**Quantum biology**

From Wikipedia, the free encyclopedia

(<https://en.wikipedia.org/wiki/Quantum_biology>)

Mark Herbert, PhD

World Development Institute

39 Main Street, Flushing, Queens, New York 11354, USA, [ma708090@gmail.com](mailto:ma708090@gmail.com)

**Abstract:** Quantum biology is the study of applications of [quantum mechanics](https://en.wikipedia.org/wiki/Quantum_mechanics) and [theoretical chemistry](https://en.wikipedia.org/wiki/Theoretical_chemistry) to [biological](https://en.wikipedia.org/wiki/Biology) objects and problems. Many biological processes involve the conversion of [energy](https://en.wikipedia.org/wiki/Energy) into forms that are usable for chemical transformations, and are quantum mechanical in nature. Such processes involve [chemical reactions](https://en.wikipedia.org/wiki/Chemical_reactions), [light absorption](https://en.wikipedia.org/wiki/Light_absorption), formation of [excited electronic states](https://en.wikipedia.org/wiki/Excited_state), [transfer of excitation energy](https://en.wikipedia.org/wiki/Exciton), and the transfer of [electrons](https://en.wikipedia.org/wiki/Electron) and [protons](https://en.wikipedia.org/wiki/Proton) in chemical processes, such as [photosynthesis](https://en.wikipedia.org/wiki/Photosynthesis), [olfaction](https://en.wikipedia.org/wiki/Olfaction) and [cellular respiration](https://en.wikipedia.org/wiki/Cellular_respiration).

[Mark Herbert. **Quantum biology.** *Researcher* 2020;12(12):25-31]. ISSN 1553-9865 (print); ISSN 2163-8950 (online). <http://www.sciencepub.net/researcher>. 4. doi:[10.7537/marsrsj121220.04](http://www.dx.doi.org/10.7537/marsrsj121220.04).

**Keywords**: Quantum biology**;** [quantum mechanics](https://en.wikipedia.org/wiki/Quantum_mechanics); [theoretical chemistry](https://en.wikipedia.org/wiki/Theoretical_chemistry); [electron](https://en.wikipedia.org/wiki/Electron); [proton](https://en.wikipedia.org/wiki/Proton); [photosnthesis](https://en.wikipedia.org/wiki/Photosynthesis); [olfaction](https://en.wikipedia.org/wiki/Olfaction); [cellular respiration](https://en.wikipedia.org/wiki/Cellular_respiration)

**Quantum biology** is the study of applications of [quantum mechanics](https://en.wikipedia.org/wiki/Quantum_mechanics) and [theoretical chemistry](https://en.wikipedia.org/wiki/Theoretical_chemistry) to [biological](https://en.wikipedia.org/wiki/Biology) objects and problems. Many biological processes involve the conversion of [energy](https://en.wikipedia.org/wiki/Energy) into forms that are usable for chemical transformations, and are quantum mechanical in nature. Such processes involve [chemical reactions](https://en.wikipedia.org/wiki/Chemical_reactions), [light absorption](https://en.wikipedia.org/wiki/Light_absorption), formation of [excited electronic states](https://en.wikipedia.org/wiki/Excited_state), [transfer of excitation energy](https://en.wikipedia.org/wiki/Exciton), and the transfer of [electrons](https://en.wikipedia.org/wiki/Electron) and [protons](https://en.wikipedia.org/wiki/Proton) in chemical processes, such as [photosynthesis](https://en.wikipedia.org/wiki/Photosynthesis), [olfaction](https://en.wikipedia.org/wiki/Olfaction) and [cellular respiration](https://en.wikipedia.org/wiki/Cellular_respiration).[[1]](https://en.wikipedia.org/wiki/Quantum_biology" \l "cite_note-1)

