plays a role in redox reactions in enzymes of cellular respiration.^[46] Without quantum tunneling, organisms would not be able to convert energy quickly enough to sustain growth. Even though there are such large separations between redox sites within enzymes, electrons successfully transfer in a generally temperature independent and distance dependent manner.^[43] This suggests the ability of electrons to tunnel in physiological conditions. Further research is needed to determine whether this specific tunneling is also **coherent**.

Magnetoreception

Magnetoreception refers to the ability of animals to navigate using the inclination of the magnetic field of the earth.^[47] A possible explanation for magnetoreception is the **entangled radical pair mechanism**.^{[48][49]} The radical-pair mechanism is well-established in **spin chemistry**,^{[50][51][52]} and was speculated to apply to magnetoreception in 1978 by Schulten et al. The ratio between singlet and triplet pairs is changed by the interaction of entangled electron pairs with the magnetic field of the earth.^[53] In 2000, **cryptochrome** was proposed as the magnetic molecule that could harbor magnetically sensitive radical-pairs. Cryptochrome, a **flavoprotein** found in the eyes of **European robins** and other animal species, is the only protein known to form photoinduced radical-pairs in animals.^[47] When it interacts with light particles, cryptochrome goes through a **redox** reaction, which yields radical pairs both during the photo-reduction and the oxidation. The function of cryptochrome is diverse across species, however, the photoinduction of radical-pairs occurs by exposure to blue light, which excites an electron in a **chromophore**.^[53] Magnetoreception is also possible in the dark, so the mechanism must rely more on the radical pairs generated during light-independent oxidation.

Experiments in the lab support the basic theory that radical-pair electrons can be significantly influenced by very weak magnetic fields, i.e. merely the direction of weak magnetic fields can affect radical-pair's reactivity and therefore can catalyze the formation of chemical products. Whether this mechanism applies to magnetoreception and/or quantum biology, that is, whether earth's magnetic field catalyzes the formation of **biochemical** products by the aid of radical-pairs, is undetermined for two

reasons. The first is that radical-pairs may need not be entangled, the key *quantum* feature of the radical-pair mechanism, to play a part in these processes. There are entangled and non-entangled radical-pairs. However, researchers found evidence for the radical-pair mechanism of magnetoreception when European robins, cockroaches, and garden warblers, could no longer navigate when exposed to a **radio frequency** that obstructs **magnetic fields**^[47] and radical-pair chemistry. To empirically suggest the involvement of entanglement, an experiment would need to be devised that could disturb entangled radical-pairs without disturbing other radical-pairs, or vice versa, which would first need to be demonstrated in a laboratory setting before being applied to in vivo radical-pairs.

Other biological applications

Other examples of quantum phenomena in biological systems include the conversion of **chemical energy** into motion^[54] and **brownian motors** in many cellular processes.^[55]

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