Quantum biology may use computations to model biological interactions in light of quantum mechanical effects.[[2]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-2) Quantum biology is concerned with the influence of non-trivial quantum phenomena,[[3]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-3) which can be explained by reducing the [biological](https://en.wikipedia.org/wiki/Biological) process to fundamental [physics](https://en.wikipedia.org/wiki/Physics), although these effects are difficult to study and can be speculative.[[4]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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](https://en.wikipedia.org/wiki/Erwin_Schr%C3%B6dinger)'s 1944 book [*What is Life?*](https://en.wikipedia.org/wiki/What_Is_Life%3F) discussed applications of quantum mechanics in biology.[[5]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-5) Schrödinger introduced the idea of an aperiodic crystal that contained genetic information in its configuration of covalent [chemical bonds](https://en.wikipedia.org/wiki/Chemical_bond). He further suggested that [mutations](https://en.wikipedia.org/wiki/Mutation) are introduced by quantum leaps. Other pioneers [Niels Bohr](https://en.wikipedia.org/wiki/Niels_Bohr), [Pascual Jordan](https://en.wikipedia.org/wiki/Pascual_Jordan), and [Max Delbruck](https://en.wikipedia.org/wiki/Max_Delbr%C3%BCck) argued that the quantum idea of [complementarity](https://en.wikipedia.org/wiki/Complementarity_(physics)) was fundamental to the life sciences.[[6]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-:0-6) In 1963, [Per-Olov Löwdin](https://en.wikipedia.org/wiki/Per-Olov_L%C3%B6wdin) published proton [tunneling](https://en.wikipedia.org/wiki/Tunneling_effect) as another mechanism for [DNA](https://en.wikipedia.org/wiki/DNA) mutation. In his paper, he stated that there is a new field of study called quantum biology".[[7]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-Lowdin,_P.O._1965_pp_213%E2%80%93360-7)

## Applications

## Photosynthesis

Organisms that undergo photosynthesis initially absorb light energy through the process of [electron excitation](https://en.wikipedia.org/wiki/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](https://en.wikipedia.org/wiki/Chlorophyll) [pigments](https://en.wikipedia.org/wiki/Pigment) 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](https://en.wikipedia.org/wiki/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](https://en.wikipedia.org/wiki/Fenna-Matthews-Olson_complex) in green sulfur bacteria. [FT electron spectroscopy](https://en.wikipedia.org/wiki/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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-8) This high efficiency cannot be explained by classical mechanics such as a [diffusion](https://en.wikipedia.org/wiki/Diffusion) model.

A study published in 2007 claimed the identification of electronic [quantum coherence](https://en.wikipedia.org/wiki/Quantum_coherence)[[9]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-11)[[12]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-12)[[13]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-13)[[14]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-14)[[15]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-15)[[16]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-16)[[17]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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](https://en.wikipedia.org/wiki/Thermal_energy) environment, but proceed to the reaction site via [quantum walks](https://en.wikipedia.org/wiki/Quantum_walk).[[18]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-18)[[19]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-19)[[20]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-Lloyd2014-20) Another proposal is that the rate of quantum coherence combined with electron [tunneling](https://en.wikipedia.org/wiki/Tunneling_effect) creates an energy sink that moves the electron to the reaction site quickly.[[21]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-22) However, experiments with artificial dye molecules casted doubts on the interpretation that quantum effects last any longer than one hundred femtoseconds.[[23]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-Cao2020-25)

**DNA mutation**

Deoxyribonucleic acid, [DNA](https://en.wikipedia.org/wiki/DNA), acts as the instructions for making proteins throughout the body. It consists of 4 nucleotides guanine, thymine, cytosine, and adenine.[[26]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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](https://en.wikipedia.org/wiki/Mutation) is explained in the Lowdin DNA mutation model.[[27]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-:02-27) In this model, a nucleotide may change its form through a process of [quantum tunneling](https://en.wikipedia.org/wiki/Quantum_tunnelling). 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](https://en.wikipedia.org/wiki/Pyrimidine) and cause them to bond with themselves creating a dimer.[[28]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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](https://en.wikipedia.org/wiki/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](https://en.wikipedia.org/wiki/Dimer_(chemistry)). 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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-:02-27)

**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](https://en.wikipedia.org/wiki/Aroma_compound) is still under question. One theory named the [shape theory of olfaction](https://en.wikipedia.org/wiki/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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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](https://en.wikipedia.org/wiki/Vibration_theory_of_olfaction), created in 1938 by Malcolm Dyson[[30]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-30) but reinvigorated by Luca Turin in 1996,[[31]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-:12-31) 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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-:12-31) In this process a molecule would fill a binding site with a [G-protein](https://en.wikipedia.org/wiki/G_protein-coupled_receptor) 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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-:12-31)[[32]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-32)

While the vibration theory has some experimental proof of concept,[[33]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-33)[[34]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-35) other experiments show that people are unaware distinguishing smells due to distinct molecular frequencies.[[36]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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](https://en.wikipedia.org/wiki/Visual_phototransduction). In phototransduction, a photon interacts with a [chromophore](https://en.wikipedia.org/wiki/Chromophore) in a light receptor. The chromophore absorbs the photon and undergoes [photoisomerization](https://en.wikipedia.org/wiki/Photoisomerization). This change in structure induces a change in the structure of the photo receptor and resulting [signal transduction](https://en.wikipedia.org/wiki/Signal_transduction) pathways lead to a visual signal. However, the photoisomerization reaction occurs at a rapid rate, in under 200 [femtoseconds](https://en.wikipedia.org/wiki/Femtosecond),[[37]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-37) with high yield. Models suggest the use of quantum effects in shaping the [ground state](https://en.wikipedia.org/wiki/Ground_state) and [excited state](https://en.wikipedia.org/wiki/Excited_state) potentials in order to achieve this efficiency.[[38]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-39) Single [photon](https://en.wikipedia.org/wiki/Photon) detection could lead to multiple different technologies. One area of development is in quantum communication and [cryptography](https://en.wikipedia.org/wiki/Cryptography). The idea is to use a biometric system to measure the eye using only a small number of points across the [retina](https://en.wikipedia.org/wiki/Retina) with random flashes of photons that “read” the retina and identify the individual.[[40]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-41)

**Enzymatic activity**

[Enzymes](https://en.wikipedia.org/wiki/Enzyme) may use [quantum tunneling](https://en.wikipedia.org/wiki/Quantum_tunnelling) to transfer electrons long distances. It is possible that protein quaternary architecture may have evolved to enable sustained quantum entanglement and coherence.[[42]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-42) More specifically, they can increase the percentage of the reaction that occurs through hydrogen tunneling.[[43]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-:2-43) Tunneling refers to the ability of a small mass particle to travel through energy barriers. This ability is due to the principle of [complementarity](https://en.wikipedia.org/wiki/Complementarity_(physics)), 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](https://en.wikipedia.org/wiki/Wave%E2%80%93particle_duality) 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](https://en.wikipedia.org/wiki/Redox) centers through quantum tunneling plays important roles in [enzymatic](https://en.wikipedia.org/wiki/Enzyme) activity of [photosynthesis](https://en.wikipedia.org/wiki/Photosynthesis) and [cellular respiration](https://en.wikipedia.org/wiki/Cellular_respiration).[[44]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-44)[[45]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-:1-46) 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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-:2-43) This suggests the ability of electrons to tunnel in physiological conditions. Further research is needed to determine whether this specific tunneling is also [coherent](https://en.wikipedia.org/wiki/Coherence_(physics)).

**Magnetoreception**

[Magnetoreception](https://en.wikipedia.org/wiki/Magnetoreception) refers to the ability of animals to navigate using the inclination of the magnetic field of the earth.[[47]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-Hore2016-47) A possible explanation for magnetoreception is the [entangled](https://en.wikipedia.org/wiki/Entanglement_(physics)) [radical pair mechanism](https://en.wikipedia.org/wiki/Radical_pair_mechanism).[[48]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-48)[[49]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-49) The radical-pair mechanism is well-established in [spin chemistry](https://en.wikipedia.org/wiki/Spin_chemistry),[[50]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-50)[[51]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-51)[[52]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-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]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-:3-53) In 2000, [cryptochrome](https://en.wikipedia.org/wiki/Cryptochrome) was proposed as the magnetic molecule that could harbor magnetically sensitive radical-pairs. Cryptochrome, a [flavoprotein](https://en.wikipedia.org/wiki/Flavoprotein) found in the eyes of [European robins](https://en.wikipedia.org/wiki/European_robin) and other animal species, is the only protein known to form photoinduced radical-pairs in animals.[[47]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-Hore2016-47) When it interacts with light particles, cryptochrome goes through a [redox](https://en.wikipedia.org/wiki/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](https://en.wikipedia.org/wiki/Chromophore).[[53]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-:3-53) 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 *bio*chemical 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](https://en.wikipedia.org/wiki/Radio_frequency) that obstructs [magnetic fields](https://en.wikipedia.org/wiki/Magnetic_field)[[47]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-Hore2016-47) 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](https://en.wikipedia.org/wiki/Chemical_energy) into motion[[54]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-54) and [brownian motors](https://en.wikipedia.org/wiki/Brownian_motor) in many cellular processes.[[55]](https://en.wikipedia.org/wiki/Quantum_biology#cite_note-55)

## References

* 1. ^ Quantum Biology. University of Illinois at Urbana-Champaign, Theoretical and Computational Biophysics Group.
  2. ^ Quantum Biology: Powerful Computer Models Reveal Key Biological Mechanism Science Daily Retrieved Oct 14, 2007.
  3. ^ Brookes, J. C. (2017). "Quantum effects in biology: golden rule in enzymes, olfaction, photosynthesis and magnetodetection". Proceedings of the Royal Society A. 473 (2201): 20160822. Bibcode:2017RSPSA.47360822B. doi:10.1098/rspa.2016.0822. PMC 5454345. PMID 28588400.
  4. ^ Al-Khalili, Jim, How quantum biology might explain life's biggest questions, retrieved 2018-12-07.
  5. ^ Margulis, Lynn; Sagan, Dorion (1995). What Is Life?. Berkeley: University of California Press. p. 1.
  6. ^ Joaquim, Leyla; Freira, Olival; El-Hani, Charbel (September 2015). "Quantum Explorers: Bohr, Jordan, and Delbruck Venturing into Biology". Physics in Perspective. 17 (3): 236–250. Bibcode:2015PhP....17..236J. doi:10.1007/s00016-015-0167-7. S2CID 117722573.
  7. ^ Lowdin, P.O. (1965) Quantum genetics and the aperiodic solid. Some aspects on the Biological problems of heredity, mutations, aging and tumours in view of the quantum theory of the DNA molecule. Advances in Quantum Chemistry. Volume 2. pp. 213–360. Academic Press.
  8. ^ Dostál, Jakub; Mančal, Tomáš; Augulis, Ramūnas; Vácha, František; Pšenčík, Jakub; Zigmantas, Donatas (2012-07-18). "Two-dimensional electronic spectroscopy reveals ultrafast energy diffusion in chlorosomes". Journal of the American Chemical Society. 134 (28): 11611–11617. doi:10.1021/ja3025627. ISSN 1520-5126. PMID 22690836.
  9. ^ Engel GS, Calhoun TR, Read EL, Ahn TK, Mancal T, Cheng YC, et al. (2007). "Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems". Nature. 446 (7137): 782–6. Bibcode:2007Natur.446..782E. doi:10.1038/nature05678. PMID 17429397. S2CID 13865546.
  10. ^ Panitchayangkoon, G.; Hayes, D.; Fransted, K. A.; Caram, J. R.; Harel, E.; Wen, J. Z.; Blankenship, R. E.; Engel, G. S. (2010). "Long-lived quantum coherence in photosynthetic complexes at physiological temperature". Proc. Natl. Acad. Sci. 107 (29): 12766–12770. arXiv:1001.5108. Bibcode:2010PNAS..10712766P. doi:10.1073/pnas.1005484107. PMC 2919932. PMID 20615985.
  11. ^ R. Tempelaar; T. L. C. Jansen; J. Knoester (2014). "Vibrational Beatings Conceal Evidence of Electronic Coherence in the FMO Light-Harvesting Complex". J. Phys. Chem. B. 118 (45): 12865–12872. doi:10.1021/jp510074q. PMID 25321492.
  12. ^ N. Christenson; H. F. Kauffmann; T. Pullerits; T. Mancal (2012). "Origin of Long-Lived Coherences in Light-Harvesting Complexes". J. Phys. Chem. B. 116 (25): 7449–7454. arXiv:1201.6325. Bibcode:2012arXiv1201.6325C. doi:10.1021/jp304649c. PMC 3789255. PMID 22642682.
  13. ^ A. Kolli; E. J. O’Reilly; G. D. Scholes; A. Olaya-Castro (2012). "The fundamental role of quantized vibrations in coherent light harvesting by cryptophyte algae". J. Chem. Phys. 137 (17): 174109. arXiv:1203.5056. Bibcode:2012JChPh.137q4109K. doi:10.1063/1.4764100. PMID 23145719. S2CID 20156821.
  14. ^ V. Butkus; D. Zigmantas; L. Valkunas; D. Abramavicius (2012). "Vibrational vs. electronic coherences in 2D spectrum of molecular systems". Chem. Phys. Lett. 545 (30): 40–43. arXiv:1201.2753. Bibcode:2012CPL...545...40B. doi:10.1016/j.cplett.2012.07.014. S2CID 96663719.
  15. ^ V. Tiwari; W. K. Peters; D. M. Jonas (2013). "Electronic resonance with anticorrelated pigment vibrations drives photosynthetic energy transfer outside the adiabatic framework". Proc. Natl. Acad. Sci. USA. 110 (4): 1203–1208. doi:10.1073/pnas.1211157110. PMC 3557059. PMID 23267114.
  16. ^ E. Thyrhaug; K. Zidek; J. Dostal; D. Bina; D. Zigmantas (2016). "Exciton Structure and Energy Transfer in the Fenna−Matthews− Olson Complex". J. Phys. Chem. Lett. 7 (9): 1653–1660. doi:10.1021/acs.jpclett.6b00534. PMID 27082631.
  17. ^ Y. Fujihashi; G. R. Fleming; A. Ishizaki (2015). "Impact of environmentally induced fluctuations on quantum mechanically mixed electronic and vibrational pigment states in photosynthetic energy transfer and 2D electronic spectra". J. Chem. Phys. 142 (21): 212403. arXiv:1505.05281. Bibcode:2015JChPh.142u2403F. doi:10.1063/1.4914302. PMID 26049423. S2CID 1082742.
  18. ^ Mohseni, Masoud; Rebentrost, Patrick; Lloyd, Seth; Aspuru-Guzik, Alán (2008-11-07). "Environment-assisted quantum walks in photosynthetic energy transfer". The Journal of Chemical Physics. 129 (17): 174106. arXiv:0805.2741. Bibcode:2008JChPh.129q4106M. doi:10.1063/1.3002335. ISSN 0021-9606. PMID 19045332. S2CID 938902.
  19. ^ Plenio, M B; Huelga, S F (2008-11-01). "Dephasing-assisted transport: quantum networks and biomolecules – IOPscience". New Journal of Physics. 10 (11): 113019. arXiv:0807.4902. Bibcode:2008NJPh...10k3019P. doi:10.1088/1367-2630/10/11/113019. S2CID 12172391.
  20. ^ Lloyd, Seth (2014-03-10). Optimal Energy Transport in Photosynthesis (Speech). From Atomic to Mesoscale: The Role of Quantum Coherence in Systems of Various Complexities. Institute for Theoretical, Atomic and Molecular and Optical Physics, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts. Retrieved 2019-09-30.
  21. ^ Lee, Hohjai (2009). "Quantum coherence accelerating photosynthetic energy transfer". Ultrafast Phenomena XVI. Chemical Physics. Springer Series in Chemical Physics. 92. pp. 607–609. Bibcode:2009up16.book..607L. doi:10.1007/978-3-540-95946-5\_197. ISBN 978-3-540-95945-8. [permanent dead link]
  22. ^ Walschaers, Mattia; Fernandez-de-Cossio Diaz, Jorge; Mulet, Roberto; Buchleitner, Andreas (2013-10-29). "Optimally Designed Quantum Transport across Disordered Networks". Physical Review Letters. 111 (18): 180601. arXiv:1207.4072. Bibcode:2013PhRvL.111r0601W. doi:10.1103/PhysRevLett.111.180601. PMID 24237498. S2CID 40710862.
  23. ^ Halpin, A.; Johnson, P.J.M.; Tempelaar, R.; Murphy, R.S.; Knoester, J.; Jansen, T.L.C.; Miller, R.J.D. (2014). "Two-Dimensional Spectroscopy of a Molecular Dimer Unveils the Effects of Vibronic Coupling on Exciton Coherences". Nature Chemistry. 6 (3): 196–201. Bibcode:2014NatCh...6..196H. doi:10.1038/nchem.1834. PMID 24557133.
  24. ^ Duan, H.-G.; Prokhorenko, V.I.; Cogdell, R.; Ashraf, K.; Stevens, A.L.; Thorwart, M.; Miller, R.J.D. (2017). "Nature does not rely on long-lived electronic quantum coherence for photosynthetic energy transfer". Proc. Natl. Acad. Sci. 114 (32): 8493–8498. doi:10.1073/pnas.1702261114. PMC 5559008. PMID 28743751.
  25. ^ Cao, Jianshu; Cogdell, Richard J; Coker, David F; Duan, Hong-Guang; Hauer, Jürgen; Kleinekathöfer, Ulrich; Jansen, Thomas LC; Mančal, Tomáš; Miller, RJ Dwayne; Ogilvie, Jennifer P; Prokhorenko, Valentyn I; Renger, Thomas; Tan, Howe-Siang; Tempelaar, Roel; Thorwart, Michael; Thyrhaug, Erling; Westenhoff, Sebastian; Zigmantas, Donatas (2020). "Quantum Biology Revisited". Science Advances. 6 (14): eaaz4888. doi:10.1126/sciadv.aaz4888. PMID 32284982.
  26. ^ "DNA and Mutations". evolution.berkeley.edu. Retrieved 2018-11-05.
  27. ^ Jump up to:a b Trixler, Frank (August 2013). "Quantum Tunnelling to the Origin and Evolution of Life". Current Organic Chemistry. 17 (16): 1758–1770. doi:10.2174/13852728113179990083. ISSN 1385-2728. PMC 3768233. PMID 24039543.
  28. ^ Yu, Sung-Lim; Lee, Sung-Keun (March 2017). "Ultraviolet radiation: DNA damage, repair, and human disorders". Molecular & Cellular Toxicology. 13 (1): 21–28. doi:10.1007/s13273-017-0002-0. ISSN 1738-642X. S2CID 27532980.
  29. ^ Klopping, Hein L. (May 1971). "Olfactory theories and the odors of small molecules". Journal of Agricultural and Food Chemistry. 19 (5): 999–1004. doi:10.1021/jf60177a002. ISSN 0021-8561. PMID 5134656.
  30. ^ Malcolm Dyson, G. (1938-07-09). "The scientific basis of odour". Journal of the Society of Chemical Industry. 57 (28): 647–651. doi:10.1002/jctb.5000572802. ISSN 0368-4075.
  31. ^ Jump up to:a b c Turin, Luca (1996). "A Spectroscopic Mechanism for Primary Olfactory Reception". Chemical Senses. 21 (6): 773–791. doi:10.1093/chemse/21.6.773. ISSN 0379-864X. PMID 8985605.
  32. ^ Brookes, Jennifer C. (2017-05-01). "Quantum effects in biology: golden rule in enzymes, olfaction, photosynthesis and magnetodetection". Proc. R. Soc. A. 473 (2201): 20160822. Bibcode:2017RSPSA.47360822B. doi:10.1098/rspa.2016.0822. ISSN 1364-5021. PMC 5454345. PMID 28588400.
  33. ^ "Odorant shape and vibration likely lead to olfaction satisfaction". Retrieved 2018-11-08.
  34. ^ "A Novel Multigene Family May Encode Odorant Receptors: A Molecular Basis for Odor Recognition" (PDF). April 5, 1991. Retrieved November 7, 2018.
  35. ^ Block, Eric; Batista, Victor S.; Matsunami, Hiroaki; Zhuang, Hanyi; Ahmed, Lucky (2017-05-10). "The role of metals in mammalian olfaction of low molecular weight organosulfur compounds". Natural Product Reports. 34 (5): 529–557. doi:10.1039/c7np00016b. ISSN 0265-0568. PMC 5542778. PMID 28471462.
  36. ^ Keller, Andreas; Vosshall, Leslie B (2004-03-21). "A psychophysical test of the vibration theory of olfaction". Nature Neuroscience. 7 (4): 337–338. doi:10.1038/nn1215. ISSN 1097-6256. PMID 15034588. S2CID 1073550.
  37. ^ Johnson, P. J. M.; Farag, M. H.; Halpin, A.; Morizumi, T.; Prokhorenko, V. I.; Knoester, J.; Jansen, T. L. C.; Ernst, O. P.; Miller, R. J. D. (2017). "The Primary Photochemistry of Vision Occurs at the Molecular Speed Limit". J. Phys. Chem. B. 121 (16): 4040–4047. doi:10.1021/acs.jpcb.7b02329. PMID 28358485.
  38. ^ Schoenlein, R. W.; Peteanu, L. A.; Mathies, R. A.; Shank, C. V. (1991-10-18). "The first step in vision: femtosecond isomerization of rhodopsin". Science. 254 (5030): 412–415. Bibcode:1991Sci...254..412S. doi:10.1126/science.1925597. ISSN 0036-8075. PMID 1925597.
  39. ^ "The Human Eye and Single Photons". math.ucr.edu. Retrieved 2018-11-05.
  40. ^ Panitchayangkoon, Gitt; Hayes, Dugan; Fransted, Kelly A.; Caram, Justin R.; Harel, Elad; Wen, Jianzhong; Blankenship, Robert E.; Engel, Gregory S. (2017). "Quantum Biometrics with Retinal Photon Counting". Physical Review Applied. 8 (4): 044012. arXiv:1704.04367. Bibcode:2017PhRvP...8d4012L. doi:10.1103/PhysRevApplied.8.044012. S2CID 119256067.
  41. ^ Emerging Technology from the arXiv. "The unique way your eyes detect photons could be used to guarantee your identity, say physicists". MIT Technology Review. Retrieved 2018-11-08.
  42. ^ Apte SP, Quantum biology: Harnessing nano-technology’s last frontier with modified excipients and food ingredients, J. Excipients and Food Chemicals, 5(4), 177–183, 2014.
  43. ^ Jump up to:a b Nagel, Zachary D.; Klinman, Judith P. (2006-10-24). "Tunneling and Dynamics in Enzymatic Hydride Transfer". ChemInform. 37 (43): 3095–118. doi:10.1002/chin.200643274. ISSN 0931-7597. PMID 16895320.
  44. ^ Gray, Harry B.; Winkler, Jay R. (2003-08-01). "Electron tunneling through proteins". Quarterly Reviews of Biophysics. 36 (3): 341–372. doi:10.1017/S0033583503003913. ISSN 1469-8994. PMID 15029828.
  45. ^ Nagel, Zachary D.; Klinman, Judith P. (2006-08-01). "Tunneling and Dynamics in Enzymatic Hydride Transfer". Chemical Reviews. 106 (8): 3095–3118. doi:10.1021/cr050301x. ISSN 0009-2665. PMID 16895320.
  46. ^ Lambert, Neill; Chen, Yueh-Nan; Cheng, Yuan-Chung; Li, Che-Ming; Chen, Guang-Yin; Nori, Franco (2013-01-01). "Quantum biology". Nature Physics. 9 (1): 10–18. Bibcode:2013NatPh...9...10L. doi:10.1038/nphys2474. ISSN 1745-2473.
  47. ^ Jump up to:a b c Hore, P. J.; Mouritsen, Henrik (5 July 2016). "The Radical-Pair Mechanism of Magnetoreception". Annual Review of Biophysics. 45 (1): 299–344. doi:10.1146/annurev-biophys-032116-094545. PMID 27216936.
  48. ^ Schulten, Klaus; Swenberg, Charles E.; Weller, Albert (1978). "A Biomagnetic Sensory Mechanism Based on Magnetic Field Modulated Coherent Electron Spin Motion: Zeitschrift für Physikalische Chemie". Zeitschrift für Physikalische Chemie. 111: 1–5. doi:10.1524/zpch.1978.111.1.001. S2CID 124644286.
  49. ^ Kominis, I.K. (2015). "The radical-pair mechanism as a paradigm for the emerging science of quantum biology". Mod. Phys. Lett. B. 29: 1530013. arXiv:1512.00450. Bibcode:2015MPLB...29S0013K. doi:10.1142/S0217984915300136. S2CID 119276673.
  50. ^ T., Rodgers, Christopher (2009-01-01). "Magnetic field effects in chemical systems". Pure and Applied Chemistry. 81 (1): 19–43. doi:10.1351/PAC-CON-08-10-18. ISSN 1365-3075.
  51. ^ Steiner, Ulrich E.; Ulrich, Thomas (1989-01-01). "Magnetic field effects in chemical kinetics and related phenomena". Chemical Reviews. 89 (1): 51–147. doi:10.1021/cr00091a003. ISSN 0009-2665.
  52. ^ Woodward, J. R. (2002-09-01). "Radical Pairs in Solution". Progress in Reaction Kinetics and Mechanism. 27 (3): 165–207. doi:10.3184/007967402103165388. S2CID 197049448.
  53. ^ Jump up to:a b Wiltschko, Roswitha; Ahmad, Margaret; Nießner, Christine; Gehring, Dennis; Wiltschko, Wolfgang (2016-05-01). "Light-dependent magnetoreception in birds: the crucial step occurs in the dark". Journal of the Royal Society, Interface. 13 (118): 20151010. doi:10.1098/rsif.2015.1010. ISSN 1742-5662. PMC 4892254. PMID 27146685.
  54. ^ Levine, Raphael D. (2005). Molecular Reaction Dynamics. Cambridge University Press. pp. 16–18. ISBN 978-0-521-84276-1.
  55. ^ Harald Krug; Harald Brune; Gunter Schmid; Ulrich Simon; Viola Vogel; Daniel Wyrwa; Holger Ernst; Armin Grunwald; Werner Grunwald; Heinrich Hofmann (2006). Nanotechnology: Assessment and Perspectives. Springer-Verlag Berlin and Heidelberg GmbH & Co. K. pp. 197–240. ISBN 978-3-540-32819-3.

12/7/2020